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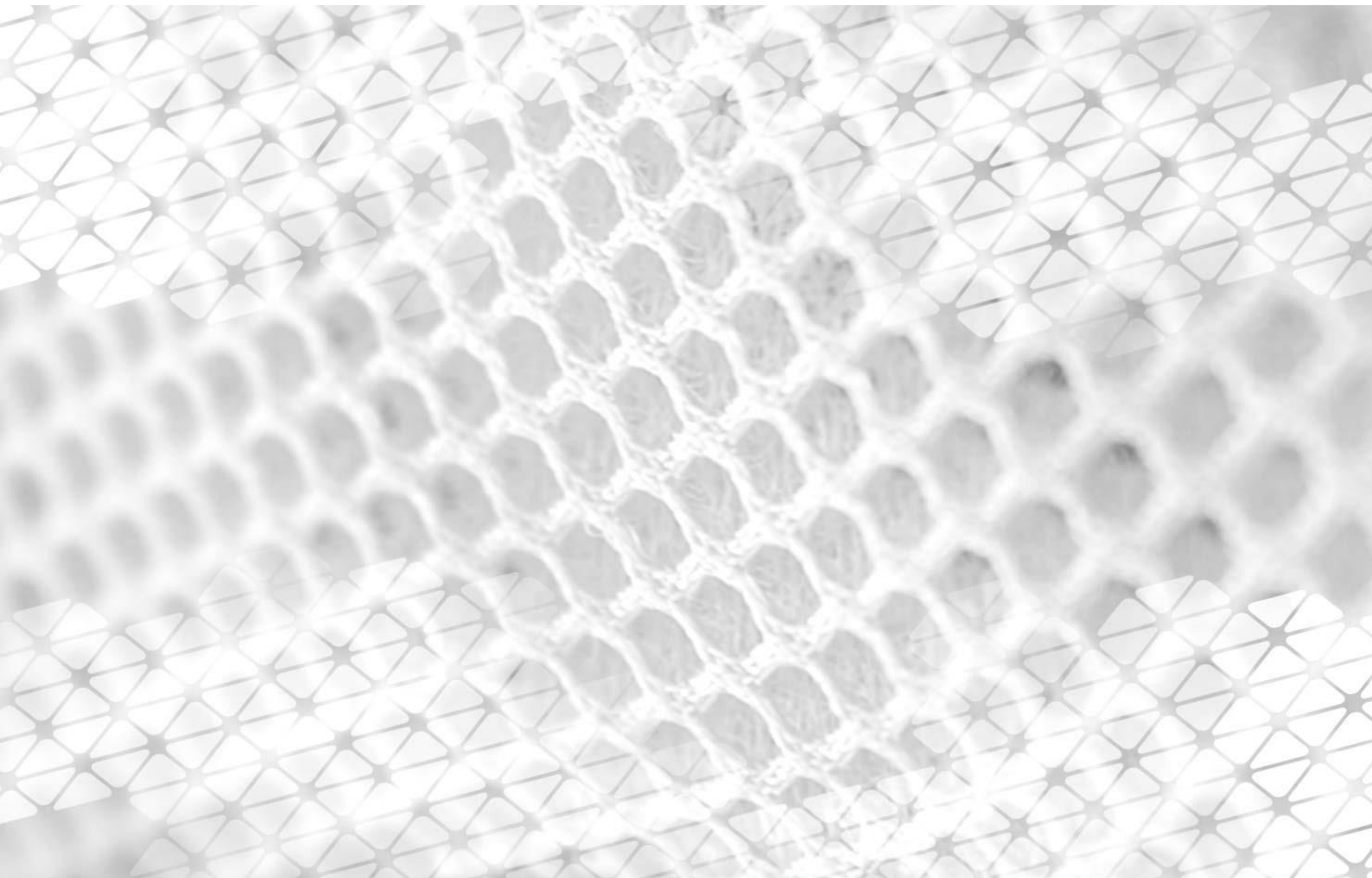
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Chemnitz, Germany
15–16 July 2021

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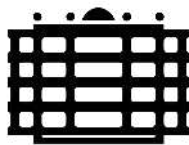CHEMNITZ

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Editors

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Uwe Götze
Martin Dix
Giuseppe Amodeo
Dominik Krumm
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Foreword

Dear future Scientists and Researchers, dear Colleagues, dear Students,

it is our great pleasure to present the Book of Abstracts of the 1st edition of the Advanced Manufacturing Student Conference (AMSC). The first edition of the conference (AMSC21) was jointly organised by the Faculty of Mechanical Engineering at Chemnitz University of Technology and the Fraunhofer Institute for Machine Tools and Forming Technology.

The AMSC represents an educational format designed to foster the acquisition and application of skills related to Research Methods in Engineering Sciences. Participating students are required to write and submit a conference paper and are given the opportunity to present their findings during the conference. Thus, the AMSC provides a tremendous opportunity for participants to practice critical skills associated with scientific publication. This first Conference Proceeding illustrates the broad interest of the participants in the field of Advanced Manufacturing.

The publication of the conference papers under Open Access License does allow free and unrestricted access. Open Access publishing ensures that the conference papers can be found, accessed and cited by other researchers and, thus, elevates academic visibility of the participants in an early stage of their career.

Another important aspect of the AMSC is the Peer-Review process for submitted papers. A two-stage review process is applied. During a first phase, the papers are reviewed by two fellow participants. In a second stage experienced "professional" reviewers are involved to check and improve the participants' reviews, ensuring a good quality of reviews and final articles.

We look forward to meeting you at the motivating and engaging next event in 2022, that will provide you an inspiring taste of the Future of Manufacturing.

Best regards,

Chemnitz, 3rd January 2022

Prof. Dr.-Ing. Stephan Odenwald   Prof. Dr. Uwe Götze   Prof. Dr.-Ing. Martin Dix

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Advances in "classical" Manufacturing Technologies

Review article

Analysis of spot joining technologies for steel and aluminum alloys in structures of a vehicle body†

Husain Signalwala [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: husain.signalwala@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: The use of different metals in the automobile industry to reduce the structure's weight is a norm nowadays. The problem that arises here is joining such dissimilar metals, for example, steel and aluminum alloys. The issues that occur with conventional spot welding are solved by making amendments to the workpiece geometry, adding some materials, or altering the electrode geometry. The patents were obtained from databases such as USPTO and Google patents. The research conducted could solve the problems occurring in the joining of steel and aluminum alloys in a vehicle body by altering the geometry of the electrodes or the workpieces. Incorporating these researches into the production process is still a huge challenge.

Keywords: steel; aluminium; electrode; spot; joining.

1. Introduction

The joining of dissimilar metals is not an easy task and cannot be performed by conventional spot joining technologies. Here, we investigate some spot joining technologies that can successfully conduct the joining of steel and aluminum alloys that are to be used in a structure of a passenger vehicle body.

There is an inclination towards using multiple metal alloys in the manufacturing process of a vehicle body to provide a lightweight structure. Hence, in various structures such as roof, trunk lids, and doors, aluminum alloys are used where the high strength of steel is not too necessary. The inclusion of aluminum brings the problem of joining aluminum alloys with steel alloys. Spot welding is already an established method used in automobile industries to increase automation and reduce cycle time. However, the spot welding of dissimilar metals such as steel and aluminum poses challenges. Compared to aluminum alloys, steel alloys have some significant properties, such as higher melting points and higher thermal and electrical resistivities. Due to these differences, the weld pool of aluminum forms quickly during the spot welding as it melts faster and cools down faster. This leads to defects such as shrinkage, gas porosity, and microcracking at the welding junction. As steel has higher heat resistance, there are chances of formation of brittle Fe-Al intermetallic compounds at elevated temperatures during the spot welding (Sigler et al., 2015).

Such problems may reduce the peel strength of the welded joint and decrease the overall strength and integrity of the structure of the vehicle body, which may lead to fatal accidents. The following methods are investigated to overcome these challenges that provide a successful weld joint of steel and aluminum alloys used in a vehicle body.

2. Methods

Patents related to joining aluminum and steel alloys were searched on the website of 'United States patents and trademark office' and 'Google scholar patents.' The website of 'European Patent office' was also looked upon, but nothing close to the topic was found there. The search terms used were "Spot joining of steel and aluminum," "Joining of steel and aluminum," "Joining technologies in automobile industries," "Joining of dissimilar metals," "Joining of dissimilar metals in a vehicle body." Various state-of-the-art patents were found related to the topic.

A total of 17 patents were chosen for sampling the final patents to be reviewed. Some of the other technologies used for joining aluminum and steel were soldering, explosion bonding, friction welding process, and brazing which were not the area of concern and were not chosen for the review paper. Using the term "Joining of dissimilar metals in a vehicle body," patents related to joining magnesium alloy to aluminum alloy were found. Those were also sampled out as the focus was on joining steel and aluminum alloys only. Few patents were also related to the material in principle, but the application area was not that of the automobile industry. So, a total of 7 patents were chosen to write this

paper as the technology, material, and application aligned with that of the topic. The automobile industry dates back to the 18th century, and it would not be logical to consider the technologies of the past 200 years. Thus, the publication dates of the patents reviewed range from 1998-2020, the previous two decades.

3. Findings

Various amendments to the conventional spot-welding technique are done in the following patents. It may be adding extra material, changing the shape of electrodes, using adhesives, or altering the workpiece weld area.

Oikawa et al. (1998) use an aluminum-clad steel sheet, 0.2 to 1.2 mm thick (comprising a laminate of a steel-base metal sheet and aluminum-based metal sheet). This sheet is inserted between the steel-base metal sheet and aluminum base metal sheet so that the same types of metal face each other, and the resistance welding is carried out. The weld current is 7.5 to 15.5 kA and a weld time ranging from 80 to 280 ms. The current carrying area is generated on one of the interfaces between the steel-base metal sheet and the aluminum-clad steel sheet. This is the area where the nugget is formed, and the assembly is joined. The aluminum-clad steel sheet has a thickness ratio to the aluminum-base metal sheet to the steel-base metal sheet in the range from 1:1.3 to 1:5.0 (Oikawa et al., 1998).

Riveting is also a spot joining technology. The method of joining by Ogawa et al. (2007) makes use of a non-piercing rivet. The automobile body parts to be joined here are an aluminum roof panel and a side roof rail made of steel alloy. The electrically insulating adhesive is inserted between the surfaces of the dissimilar metals to avoid the direct contact of the metals to avoid stray current corrosion. Then a non-piercing rivet is inserted to the bottom surface of a groove portion created on the structures of the dissimilar metals, and the structures are mechanically joined (Ogawa et al., 2007).

Hayashi et al. (2010) make amendments to the structures to be joined. The outer roof panel made of aluminum alloy, the first material, is to be welded with the outer panel of roof side rail made of galvannealed steel sheet, second material. The welding of the first material and second material is not possible directly. Hence, the inner panel of the roof side rail, the third material, is made of electro-galvanized steel or non-galvanized steel that can be welded with the outer panel of the roof, the first material. The outer panel of the side roof rail, the second material, has notches that expose the inner panel's projections, third material. The height of these projections is slightly higher than the thickness of the outer panel of the side roof rail, the second material. With the help of these notches and the upward projections, the outer roof panel, the first material is in direct contact with the inner panel of the rail, third material and can be spot welded successfully (Hayashi et al., 2010).

The invention by Kobayashi et al. (2010) presents the use of a third material, a metallic compound that is to be interposed between the first material, aluminum, and the second material, steel. The third material, the metallic compound, is different than both the first and second metals. The aim is to achieve a eutectic melting at least either at an interface between the first and third metal materials or at an interface between the second and third metal materials. The interdiffusion region reaches a eutectic composition at a temperature higher than or equal to a eutectic temperature and lower than the melting points of the metals. The eutectic layer protects the dissimilar metal materials from reacting with each other. The resistance spot welding can do the eutectic melting (Kobayashi et al., 2010).

Sigler et al. (2015) use a weld face cover in their methodology of spot welding.
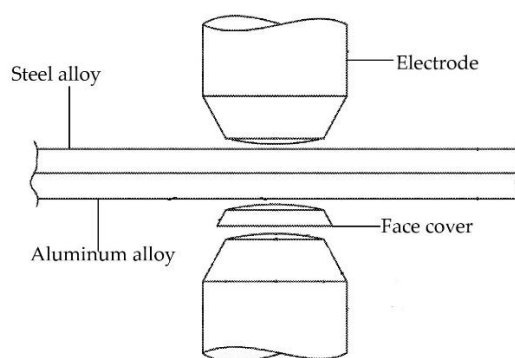
Figure 1. Spot welding arrangement using a weld face cover (Sigler et al., 2015)

The stack-up assembly of steel and aluminum alloy is welded with one of the electrodes having a removable cover on its weld face. The cover is attached by a crimping process or a screwing process. The electrode with the face cover is

to be kept in contact with the aluminum or aluminum alloy during the resistance spot welding process. The face cover can be of the material with higher heat resistivity than aluminum, such as steel, stainless steel, tungsten, molybdenum. When the spot welding occurs, the heat can be increased in the electrode as it has a face cover. It is found that the solidification of the weld joint on the aluminum surface has been altered with the help of this high heat, which can avoid defects along with the faying interface. The addition of the face cover also helps to reduce the heat generated in the steel workpiece, which in turn helps to limit the growth of intermetallic Fe-Al compounds. As a result, the peel strength of the joint is maintained, and the overall strength and integrity can be achieved (Sigler et al., 2015).

In the invention by Yang & Sigler (2015), the stack-up assembly having steel and aluminum alloys stacked is spot welded where the area to be welded has a protuberance on the steel workpiece.
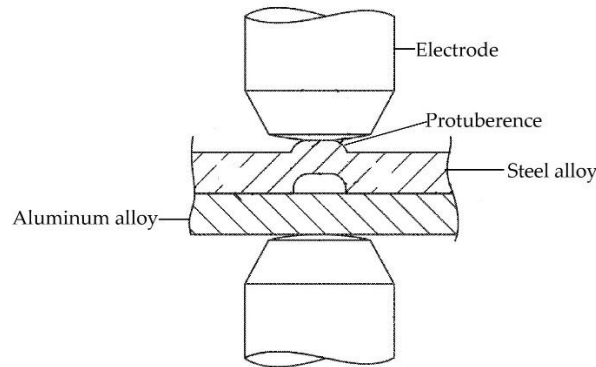
Figure 2. Spot welding arrangement using protuberance (Yang & Sigler, 2015)

The protuberance is generated by forming or by a fusion process on the steel workpiece or by a cold spraying process. The diameter of the protuberance is lesser than the face of the electrode or 3.0 mm. The protuberance on the steel workpiece encounters the electrode during the welding process, and the steel is stacked on the aluminum alloy. The heat generated by the electrode passes through the protuberance. With the help of the protuberance, the heat generated by the current is concentrated and penetrated through the oxide layers present on the inner surface of the aluminum alloy. This concentrated heat alters and modifies the solidification of the weld pool. The alteration of solidification leads to the limitation of the defects generated at the faying surface (Yang & Sigler, 2015).

In the state-of-the-art technology presented by Wang et al. (2020), the electrodes used for spot welding the aluminum and steel alloys have mating surfaces. The first electrode, which comes in contact with the aluminum sheet, has an ascending convex surface. The second electrode that meets the steel alloy sheet has a complimentary-sized concave portion that can mate with the opposite electrode.
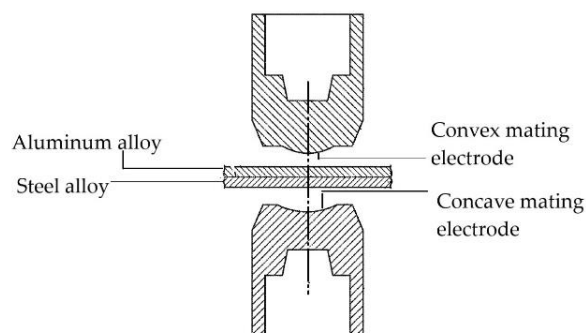
Figure 3. Spot welding arrangement using mating electrodes (Wang et al., 2020)

The first electrode is contacted so that only the convex area touches the aluminum alloy sheet. The second electrode is approached so that only the straight profile other than the concave area touches the steel alloy sheet surface. The current is then passed through the electrodes. Due to such an arrangement of the mating faces of electrodes, the current flow path is generated radially outward from the first electrode passing through the aluminum alloy and steel

alloy sheets towards the second electrode, which results in more robust, more peel and stress-resistant joints with a thinner layer of intermetallic compounds formed (Wang et al., 2020).

4. Conclusion

The findings depict the successful joining of aluminum alloys and steel alloys in the structure of a vehicle body. As it has been observed, there are quite a few changes made to the conventional resistance spot welding process. The main focus of most of the inventions has been to reduce the heat accumulated in the steel workpiece so that the inter-metallic brittle Fe-Al compounds are not formed and to modify the solidification of the weld pool on the aluminum alloy surface to minimize the defects such as shrinkage and microcracks.

Some state-of-the-art technologies use extra materials in the workpiece assembly like a clad sheet or an electrically insulated adhesive. Using a clad sheet may increase the number of materials in the structure and increase the material cost. Compared to the technologies that increase the number of materials, technologies with alterations made in the electrodes can be more cost and material efficient. The reason being that is, the altered electrodes, such as the mating electrodes and electrodes with face cover, can be used for the entire production life of the product. Other technologies do not add material in the workpiece assembly but make few changes in the workpiece geometry, such as providing notches and protuberance to the metal sheets. Such technologies can also prove to be competitive. The only drawback here is to add a step in the production process to alter the workpiece geometry. If done efficiently, such methods could solve the problems and make the tasks easier from a long-term perspective.

In all the findings discussed, the problem of spot joining the aluminum and steel alloys was solved successfully. The technologies, from a research point of view, were helpful to get rid of the problems, but in some findings, it is an area of concern to incorporate these researches in the production process. Some findings by research could not even mention the values of the strength achieved by using the particular invention. Such data and numerical values would be more helpful to compare the inventions. The automobile industry cannot survive without the joining technologies, and it will be exciting to see further developments made in the spot joining technologies used in the automobile industry.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

A review on forming processes and material design adopted for the improved formability of Fiber Metal Laminates[†]

Pravishan Bhandari [1,*]

[1]   Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: pravishan.bhandari@s2020.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: The fiber metal laminates (FMLs) are the lightweight structural materials used especially in the aerospace applications because of relatively low density, higher fatigue, impact and fire resistance and higher energy absorption characteristics. However, the current manufacturing technology is only limited to the small curvature parts with time consuming and costly process chain. The damage mechanisms like fiber tearing, cracking, wrinkling and delamination during forming process limits the use of FMLs in automotive application. Thus, the aim of this review study is to focus on the forming processes and material designs adopted for the improved formability of thermoset FMLs. The papers that showed the clear improvement in formability with respect to different processes and material parameters were screened among many for the purpose of this review. It was found that the radial fiber orientation, pre-heating of blank, use of filler materials, hot stamping, introduction of additional elastomer layer, simultaneous resin injection and deep drawing, and non-conventional forming like electromagnetic forming and hydro mechanical forming, all contributed towards the improved formability of FMLs.

Keywords: fiber metal laminate; improved formability; deep drawing; damage mechanisms; lightweight material.

1. Introduction

The challenges of reducing the fuel consumption and CO_2 emission can be achieved using lightweight structural materials. One such class of material is fiber metal laminate. FMLs are hybrid composite structures in which fiber-reinforced polymeric material is bonded between the thin sheets of metal/alloys. They possess relatively low density with higher fatigue and impact resistance, fire resistance and higher energy absorption.

Especially, the aerospace and defense industries use commercially available Aramid-Reinforced Aluminum Laminate (ARALL) and Glass-Reinforced Aluminum Laminate (GLARE). The small curvature parts are made by direct forming of large FML sheets. The other approach is to preform the face sheet, mold the core separately and then finally produce the required part using bonding operation. However, this time consuming and costly process chain is not reasonable for mass production of the complex parts as in automotive industries (Heggemann & Homberg, 2019).

The different properties of metal, fiber and matrix causes restriction in formability of the laminates. The metal has capability to endure elastic and plastic state whereas fibers have very low formability. The material properties like matrix viscosity, fiber orientation as well forming parameters like punching force, punch speed, holding force etc. all influence the quality of the formed part. Dependently, the appearance of crack, fiber tearing, wrinkling and delamination are some of the failures associated with the forming of FMLs (Blala, Lang, Li, & Alexandrov, 2021).Therefore, the objective of this review paper is to present the findings in relation to the forming processes and material design adopted for the improvement in formability of FMLs.

2. Methods

A first glance of the literatures to be included in this review paper were obtained using the scholarly literature search engine Google Scholar with combination of key words: "forming", "potential", "fiber metal laminates" and "formability". After the first overview, further keywords such as: "deep drawing", "stamping", "defects", "hydroforming ", "increasing/improving" were combined in a logical manner to show only the relevant articles. These logically combined keywords were used again in the database of Scopus, ResearchGate and Elsevier so as not to omit any important papers.

Based on the closeness of the title to the objective of this review paper, around sixteen articles were selected, which were further categorized into sufficient, good, and not good after studying the abstract, introduction, and discussion/conclusion sections. The sufficient articles were immediately accepted, not good articles were immediately rejected, and good articles were studied thoroughly before accepting them. The papers with experimental study showing the clear relation between different processes and material parameters with the improved formability and quality associated with the FMLs were only considered.

3. Results

Experiments were conducted with selective placement of fibers with different orientations to reduce wrinkling on the flange of the part. The radial orientation of fibers with angle of $45^0/135^0$ prevented the compression in fiber resulting due to the tangential stress. This approach reduced the wrinkle height by 62% as shown in Figure 1 (Heggemann & Homberg, 2019). The similar improvement in forming performance due to 45^0 layup of prepreg was seen in the experiment done by (Li, Lang, Hamza, & Alexandrov, 2020). Here, the positive effect for FMLs with prepreg, dry textile and pre-heated prepreg having the skin layer thickness of 0.5mm was seen.
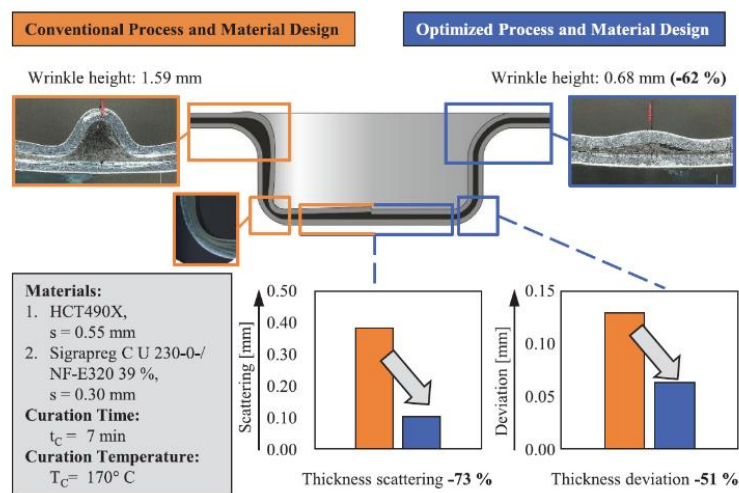
Figure 1. Comparative image for the conventional and optimized process and material design (Heggemann & Homberg, 2019).

The homogenous wall thickness was another requirement for quality forming process. The problem of local thinning in the radii zone was accounted for the normal stress generated by the punch force. In case of GLARE laminate with the hot pressing, the absolute total thickness reduction was decreased by 52.85% for the different layers of FMLs (Blala et al., 2021). In the next approach glass beads were used as filler material without major effect on the bonding area between the metal and core. The absolute thickness deviation was decreased by 51% as in figure 1. Also, the pre-curing in the bottom and flat areas before the actual combined forming and curing, reduced the scattering of wall thickness by 73% (Heggemann & Homberg, 2019).
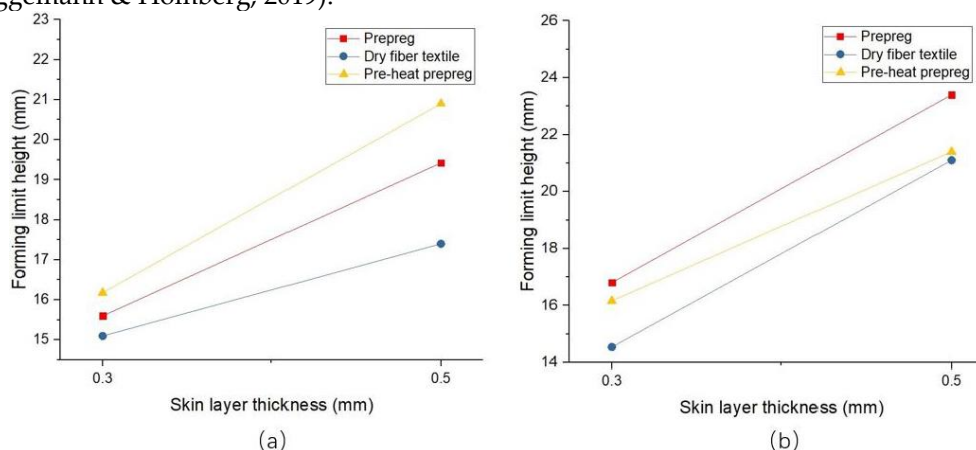
Figure 2. The plot of forming limit height for the different thickness of skin layer (a) The direction of core layer is 0^0 (b) The direction of core layer is 45^0 (Li et al., 2020).

The use of epoxy resin transmits the stress uniformly, hence a 6.5% of improvement in formability was seen as compared to using dry fibers in between aluminum layers. With the pre-heating of laminating prepreg a 9.5% improvement was observed. In the same experiment, it was seen that under the other conditions being similar, the formability of laminates improved as the skin layer thickness increased as shown in figure 2 (Li et al., 2020).

In the other attempt to increase forming, elastomer layers were introduced between the core and outer aluminum layer. For this fiber metal elastomer laminate (FMEL), the achieved bending radii was 1.2 mm instead of 10 mm for the comparable FML. Moreover, the curing time was reduced to 300 s, which made the process much shorter. The formed specimen had homogenous distribution of Carbon Fiber Reinforced Polymer (CFRP) layer while in absence of elastomer, thinner CFRP layer on concave side and thick layer in parallel to bending axis on the convex side of profile was observed as shown in figure 3 (Roth, Coutandin, & Fleischer, 2019).
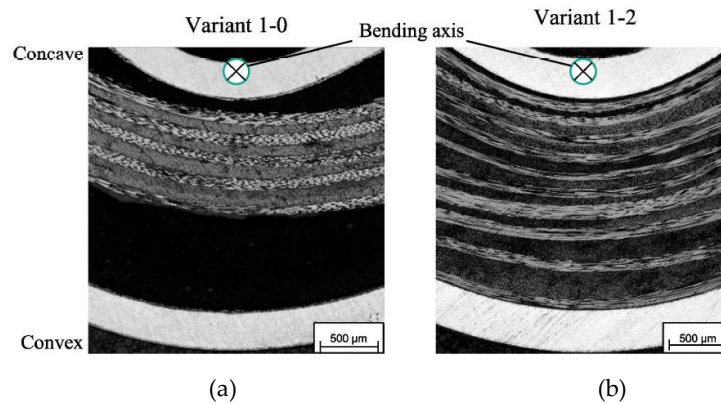
Figure 3. Microsection of formed laminates for (a) FMEL (b) FML (Roth et al., 2019).

The deep drawing by resin transfer molding is the single step chain to improve the formability of FMLs. In this method, when the punch travel was not 100% or without any contact with the female die, the low viscous polymer accumulated on no pressure region and created a bulged area. Also, the starting point of resin injection was the deciding factor for the failure free process. The too early injection caused low reaction force and hence overflow of the resin whereas too late injection caused large reaction force leading to reduced flow of resin and hence the breakage of fiber while forming. For the given experiment, the optimized starting point of injection was at 7% of the total punch travel, where the blank was completely in contact with the punch (Mennecart, Werner, Ben Khalifa, & Weidenmann, 2018).

The non-conventional metal forming technology such as electro-magnetic forming (EMF) was applied to FML. The experiment done with five-layer metal polymer laminate was compared against rubber pad forming (RPF). The equivalent strains after EMF were much less than after RPF on the convex side. The compressive value for circumferential strain and smaller tensile value for radial strain indicated the increase in formability as compared to conventional RPF. The penetration of magnetic field was calculated to be smaller than the metallic layer thickness due to which no difference in velocities of two outer layers was observed, thus confirming no delamination (Chernikov, Erisov, Petrov, Alexandrov, & Lang, 2019).
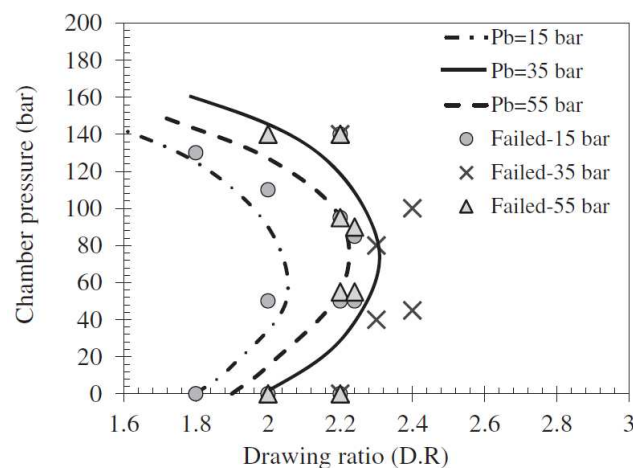
Figure 4. Influence of pre-bulging pressure on drawing ratio for different chamber pressure during HMD (Saadatfard et al., 2020).

For the hydromechanical drawing (HMD), (Saadatfard, Gerdooei, & Jalali Aghchai, 2020) provided a forming window (figure 4) showing the influence of pre-bulging and chamber pressure on the drawing ratio of FML. The characteristic curve of HMD process with respect to fluid pressure vs drawing ratio showed that HMD process increased the formability of FMLs sheet as compared to the conventional deep drawing, corresponding to chamber pressure of 0 bar. The optimum pre-bulging pressure of 35 bar had positive influence on drawability, while on increasing the pre-bulging pressure the excess thinning of sheet occurred. This phenomenon is shown by the nose of forming window being shifted to right side of the diagram for 35 bars compared to 15 and 55 bars as in figure 4.

4. Discussion

The compact result of different experimental findings focused on improving the formability and quality of FMLs has been presented in this paper. The analysis of the results shows the clear dependency of the formed FMLs with the process parameters and the material design. For reducing the wrinkling effect, the direction dependent fibers can be placed in radial manner as this reduces the compression effect of tangential stress. The uneven thinning of the FMLs in radii and bottom region can also be reduced by hot forming or by introducing the gap between the layers with the filler materials like glass beads. The pre-heating of blank and increasing the thickness of outer skin showed some extent of improvement in formability. The strategy of incorporating elastomer layer also helped to reduce the stress in the inner core fibers and hence a significant improvement in formability with lower cycle time was achieved.

The tool and die design change to allow simultaneous resin injection while deep drawing process can also produce the quality part provided the enclosing of part while forming and an optimized starting point of injection. The non-conventional forming process such as electromagnetic forming had compressive strain in contrast to tensile strains as in conventional process. Similarly, for hydro mechanical forming, a clear increase in drawing ratio was observed as compared to that of zero chamber pressure. The correct pre-bulging and chamber pressure allowed the highest value of drawing ratio.

All these reviewed papers show the promising way to improve the forming characteristics of FMLs. The ultimate objective of using FMLs in time and cost intensive automotive industries to reduce the part weight is still applicable. The above-mentioned positive outcomes may further be combined to enhance the formability, for example using hydro forming for optimally designed FMLs with in-situ heating. These improvements should obviously agree with the ability of mass production. The limitation of the mentioned papers is that the mechanical properties of the parts made by using these optimized processes have not been evaluated and hence the focus of future research should be to evaluate the feasibility of FMLs in actual application stage considering the properties of the final products.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Laser-Assisted Machining for processing difficult-to-machine materials compared to Conventional Machining†

Ismail Salah Ismail Mohamed [1,*]

[1]   Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: ismail.salah@s2018.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Due to their high yield stress, high strength to weight ratio, high wear resistance, high corrosion resistance, and ability to keep high strength at elevated temperatures, difficult-to-machine materials are becoming more popular in the applications of aerospace, and automotive industries. The machining of these materials using conventional methods is challenging because of the high temperature and pressure at the cutting area which increases the tool wear, decreasing the tool life, and increasing the processing time leading in the long run to a noticeable increase in the manufacturing costs. In this paper, laser-assisted machining (LAM) is reviewed as a new technique to process difficult-to-machine materials and compared to conventional machining methods. It was found that laser-assisted machining has significant advantages over conventional machining in terms of cutting force, material removal rate, tool wear, tool life, production costs, energy consumption, surface quality and roughness. On the other hand, LAM has some limitations such as excessive heating, and restriction to process round-shaped products.

Keywords: Thermal-assisted machining; laser-assisted machining; laser preheating.

1. Introduction

The need for materials with superior mechanical qualities and durability has risen in tandem with the advancement of modern manufacturing. Due to their brittle and hard qualities, difficult-to-machine materials such as ceramics, titanium alloys, and composite materials are difficult to manufacture with conventional machining techniques (CM), resulting in increased tool wear, lower feed rate, and shorter tool life. These difficult-to-machine materials are now employed in a wide range of industries, including aerospace, automotive, nuclear, and medical.

Turning, milling, and grinding are all examples of CM. Manufacturing difficult-to-machine materials with CM is usually time-consuming, expensive, and has extra environmental impact due to the constant demand for cooling fluid as a result of the high temperature and pressure at the cutting area. Thus, a new processing method known as thermally-assisted machining (TAM) to process these difficult-to-machine materials was established. TAM is a hybrid technique that combines preheating with one of the conventional machining methods, in which the workpiece is exposed to an external heat source. The main idea of TAM is to use a heat source to reduce the yield strength of brittle materials to a lesser extent than their fracture strength, making them more ductile and simpler to machine. The preheating phase can be carried out by a laser beam, plasma beam, induction heating, and ultrasonically.

The TAM that uses a laser beam as a heating source is known as Laser-Assisted Machining (LAM). The term laser is an acronym for "light amplification by stimulated emission of radiation". There are many different types of lasers, but the CO_2 laser and the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser are the most commonly utilized for production. In comparison to CO_2 lasers, Nd:YAG lasers are favored because of their higher absorptivity (Jeon, Park, & Lee, 2013). This paper compares LAM to CM in terms of cutting force, material removal rate, tool wear, tool life, cost efficiency, energy consumption, surface quality and roughness.

2. Methods

This review aims to compare, through the available data, LAM as a hybrid technique to process difficult-to-machine materials with the conventional methods of machining. The first stage of this research was the collection of data which was conducted by researching in different scientific databases such as Google Scholar, Science Direct, Elsevier, Springer, The International Journal of Advanced Manufacturing Technology, and The International Journal of Precision Engineering and Manufacturing.

Thermal-assisted manufacturing, laser-assisted manufacturing, and laser preheating were used as search terms for this topic. The search for the papers was set to be in the period 2012-2021 due to the fact that recent papers deal with new technologies resulting in more accurate results. After gathering sufficient information on all aspects of the study, the search was stopped.

The research was carried out utilizing the secondary quantitative research method to review past data. Citavi software was used to analyse the collected data narratively regarding the main research points and also to cite the references. The selection criteria were mainly based on the relevance of the abstract and results to the research questions. The most relevant papers were chosen to be the core of this review.

3. Results

Combining a laser beam with CM to preheat the brittle materials reduces its yield strength to levels below the fracture strength, causing the material's properties to shift from brittle to ductile, resulting in plastic deformation through the machining process. This method enables the use of conventional processing tools to process difficult-to-machine materials. A comparison was made between CAM and CM viewing different perspectives.

3.1. Comparison Points

3.1.1. Cutting force

A study using Taguchi Method to analyse cutting forces of LAM of Inconel 718 using turning process, compared to CM has found an enormous reduction of all cutting forces which can reach 60%. The most reduction of the cutting forces was noticed at low laser powers Figure 1. The higher the laser power the higher the reduction of the cutting forces, but it should be taken into consideration that with elevated laser power, the excessive heating leads to changes in the material microstructure which affects the product quality (Venkatesan, Ramanujam, & Kuppa, 2014).
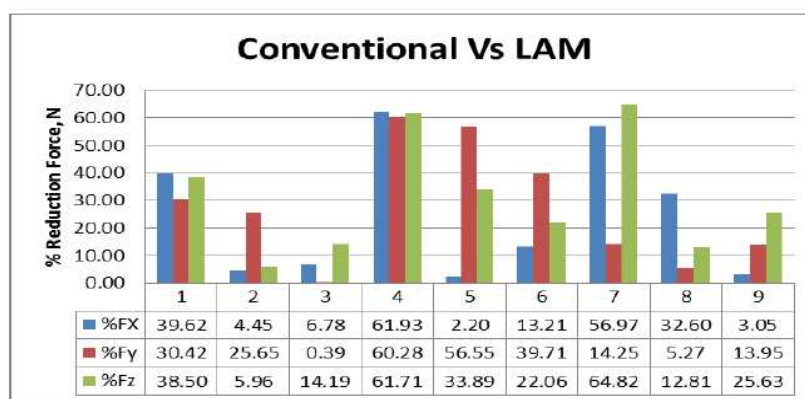
Figure 1. Reduction of the cutting forces when using CM and LAM at cutting speeds 50, 75 and 100 m/min, each speed was tested at laser power 1250, 1500 and 1750 Watt. (Venkatesan, Ramanujam, & Kuppa, 2014).

3.1.2. Material removal rate

A research on LAM to process particle-reinforced metal matrix composite (MMC) on an A359 aluminium matrix composite reinforced with 20 % by volume fraction silicon carbide particles revealed that the LAM surpassed CM in terms of volume of material removed at a fixed cutting speed (see Table 1.) (Dandekar & Shin, 2012).

Table 1. Comparison of the volume of material removed when using CM and LAM at different cutting speeds (Dandekar & Shin, 2012).

Cutting speed (m/min)	CM volume of material removed (cm³)	LAM volume of material removed (cm³)
50	6.48	15.26
100	7.00	15.38
150	12.08	21.13
200	11.45	19.20

3.1.3. Tool life and tool wear

A laser assisted turning experiment was carried out to process silicon carbide particle-reinforced aluminium matrix composites which showed that the tool life improved by 1.7 to 2.35 times when using LAM. The same study found that at higher cutting speeds, LAM resulted in less tool life because of the diffusion wear occurring at higher surface temperatures. The optimum material removal temperature was found to be 300°C with 37% reduction of surface roughness was established (Dandekar & Shin, 2012).

A study was executed to optimize the LAM process. The experiment was made at 220°C, 320°C, and 420°C. Figure 2. Shows that the optimum material removal temperature was found to be 320°C with an improvement of tool life 2.31 times over conventional machining (Kong, Yang, Zhang, Chi, & Wang, 2017).
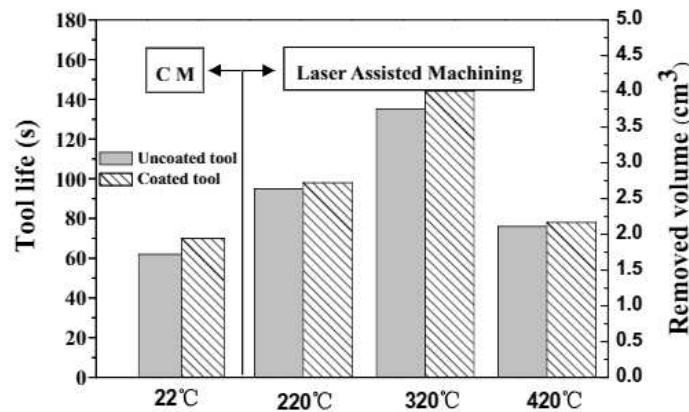
Figure 2. Comparison of tool life between CM and LAM at surface temperatures 220°C, 320°C, 420°C (Kong et al, 2017).

Another study found that by employing pulsed laser-assisted machining on nickel-based super alloys like Inconel 718, tool wear was reduced by 22% (see Figure 3.) (Dandekar & Shin, 2013).
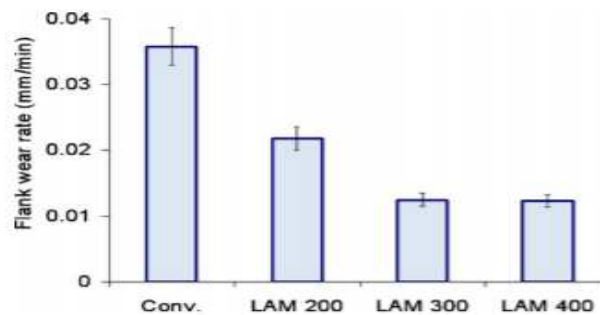
Figure 3. Comparison between CM and LAM in tool wear rate as a function of the material removal temperature (Dandekar & Shin, 2013).

3.1.4. Economical perspective and energy consumption

An investigation on laser-assisted machining of β21s titanium alloy conducted an economic analysis when using LAM and found that the economic benefit and the cutting efficiency were improved by 48.2% and 51.7% respectively (Xu, et al., 2020).

A research was executed to optimize the LAM process to machine metal matrix composites using Taguchi method and to analyse the benefit of using LAM over CM and it was found when using LAM, the machining time consumed to cut a fixed volume of material was reduced by 49% (see figure 4.) which led to a total reduction of the processing costs by 40-50% per part (Kong, Yang, Zhang, Chi, & Wang, 2017).
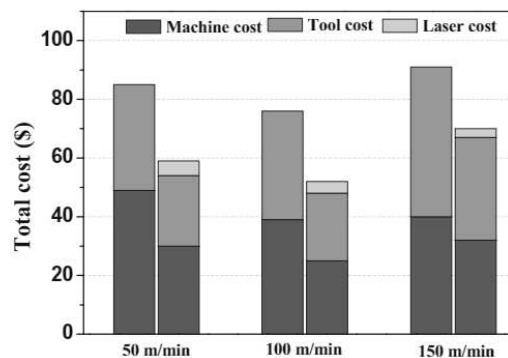
Figure 4. Comparing total cost when machining 1 m length using CM and LAM (Kong et al, 2017).

3.1.5. Surface quality and roughness

A study on the surface integrity of SiCp/2024Al composites processed by LAM achieved 81.73% reduced surface roughness (see Figure 5.) when compared to CM (Zhai et al, 2020).
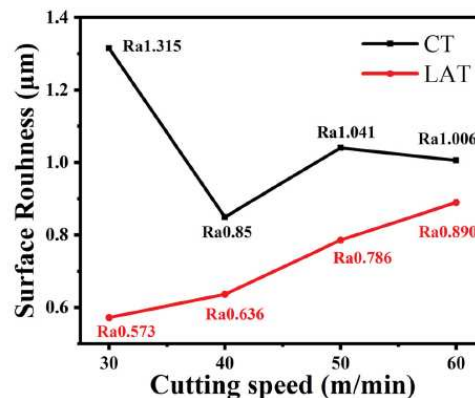
Figure 5. Comparing the surface roughness when using conventional turning (CT) and laser-assisted turning (LAT) as a function of cutting speed (Zhai et al, 2020).

4. Discussion

As previously stated, the external energy assistance using laser-assisted machining is remarkably advantageous over conventional machining in the processing of difficult-to-machine material and proven to be more efficient and more cost-effective than older approaches. On the other hand, utilizing LAM for industrial applications requires more dependable, safer, and reliable equipment.

Although LAM was proven to have noticeable advantages over CM, it is vital to remember that excessive preheating might affect the material's surface as when the surface temperature exceeds the melting point of the material, it might harden it causing a shorter tool life (Jeon Y. L., 2012). More studies are needed to determine the optimal process parameters for overall productivity, such as beam size and laser power. Additionally, more simulation-based models are needed to assess temperature distribution within the material, which is required to minimize mechanical strength.

LAM is still in the early stages of study and is only working with round-shaped products. However, some researchers proposed modifications by making laser-assisted turn-mill process to be able to machine much more complex shapes (Cha, Woo, & Lee, 2015). As a result, additional research and development for 3-D laser-assisted milling technologies is required in order to boost productivity and maintain technical superiority in global markets.

To conclude, this study on laser-assisted machining promises higher benefits compared to conventional machining, nevertheless there are still a few difficulties that require to be addressed in a future study.

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Review article

Traditional manufacturing and Additive manufacturing: A comparison†

Marmika Shinde [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: marmika.shinde@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Manufacturing industries and investors are continually trying to improve methods to reduce cost, energy and expand their capability. Since 1960's Additive Manufacturing (AM) has shown fast and continuous growth, bringing new techniques into picture to expand manufacturing capability and reinvent the wheel. At this stage, the interest of researchers and industries lies in determining whether or not AM can replace or create new manufacturing systems. Traditional manufacturing refers to subtractive manufacturing (SM) methods. This paper reviews the capability of AM and its current developments to compete with the established SM regions mainly in molding technology. This paper comparison focuses on the similarities, differences, advantages, and disadvantages from the perspective of economic and quality management in AM and SM.

1. Introduction

The rapid growth of Additive Manufacturing (AM) in the last 50 years has seen the developing manufacturing sector integrated into design and modeling as a rapid prototyping technique (Gao et al., 2015). AM better known as '3D printing', uses innovative technology to create complex shapes building a part up layer by layer. Contrary to established Traditional SM techniques, whereby material is either removed via machining, drilling, or grinding techniques or cast into molds, AM has a higher level of design freedom (Pereira, Kennedy, & Potgieter, 2019). Research in AM and integration of the technologies has pushed AM from rapid prototyping to rapid tooling and now to a future in Direct Manufacturing (Gausemeier, Echterhoff, Kokoschka, & Wall, 2011).

AM has integrated numerous manufacturing techniques (powder bed fusion, directed energy deposition, material extrusion, binder jetting, curing, lamination, etc.), to develop an extensive range of technologies of potential interest to industry (Gao et al., 2015). The reason behind the rapid advancement of AM technologies is due to the research focus on developing low-cost machines, increased material variability, and the complexity advantage to provide a wide range of applications. In some cases, the problem lies with the unpredictability of the machine to perform, introduce defects into the printed part, and difference in surface roughness across prints for the same digital input (Gao et al., 2015). Where SM produces machined components with high precision, low complexity, AM trades geometric complexity for poor tolerance and relative quality (Newman, Zhu, Dhokia, & Shokrani, 2015).

This paper aims to review where AM technologies dominate SM in established manufacturing regions. However, the key factors contributing to the slow penetration of AM into the commercial market, rapid prototyping are namely the QA/QC methods or standards, and economic strategies. The sections in this paper review and discusses the similarities, differences, advantages, and disadvantages found in AM vs SM through a compacted analysis of documented works for these key factors.

2. Methods

To address the focus question and cover relevant publications, a literature review was conducted on central topics including Traditional manufacturing and Additive manufacturing within the context of cost and quality. The research articles selected have been collected through literature searches using ScienceDirect, Emerald Insight, and Google Scholar between the years 2001-2019. This resulted in huge number of papers. So, further papers having citation more than 100 was used as a filter. For the literature search, the keywords "Traditional or Subtractive" or "Additive" and "manufacturing" were used in different forms, in combination with the keywords "cost benefits", "quality control and

quality assurance", "mass customization", "complexity", "manufacturing volume "and "comparison". After the literature had been identified, skimming through the abstracts was done to check the relevance of the papers to this study. After the identification of the selected potential papers, the papers were read independently to identify the reoccurring main themes discussed in the existing body of knowledge. In total, 7 papers are included in this review. Some papers fall under more than one theme or topic based on their scope and focus.

3. Findings

The previous works, such as that of Pereira et al. (2019) have determined the types of AM products that can fit into established manufacturing regions based on three contributing factors; customization, complexity advantage, and volume.

3.1. Various regions of manufacturing: an economic factor

Manufacturing regions can be mainly classified as three key attributes namely: Complexity advantage, Customization, and Volume. Complexity advantage is the final geometric complexity and a feature a manufacturing method can provide. Customization is the ease with which the manufacturing technology offers a feature and individual variability that makes a similar product unique from each other with a customizable feature (da Silveira, Borenstein, & Fogliatto, 2001). Volume refers to the production quantity of parts in order or batch, whereby the production volume can range from singular to multiple parts. Along with its rapid advancement, the aim of AM has moved from rapid prototyping to rapid tooling. Several factors contribute to the selection of a manufacturing method namely: cost, the complexity of the part, material usage, and material property requirements, time, energy consumption, and sustainability. The following sub-sections study the impact of volume, complexity, and customization has on an AM product vs a traditionally manufactured product. Notably, where AM can dominate SM.

- High production-based volume manufacturing

Low-cost high-volume production has been the primary focus of SM industries. This is especially true for mass manufacturing. The high capital investment required to create assembly and production lines using AM does not make it a financially feasible investment for manufacturers. Traditional methods such as injection molding still dominate this space. The complexity advantage offered by AM has provided opportunities to essentially aim two processes with one technology with the ability to eliminate the forging, and joining process by printing complete parts in one print. The third high volume-based manufacturing region is mass customization, defined by its ability to provide individually designed products and services to every customer through high process agility, flexibility, and integration (Pereira et al., 2019). An agile and quick approach to changes is key characteristic companies are after, to stay ahead of the market with innovation and competition (da Silveira et al., 2001). Due to the quick design adaption and absence of lead time in AM, with unique characterization provided by 3D scanning, sets AM ahead of SM methods for this region.

- Low production volume manufacturing

This region refers to the low-volume production of products. The product manufactured by SM methods will generally have limited complexity and customization, however with AM, manufacturers can achieve a high degree of complexity for the same cost. Hopkinson & Dickens (2003), provide a successful cost model to illustrate the breakeven point of AM vs SM for volume. The study examined the cost of fabricating a small plastic lever using AM powder bed fusion vs conventional injection molding manufacturing. The study concluded for a production volume smaller than 10,000 pieces, AM had a reduced unit cost compared to injection molding (Hopkinson & Dickens, 2003). While SM dominates the mass manufacturing region financially, AM is better suited to fabricate tooling and fixtures required for conventional mass manufacturing molds (Pereira et al., 2019). AM offers a reduced lead-time and cost to capitalize on high value, low production of parts such as those used in ships, automation, aviation, satellites, etc. This concept is known as Rapid Tooling, which means that tools are able to form several thousand or even millions of parts before wearing out. The conclusion drawn is that production volume is an independently important factor, whilst customization and complexity are interchangeable in terms of impact.

3.2. Quality assurance (QA) and Quality control (QC) for AM vs SM

Precision manufacturing and standardization of products are dependent on QA and QC standards and procedures. The complex geometry, internal lattice structure, surface finish, layer orientation, and topology optimization, all contribute to the mechanical aptitude of an AM part. In cases where powdered material is inserted into parts, careful

design optimization is required to determine how it can be extracted. Loose powder within the part could not only be considered a safety concern but also impact the mechanical and structural integrity (Pereira et al., 2019). The vast capability of AM, referring to material variety and varied manufacturing processes, has resulted in multifaceted quality requirements and standards. For this reason, SM continues to dominate AM in quality, precision, and reliability (Newman et al., 2015). In turn, the inconsistency and complexity of each AM system have made it a challenge to develop a standard set of rules causing a slow development of QA strategies. The degree of quality required is usually dependent on the risk associated with health and safety assurances required.

The size, orientation, sharpness, and location of defects within an AM part can have negative effects on mechanical properties. This is no different for SM manufacturing, the types of defects are almost similar namely: porosity, cracks, inclusions, voids, balling, rough surface finish (Rajkolhe, Khan, & R., 2014). However, in AM apart from geometric imperfections, volume mismatch, layer removal, and undesirable internal surface finish are issues that cannot be detected through typical mechanical tests. In SM, the most commonly used QA/QC technique is batch testing, where one test piece within a batch can be mechanically tested (i.e. tensile and compression tested), as a sample of the mechanical properties for the remaining parts within that batch. While some AM manufacturers attempt to use a similar method for each print. There have been concerns regarding the impact of layer orientation, heat-affected zones, and inconsistent defect introduction which indicate that batch testing cannot be applied to AM. However, regardless of the absence of AM standards, traditional standards commonly utilized in other manufacturing processes or materials, have been applied to select AM printers/products by conforming to set parameters for individual machines (i.e. laser power, scan speed, powder spread, etc.). Detailed document stating the process for AM certification has also been developed. The guidelines were developed following traditional certification process standards, with the allowance of independent testing to be done by the industry/company-specific to certain test cases. This approach is not always suitable nor efficient for AM technologies (Pereira et al., 2019). The reason for this is the complex system that makes up an AM machine which does not always ensure the repeatability or reliability required for precision manufacturing, unlike traditional calibrated machinery.

Important requirements for AM to get wider commercial market in the future, include high process stability, a database containing properties of AM materials, on-line quality control processes, continuous certification, and provision of design rules (Gausemeier et al., 2011). Furthermore, other essential factors to consider are material heterogeneity and structural reliability. The impact of risk mitigation that a product's quality needs to assure has a huge influence on the level of QA required. To ensure that manufacturers neither under prepare nor over-invest in QA technologies, it is important to evaluate the level of QA required for each part printed utilizing AM technologies (Pereira et al., 2019).

4. Discussion

This paper reviewed the capability of AM and its current development to compete with established SM technologies. These regions primarily focused on the effect of production volume, customizability, and complexity to determine whether AM or conventional manufacturing methods on a product type to be fit for purpose. It was concluded that current cost models for high production volumes are better suited for SM methods, however, the higher the complexity or customization required AM is better suited. Production volume is an independently important factor, whilst customization and complexity can be interchanged in terms of impact. The paper comparison also focused on the similarities, differences, advantages, and disadvantages found in AM vs SM studying the economic and quality management status of the industry today. AM allows manufacturers to create an optimal design for lean production due to its flexibility. AM machines offer production flexibility but are still a considerably expensive investment compared to traditional manufacturing machines. AM is cost-effective for low-volume/small-batch manufacturing with continued centralized manufacturing rather than distributed manufacturing.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Technology and Application of Additive Manufacturing

Review article

Effects of scanning strategies on properties of components manufactured using Selective Laser Melting†

Veron Antony Racharla [1,*]

[1]   Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: veronantony@gmail.com
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Scanning strategies play a major role in determining the properties of parts manufactured using Selective Laser Melting. Different scanning strategies and their effects on various properties like Microhardness, Residual stresses, Grain structure, Porosity are investigated. A total of 7 published scientific articles are studied to write this review paper. A rotating line-scanning strategy or Island scanning strategy with a rectangular pattern gave higher microhardness results. Island scanning strategy with medium island size gave the least residual stresses. Heat flux direction and laser density played a major role in determining the grain structure of the parts manufactured. Based on these findings, appropriate scan strategy gave better microstructure results. Porosity is mainly affected by the melt flow. Based on this finding, a scan strategy is selected, where each layer is melted twice, which gave very low porosity in the samples printed.

1. Introduction

Selective Laser Melting (SLM) is a powder-based additive manufacturing process, where the powder is melted layer by layer on a powder bed platform by using a laser beam.

There are various process parameters in the SLM process, that affect the properties of Manufactured components. Some of these are Scanning strategies, layer thickness, laser spot size, laser power, hatch space, scanning speed, energy density, etc. (Larimian et al., 2020). These parameters affect many properties of final components such as Microhardness, Tensile properties, Microstructure, Density, Porosity, Grain structure, and Residual Stresses etc.

Scanning strategies are one of the important parameters, which affect all the above-mentioned properties of components manufactured. In this review paper, we are going to discuss the effects of different Scanning strategies on the Microhardness, Residual Stresses, Grain structure, Porosity of components, manufactured using SLM process.

2. Methods

The articles, scientific and academic research which are published from 2016 and later years were considered for the research, so that latest findings can be obtained. The literature was collected from reliable sources and websites like ScienceDirect, Scopus, etc.

The following keywords "Selective laser melting", "Additive Manufacturing", "Scanning Strategies", "Powder bed fusion" were used to search for the articles. Based on the results, 15 articles were selected for further review, which gives more insight into the scanning strategies and their effects. The filtering was done by reading the abstract of the articles.

The software 'Citavi' was used for organizing the articles. After reading all the articles thoroughly, the various properties affected due to the scanning strategies were listed out. A few of the important properties such as Microhardness, Porosity, Grain Structure, Residual stresses were chosen for the current research. Few articles, which discuss in detail these chosen properties were selected for further detailed study and referenced for the current research.

3. Results

The effects of scanning strategies on properties such as Microhardness, Porosity, Grain Structure, Residual stresses, and their results are observed in detail.

3.1. Microhardness

Microhardness of 316L stainless samples developed using different rotate scanning strategies, as shown in Figure 1 is tested using a standard Vickers microhardness tester by (Larimian et al., 2020). It is determined that samples fabricated using strategy (a) showed higher microhardness when compared to the samples fabricated using other strategies (b), (c). In the above case, the same energy density and scanning speed was maintained throughout all the strategies. Moreover, while employing strategy (a) and using the lowest scanning speed of 0.111 mm/s and highest energy density of 150 J/mm^3, the highest microhardness (224.7 HV) is obtained when compared to other samples.
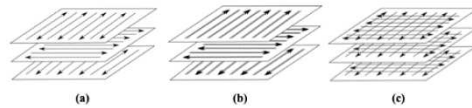
Figure 1. Scanning Strategies used by (Larimian, 2020)

Microhardness for the same 316L stainless samples fabricated using rectangular (Samples S1, S2, S3, S4) and hexagonal patterns (Sample S5) were investigated by (Y. Song et al., 2020) as shown in Figure 2. It is determined that the scanning strategy with a rectangular pattern gives higher microhardness values when compared to the hexagonal pattern. Moreover, in the rectangular pattern samples S1, S2, S3 showed similar and higher microhardness than that of S4. It is also discovered that irrespective of the adopted scanning strategy, the microhardness remains unchanged from top to bottom along the building direction.
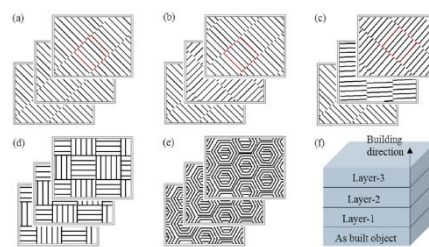
Figure 2. Scanning Strategies for samples (a)S1, (b)S2, (c)S3, (d)S4, (e)S5, (f) building direction used by (Y. Song, 2020)

3.2. Residual Stress

Residual stresses are investigated by (Zhang et al., 2020) by using the XRD spectrum and Williamson- Hall method. The Island scanning strategy was used with varying island sizes i.e., 1.2 mm, 2.4 mm, 4.8 mm, 7.2 mm as shown in Figure 3, where a 37° rotation angle between two neighboring layers is maintained. The island size is represented by 'd' in Figure 3. It is determined that as the island size increased from 2.4 mm to 7.2 mm, there was an increase in Residual stresses. Island size of 2.4 mm gave the best results, with the least amounts of residual stresses. However, at a relatively small size of 1.2 mm, the residual stresses tend to be increasing.
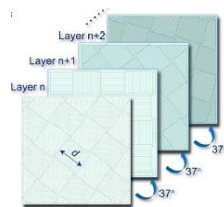
Figure 3. Island scanning strategy with a 37° rotation angle between two neighboring layers

Residual stresses are investigated through simulation of models as well as direct experimentation by (J. Song et al., 2018). Three types of strategies are used as shown in Figure 4. Case (a) is horizontal back and forth linear scanning without rotation on the next layer. Case (b) is the 15° inclined back and forth linear scanning with a 15° scan vector rotation on the next layer. Case (c) is horizontal back and forth linear scanning with a 90° scan vector rotation on the

next layer. Three residual stress components S11 (component along scanning direction), S22 (component perpendicular to the scanning direction), S33 (component along deposited direction) are considered for the investigation. Investigation results showed that S22 remains unchanged for all three scan strategies. Despite S11 and S33 stresses for case (b) are not the smallest when considered individually, comprehensive consideration leads us to the conclusion that case (b) produces the relatively smallest residual stresses. The above results produced by simulation are validated by experimentation and measurement by X-ray diffraction.
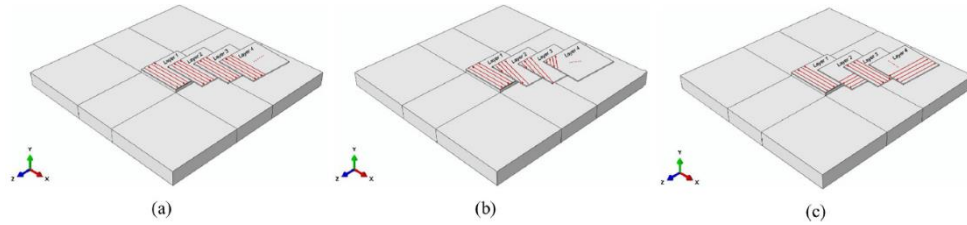
Figure 4. Scanning strategies a, b, c used by (J. Song, 2018)

Residual stresses in FeCrMoCB are investigated and compared between two different scanning strategies i.e., (a) S-type scanning strategy and (b) Chessboard scanning strategy as shown in Figure 5 by (Zou et al., 2020). X-ray diffraction measurements are applied to determine the residual stresses. The residual stresses while using the Chessboard strategy are decreased to 285 ± 60 MPa, which are only half of the stresses from the S-type strategy.
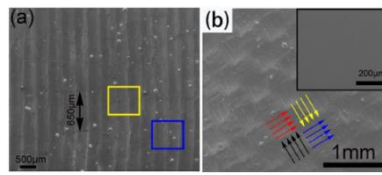
Figure 5. Samples with (a) S-type and (b) Chessboard scanning strategies

3.3. Grain Structure

The effect of scanning strategies on grain structure in Inconel 718 is investigated by (Wan et al., 2018). Two different scanning strategies i.e., X and XY are used as shown in Figure 6 (a), (b). Electron backscatter diffraction orientation maps are shown in Figure 6 (c) ((a-c) and (d-f)) in the three orthogonal cross-sections of samples fabricated by scanning strategies X and XY respectively.

(a) scanning strategy X   (b) scanning strategy XY   (c) Electron backscatter diffraction orientation maps
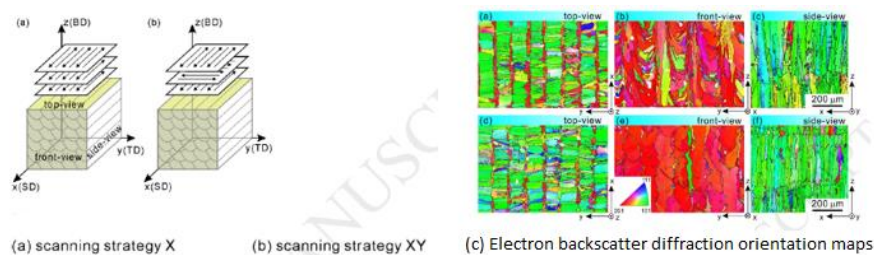
Figure 6. Scanning strategies X, XY and Electron backscatter diffraction orientation maps

From the top view of both samples (a), (d) of Figure 6(c), fine equiaxial grain bands encompassed by columnar grains can be seen. The equiaxial grain bands have random orientation in XY strategy whereas in X strategy they have a strong orientation along Build Direction (BD). The front view of the X- fabricated sample (b) shows a bimodal grain structure with large elongated columnar grains and small irregular grains with arbitrary orientation whereas the XY-fabricated sample (d) shows directional columnar grains with a length of several hundred micrometers. From the side view, the mean grain size of the X-fabricated sample (17.05 μm) is slightly larger than the XY- fabricated sample (13.34 μm).

3.4. Porosity

(Rashid et al., 2017) studied the effects of two different scan strategies on 17-4PH stainless steel samples fabricated using SLM. Scan strategy 'O' contains scanning vectors along +45° for odd-numbered layer and -45° for even-numbered layer. Scan strategy 'X' contains a single odd-numbered layer and an even-numbered layer with a first laser scan (solid lines) followed by the second intermediate laser scan (dashed line). The scan strategies can be seen in Figure 7.
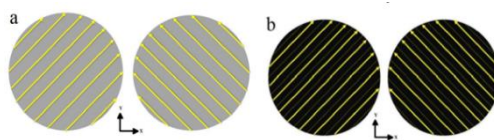
Figure 7. Scanning strategies (a) 'O' and (b) 'X'

The 2D sections of the samples were studied under a light optical microscope. The results showed that samples with the X-scan strategy showed less porosity and high relative density in both top and transverse surfaces.

4. Discussion

As per the results, it is quite evident that a single strategy cannot be adopted to achieve the best results in all the properties. The best way is to decide on the property, which we need to optimize, based on the application of the manufactured component.

A rotating line-scanning strategy and the Island scanning strategy can be adopted to achieve high microhardness, that too when used with the lowest scanning speed and highest energy density. Because the samples built using these strategies showed similar Microhardness values. The reason might be the lower cooling rate, coupled with higher energy density, which melts the particles fully so that coarser microstructure and higher density is produced.

The residual stresses are formed due to the tensile stresses in the subsequent layer and compressive stresses in the previous layer formed during the SLM process. After investigation, it is found that the Island scanning strategy achieves the least amounts of residual stresses. The higher the island size, the higher will be the residual stresses because of the increase in length of individual tracks and the resultant increase in temperature gradient (Zhang et al., 2020). But when the island size too less, we can observe an increase in residual stresses due to an increase in molten pool depth because the high laser energy is focused at a relatively small area. Direction of heat flow also plays a major role in formation of residual stresses. Moreover (Zou et al., 2020) used a variant of island scanning strategy called as "Chessboard scanning strategy"(Figure 5(b)), which showed the reduction of residual stresses, this is because of rotation of scan vectors. Thus Chessboard scanning strategy by (Zou et al., 2020) might be the best strategy to produce less residual stresses when compared to normal Island scanning strategy.

Grain structure is characterized by the complex heat flux direction caused by Marangoni flow as well as the preferred growth direction (Wan et al., 2018). Laser density is also a major factor in grain formation. Larger columnar grains are formed when a deeper melt pool is produced by applying a higher laser energy density. Both the scanning strategies 'X' and 'XY' used by (Wan et al., 2018) produced bimodal grain structure, but scanning strategy 'X' produced a weak texture, and scanning strategy 'XY' produced a strong cube texture. But since the 'X' strategy produced slightly less mean grain size, it would be better to choose this strategy for better mechanical properties.

After investigation about the Porosity by (Rashid et al., 2017) using two scanning strategies 'O' and 'X', it is indicated that porosity is mainly affected by the melt flow. Due to the opposite direction of the unstable melt flow to the laser scanning, gap valley pores are formed. In scanning strategy 'X', each layer is scanned twice, because of which, heat supplied is higher in between tracks of each printed layer (Rashid et al., 2017). This results in the elimination of gas-entrapped porosities. Thus, there is less porosity in samples printed with scan strategy 'X' and is the best choice to adopt if less porosity is the main criteria for the product.

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Review article

The Influence of Selective Laser Melting Parameters on AlSi10Mg Component†

Sivasakthi Pachiyappan [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: sivasakthi.pachiyappan@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Aluminium alloys are especially known for their strength to weight ratio, corrosion-resistant, resilient and has huge applications in the automotive and aerospace sectors. Selective laser melting of AlSi10Mg alloy paves the way to manufacture 3D components in a single step in comparison with the normal conventional manufacturing process which involves series of steps. However, in order to produce a component with high strength and good surface roughness in SLM, various parameters have to be analyzed and optimized. This review is conducted to optimize and analyze the influence of SLM parameters like laser power, hatch distance, scanning strategy, layer thickness, scan speed and powder morphology which affects the properties of the AlSi10Mg component.

1. Introduction

A material which plays a major role in material and structural engineering is called aluminium. It is the third most abundant material in the world after silicon and oxygen. The properties of aluminium are light weight, corrosion-resistant, reflectivity, good ductility, impermeable, odourless, nonmagnetic, electrical, and thermal conductivity.   Due to its high electrical and thermal conductivity, it is used in electrical systems and, it has many applications in aviation, automotive, wind and solar energy management.   To increase further the properties of aluminium, it has been alloyed with other materials such as silicon, magnesium, copper, manganese, tin, and zinc. Some aluminium alloys have strengths that are comparable to steel - with only a third of its density. Till now, aluminium alloy components are manufactured using conventional manufacturing processes like casting, forging, drawing, extrusion, and powder metallurgy. Though conventional manufacturing has advantages of low cost and good strength, it consumes more time and work because of many processing steps are involved.

To overcome the disadvantages of the conventional manufacturing process, an additive manufacturing process called Selective Laser Melting (SLM) can be used. In 1995, a research project was carried out at the Fraunhofer Institute ILT in Aachen, Germany which led to the development of a new advanced manufacturing technique called Selective laser melting and patented as ILT SLM DE 19649865. This technology has huge demand in industries because it allows high freedom of complex components, efficient usage of materials and elimination of expensive moulds. Based on the manufacturer, SLM also called as laser powder bed fusion process or direct metal laser melting (DMLM), it is an advanced manufacturing technology uses a high-intensity laser beam to combine the metal powders into a 3D component. The process begins with the designing of a component in Cad systems and then dividing the Cad file data into many layers of 2D images based on the layer thickness, normally 20 to 100 µms. After making the layers, the data is sent to a file preparation software package to assign the parameters and physical supports based on the operations of selective laser melting. In the end, the file is stored in. stl format which is used in most of the additive manufacturing technologies. Initially, the roller deposits the powder material on the substrate table that is interconnected to a piston-type rod which moves up and down based on the powder layer thickness. After that, a high-intensity laser beam like ytterbium fiber laser or CO_2 is focused on each layer to fuse the powder. The process step is repeated until the entire component is manufactured. The SLM process is carried in an inert atmosphere chamber because aluminium alloys are susceptible to oxidation.   The main advantages of SLM are that the part is made at a single stretch without using any intermediate process. Moreover, in SLM nearly no wastage of material occurs because the remaining powder material can be reused. Thus, using SLM, complex parts can be manufactured with good properties like the conventional process.

AlSi10Mg alloy is a long-established alloy that is frequently used for die extrusion and die casting. Since this alloy has a high strength to weight ratio and good mechanical properties, it has been widely used in the automobile, aerospace, chemical and catering industry. The composition of AlSi10Mg alloy is found in Table 1. It has good weldability since it has a close eutectic composition of Al and Si. Mg plays a prominent role in age hardening and combining 0.45 to 0.6% magnesium to aluminium and silicon alloy enables the formation of Mg2Si which will reinforce the matrix without compromising the other mechanical properties to a certain limit. Since aluminium alloys have higher reflectivity and heat conductivity, it is required to analyze the SLM parameters to overcome the defects of these properties. In addition to that, AlSi10Mg can offer good mechanical properties, in both processed and heat-treated conditions, these properties can be influenced significantly by the selection of different SLM-processing parameters like laser beam intensity, hatch distance, scanning strategy, layer thickness, scan velocity and powder morphology. Since the quality of the final product is influenced by the process parameters of Selective Laser Melting, it makes arduous for the industry to use additive manufacturing technique for real applications, and consequently, every machine and processing parameters need to be qualified separately. Hence, this review paper analyzes the various parameters of SLM which contributes to the better manufacturing of the AlSi10Mg alloy.

Table 1. Composition of AlSi10Mg alloy (Kempen et al. 2011)

Alloying element	Al	Si	Cu	Mn	Mg	Zn	Fe
Weight %	Rest	9-11	< 0.1	0.05	0.45 - 0.6	0.05	< 0.55

2. Methods

Since additive manufacturing is a growing topic, a lot of topics were found on Google Scholar, Science Direct, Springer and Scopus websites with the keywords of parameters, selective laser melting, SLM, and AlSi10Mg. By using the keywords, nearly 5,530 articles were found. In order to narrow down, only articles which are published after 2010 were filtered. Still, nearly 4,000 articles were obtained. It was further refined by using the search filter options like articles type, discipline, article language, source title and accessibility, then around 48 articles were found. From that, by reading the title, 16 articles were shortlisted. After going through the abstract and conclusions of the 16 articles, 8 articles that investigate the parameters of SLM manufactured AlSi10Mg were selected.

3. Results

One of the major problems of the SLM manufactured AlSi10Mg component is the porosity which is caused by the improper selection of parameters. Porosity formation reduces the fatigue tolerance properties of the component. Read et al. (2015) observed that the laser power, scan speed, and the interaction between the scan speed and scan spacing have a major influence on the porosity. From Figure 1 it can be seen that the increase in the scan velocity and decrease in laser power leads to reduction of energy input to the material, so this diminishes the formation of the melt pool and causes the evolution of porosity due to the incomplete consolidation. While low hatch spacing helps to lower the effect of the scan speed on the porosity, the formation can be mitigated by varying one of these parameters. Also, in their experiment, it has been found that there is no big difference in the tensile and creep strength concerning the build direction and the optimum energy density that gives minimum pore fraction for AlSi10Mg alloy, approximately 60 J/m^3.

Density and surface quality play a crucial role in the SLM manufactured component. Kempen et al. (2011) analysed certain parameters and observed that the density of a part increases when increasing the scan speed. The higher density is reached for the optimal energy input with higher scan speed and powers. However, it has been found that the scan spacing does not have a significant effect on the density. While the higher surface quality is obtained for lower scan speed and higher laser power with optimal energy input. By combining the results of density and surface quality, he defined two sets of parameters. For higher density and productivity, the optimum laser power of 200 W and a scan speed of 1400 mm/s with a scan spacing of 105 μm is needed, which gives scanning productivity of 4.4 mm^3/s. Besides, the optimum parameters for combining density and surface quality are found to be a laser power of 200 W and a scan speed of 1200mm/s leading to the productivity of 3.8 mm^3/s. Similarly, Majeed et al. (12019) also conducted a study to optimize the processing parameters for manufacturing quality products from AlSi10Mg alloy by using SLM technology. He also got the same result, increasing the laser power and scanning speed leads to a decrease in surface roughness. On the contrary, an increase in overlap rate steers to a decrease in surface roughness. The optimum parameters to achieve the roughness of 3.85 μm are laser power 320 W, scanning speed 750 mm/s and overlap rate of 35%.
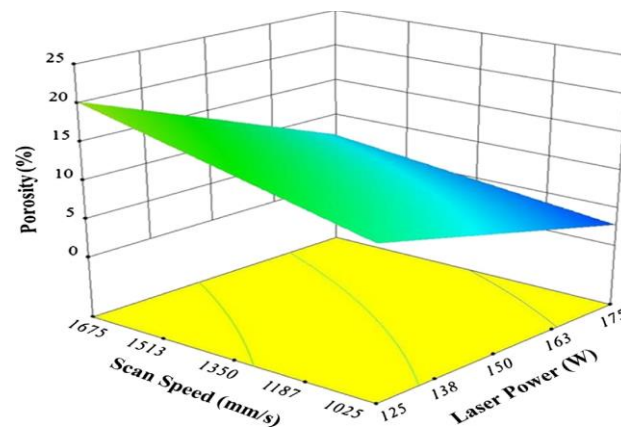
Figure 1. The effect of the laser power and scan speed on the porosity (Read et al., 2015)

Raus et al. (2016) investigated the influence of SLM parameters such as laser power, scanning speed and hatching distance on the AlSi10Mg part samples using one factor at a time (OFAT). In that study, he analyzed the effect of these parameters on density by keeping one parameter as variable and the other two parameters as constant. In the end, it has been seen that variation of laser power gives the higher density value of 99.07%, the variation of scan speed leads to a slighter rise in density of 99.11% and the change in hatch distance reaches the highest density of 99.34%. The influence of the SLM parameter on density is shown in Figure 2. In addition to that, it is observed that the size distribution of powder material affects the density and quality of the surface. When the powders have more spherical morphology and fewer satellite particles, this supports better flowability and homogenous powder layer deposition. Further, the authors compared the mechanical properties of AlSi10Mg alloy to the HDPC A360F and HDPC A360T6 alloys without including any post-processing methods and demonstrated the higher values of hardness, yield strength, tensile strength, and elongation.
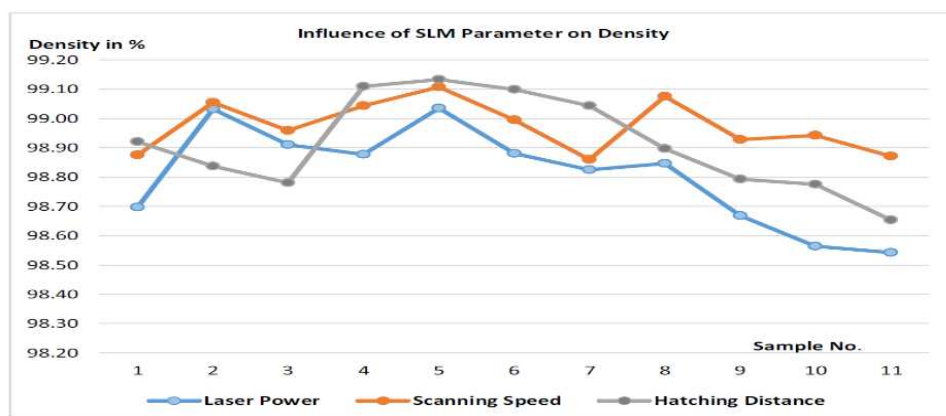
Figure 2. Density with SLM parameters (Raus et al., 2016)

From Raus et al. (2016) study, it is observed that powder properties have an impact on the SLM manufactured component. Likewise, Aboulkhair et al. (2015) conducted a study on powder properties which paves the way to avoid defects and porosity. Two powders from a different supplier were taken, one is specially made for additive manufacturing systems and the other is normal AlSi10Mg powder. The special one has higher silicon content, good size distribution and spherical morphology with some small satellites, so it gives better flowability and higher packing density. Moreover, the presence of high silicon content enhances laser absorption and metal fluidity. Whereas the conventional powder has an irregular structure in addition to a skewed particle size distribution and contains moisture on the particle's surface which resulted in low packing density and porosity due to bad flowability. However, it is observed that using the pre-sinter scan strategy, the drawbacks of conventional powder can be reduced, and higher mechanical properties are achieved like special powder.

In the conventional manufacturing method, it is hard to reduce the porosity because based on the solidification conditions, the defects will vary from zone to zone. Ferro et al. (2020) carefully analysed the porosity inducing

parameters porosity in selective laser melted AlSi10Mg alloy intending to find optimal conditions that guarantee the maximum material density and the best mechanical properties. It has been observed the reasons for forming the porosity in SLM is due to non-homogeneous wetting and balling effects which also reduces the ultimate tensile strength. In this study, laser power and exposure time have been taken as a variable parameter and the remaining parameters are kept constant. It is found that the pore diameter value and its standard deviation lower as the energy density decreases and minimum porosity values are obtained for the energy values between 50 and 60 J/mm^3.

Wang et al. (2017) also conducted an experiment on densification behaviour and surface roughness of AlSi10Mg powders produced by selective laser melting. In that, it has been noticed that laser energy density (LED) has an important effect on the surface roughness, very high LED lead to balling effect, while too low LED tends to produce defects, such as porosity and microcrack which affects surface roughness of the SLM manufactured AlSi10Mg part. Also, the relation between laser spot diameter and point distance affects the surface quality and density of the product. When the laser spot size is greater than the scanning point distance, sufficient laser energy is supplied to the powder, so high density, and good surface quality of the AlSi10Mg component is obtained. However, if the point distance is lower than the laser spot diameter, the AlSi10Mg particles will not melt and cause low density and poor surface finish. In addition to that, a maximum density of 99% is obtained during the exposure times lies between 140 to 160 μs, lower and greater than these value leads to the lower density because lower value does not melt the powder and the higher exposure time causes the balling effect. The investigation also indicated the decrease of porosity from 1.24% to 0.25% when the LED rises from 109 J/mm^3 to 131 J/mm^3. Though the pores exist in the SLM component, they are very small and mostly in a spherical shape.

Similar to Wang et al. (2017), Majeed et al. (2019) also analysed the effects of the SLM parameters like laser power, scan speed, overlap rate and hatch distance on the surface quality of the AlSi10Mg component. It has been observed from the experiment that laser power and hatch distance have a positive correlation with surface roughness which means the surface roughness increases with increasing the laser power, whereas overlap rate and scan speed showed a negative correlation. In addition to that, it has also been observed that the solution treatment decreases the surface roughness of most of the samples while artificial ageing helped to increase the surface roughness. Conclusively, the process parameters 0.32 kW laser power, 0.60 m/s scan speed, 35% overlap rate and 88.7 mm hatch distance were determined as optimized parameters for best surface quality in as-built condition.

4. Discussion

From the study of these articles, it is observed that the scan speed, laser power and hatch distance have a greater effect on the strength of the SLM manufactured AlSi10Mg component. Since the porosity formation has a greater impact on the mechanical properties, it can be decreased by lowering scan speed and increasing the energy density of the laser beam (Read et al. 2015). However, lowering of scan speed leads to reduction of density which further imparts the quality of the AlSi10Mg component. Hence further study must be conducted by combining the density and porosity to improve the mechanical properties of AlSi10Mg. From Raus et al. (2016) investigation, it is evident that hatch distance has a significant effect on the density when compared to scanning speed and laser power. In addition to that, powder morphology also has an effect on the porosity and density of the AlSi10Mg component which is observed from the study of (Aboulkhair et al. 2015) and the pre-sinter scan strategy can be used to overcomes the defects of powder morphology. When observing the surface roughness of the AlSi10Mg component, laser power and hatch distance have a productive influence, while scan speed and overlap rate showed the destructive behavior on the surface finish. Also, the solution heat treatment helps to reduce the influence of scan speed and overlap rate on the surface finish. Though authors recommended the optimum parameters for reducing the surface roughness, some unmelted powders are seen on the surface which gives rise to cracking. Therefore, more investigation is required to completely remove these unfused powders.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Additive manufacturing of glass with stereolithography and direct light processing[†]

Yashodhan Deshpande [1,*]

[1]   Technische Universitat Chemnitz; Chemnitz; Germany
[*]   Correspondence: Yashodhan-rajendra.deshpande@s2019.tu-chemnitz.de
[†]   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Glass, a versatile material with highly desirable chemical, thermal, insulating and most importantly its optical properties, combined with the trending technology of additive manufacturing has produced some novel results with high-tech applications. Stereolithography based 3D printing has been particularly found to be a well-suited process for glass material when it comes to various methods of additive manufacturing. The primary reason for this is that glass can be processed like a polymer at room temperature and gives satisfactory mechanical properties with transparent parts. Heavy research work is being carried out with numerous strategies in this regard. Although the fundamental principle remains the same where a green part comprising of polymer matrix with glass particles embedded in it is first produced through SLA technique and then subsequently de-bonded and sintered to obtain fused glass product, variations exist with regards to starting materials and UV curing strategies like SLA or DLP. It can be deduced that these photo-curing methods have much higher potential to be used for mass manufacturing of precision parts because of their high similarity to polymer 3D printing which is a standard in today's industry. This review paper briefly aims at comparing such research instances.

Keywords: sintering; SLA (Stereolithography); DLP (Direct Light Photography); FDM (fused deposition modeling); SLM/S (Selective laser melting/sintering).

1. Introduction

Additive manufacturing (AM) is a highly trending technology with the potential to disrupt conventional manufacturing techniques. It has now become a well-established process for polymers and plastic processing. Until recently glass and glass-ceramics were out of the question because of the high levels of energy required to melt them, especially when considering fused deposition modelling or selective laser melting. However, with research breakthroughs, it has now become feasible to manufacture single as well as multi-component glass-based high precision components with simple techniques such as Stereolithography and/or Digital Light Processing techniques, using simple benchtop 3D printers. The main driving principle is either the processing of resins laden with particles of glass or glass-precursors mixed homogeneously in a polymer. Thus, it is very similar to 3D printing a polymer-based part. Subsequent processing in the form of polymer pyrolysis and sintering after the printing is complete yields the product in pure glass form. There exist variations in the mechanics behind the polymerization and curing of the starting material that is used. Other AM techniques such as SLS or FDM for glass have also been tried and tested and are still in development. However, they possess certain limitations. Applications for such 3D printed glass products are ranging far and wide. They have the potential to replace the cheaply produced inferior quality polymer components. For example, most optical lenses are made up of polymers. The main reason for this is that glass is too expensive to post-process although all its raw materials are cheaply available. The additive manufacturing technique using photo-curing followed by sintering aims at eliminating or limiting the post-processing step to a minimum thereby drastically reducing the production costs. Furthermore, additively manufactured glass products have potential applications in microfluidic devices such as mixers and flow reactors, optics, and photonics, etc.

This article aims at reviewing the research progress in the development of technologies associated with 3D printing of glass using SLA and its suitability as also the drawbacks of the competing processes which make them unfeasible. The focus of the discussion is on the glass materials used for the 3D printing technique, and the problem associated with 3D printing of glass. Evaluation and comparison of SLA and DLP is another important aspect of this review.

2. Methods

Additive manufacturing is quite a new topic that is still in the development phase. On top of that, glass 3D printing is largely an untouched area. The SLA-based technique of additive manufacturing of glass and glass-ceramics is a development from recent years. Despite this, the search on scholarly pages with the keywords "Additive Manufacturing of glass" returned thousands of results. To narrow it down, keywords such as stereolithography, pure glass, sintering were used. This resulted in a very specific subset of papers and research articles since the use of SLA (& DLP) technology for additive manufacturing of glass has been newly conceived. This review paper aims at focusing on the additive manufacturing work with regards to glass (and glass ceramics) with this technology at the focal point. Glass as a material is not much referred to in general mechanical engineering. To understand this material better on a ground level, the book Pfaneder, H.G. (1996) *Schott: Guide to Glass* Darmstadt, Germany; Springer was referred to. Only articles published within last 5-6 years were referred to, so as to take into account the state-of-the-art processes. The organizational websites of the authors were also referred to understand their projects better. Other websites like https://additivemanufacturing.com/ were also referred to. The articles of other competing methods for AM of glass were also studied so as to avoid a biased review.

3. Results

3.1. 3D Printing of glasses using phase separating resins (Method 1)

This research makes use of phase separating resins as the starting material. Basically, it uses a multi-component acrylate resin which consists of the pre-cursors of boron, silica, and phosphorous oxides which eventually turn to glass after the pyrolysis and photo-curing method. For example, poly-diethoxysilane forms silicon dioxide, trimethyl borate forms boron dioxide, and so on. As shown in figure 1., The inorganic pre-cursors undergo phase separation to form porous structures on pyrolysis. They are then sintered/melted to form the glass components. The phase separation serves two purposes: enabling the formation of a continuous polymer network capable of forming stable 3D parts and formation of inorganic phase upon heat treatment. DLP is used as a shaping method or printing method. Because polymerization-induced phase separation is a universal physical process, the authors expect its applicability to a broad range of chemical compositions.
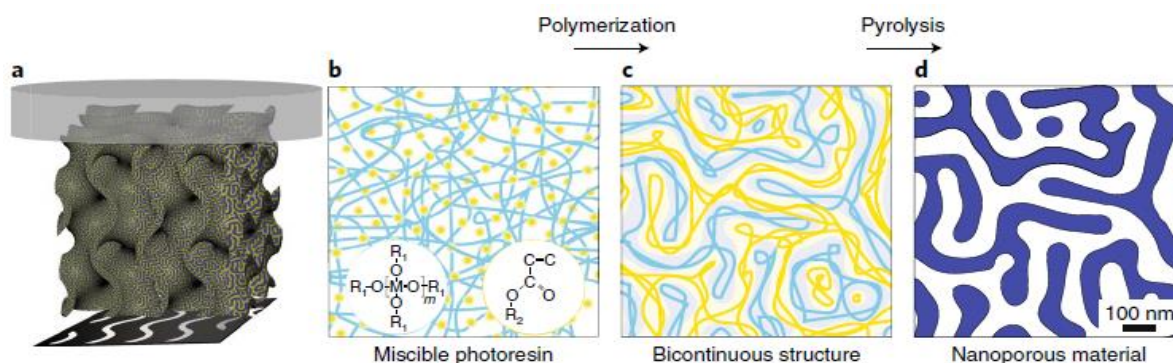
Figure 1. Process stages in the use of phase separating resins for multi-component glass 3D printing.

3.2. Glassomer – Glass nanoparticles dispersed in a monomeric matrix (Method 2)

Amorphous nanoparticles of silica were dispersed in a monomeric matrix. The monomer is basically in the form of hydroxyethylmethacrylate or HEMA. It permits the high dispersion of nanoparticles because of the formation of the solvation layer without the need for any additives. Figure 2. shows how this starting material is processed through the SLA method through free radical polymerization to obtain the green part. The green part is then thermally debinded from the polymer by means of thermal decomposition. Finally, the component is sinter melted at 1300 °C to obtain the glass component which is free from porosity and cracks. Kotz, Bauer, Schild & Sachsenheimer (2018) use this same method. However, the starting material was tweaked by taking di- and tri-acrylates in addition to HEMA. This resulted in better stability of the cross-linked nanocomposites. Digital mirror device SLA was used. Glass components made via microlithography as well as the top surfaces of stereolithography printed parts show exceptionally smooth surfaces with a roughness of about 2 nm, suitable for optical applications. The authors of these articles went on to establish Glassomer GmbH which commercially supplies this starting material in the market.
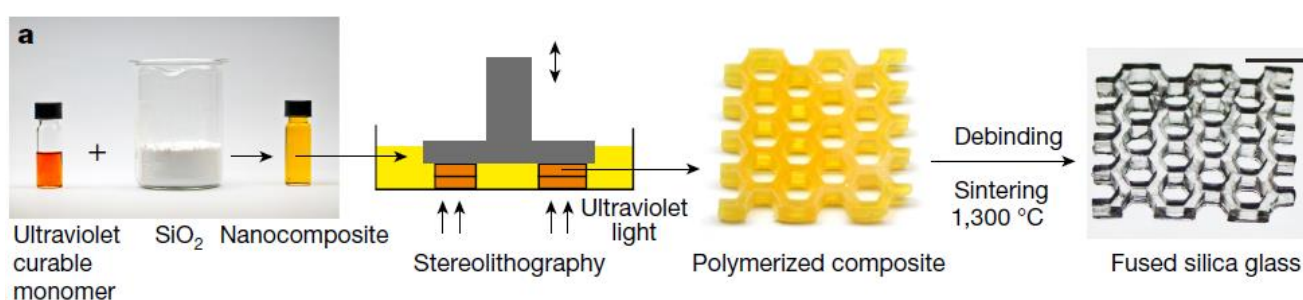
Figure 2. Process steps using Glassomer as the starting material.

3.3. Sol-Gel Method (Method 3)

This approach uses UV polymerization ability and a group that can undergo the sol-gel process to yield hybrid objects. The precursors for this approach are based on organically modified hybrid organic-inorganic sol-gel-based inks with very high silica contents. For example, a combination of modified metal-alkoxy precursor with conventional metal-alkoxy sol-gel precursor leads to the formation of oligomer sol with high silica content that can be both polymerized under UV-light and undergo a gelation process. It can be seen in Figure 3. that curing of the 2D layers of the 3D structure is done by means of photopolymerization through the DLP technique, where the entire image of the layer is projected onto an LCD screen and the corresponding pixels allow the UV light to pass through. A poly-condensation reaction takes place after printing between the adjacent silanol groups which form a stronger network. This method enables the printing of 3D objects with very high silica content. They are glossy and crack-free with good mechanical properties and most importantly transparent.
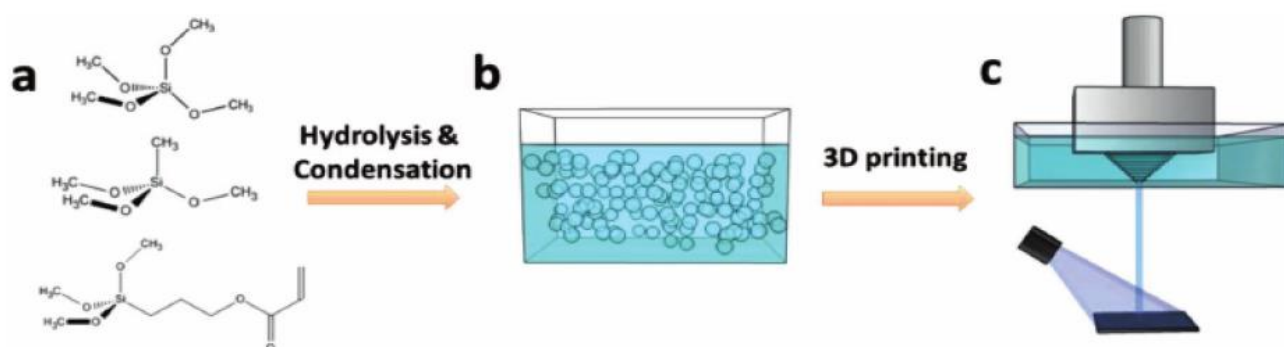
Figure 3. Schematic of the process using sol-gel method.

3.4. Characterization of processed parts.

Table 1. compares the characteristics of the parts produced by methods 1 through 3 on the basis of properties which have been provided in the literature with clear evidences.

Table 1. Characterization of parts

Method 1	Method 2	Method 3
Multi-component glass	Single component glass (silica)	Single component glass (silica)
High transparency	High transparency	High transparency
Poor mechanical strength	No conclusive evidence for strength	Highest mechanical strength
Linear isotropic shrinkage (up to 60%)	Linear isotropic shrinkage (up to 40%)	Linear isotropic shrinkage (max 32%)

3.5. Non-feasibility of other 3D printing processes for glass

Apart from the photo-curing technique, other methods for 3D printing of glass and glass-ceramics have also been implemented and are in further developmental stages. This section aims at putting forward such research and the reasons why they are challenging to be used for production at least in their current state of the art, which further supports the inference that currently, SLS/DLP methods are the better processes. Few instances of such research are as follows:

3.5.1. Molten Glass Extrusion

Molten glass heated in a kiln is extruded through an alumina-zirconia nozzle. This process is capable of producing highly transparent cylindrical components with good inter-layer fusion. The main drawback of this process is that it is energy-intensive since continuous heating of the furnace to keep the glass in a molten viscous state throughout the printing process is required. The extrusion nozzle is heated to ensure that the flowability of the glass was maintained. Finally, the bed was also heated to ensure gradual solidification so as to not allow cracking. The molten glass was extruded by means of gravity which made it necessary to maintain the amount of melt inside the kiln at a certain minimum level. The process lacked automation since the cutting of the glass, feeding inside the furnace chamber needs to be done manually. Lastly, this process does not eliminate the need for melting furnaces for glass which are the main reason for high energy requirements.

3.5.2. Direct Laser Sintering of Soda-Lime Glass

Soda-lime glass is amongst one of the standard glass materials. The components are produced from glass powder which is sintered using a laser. The SLS method produces components with cracks because of thermal shock. The result of this is fracture-prone unstable components. To avoid cracks, it becomes necessary to lower the laser power. This in turn may result in insufficient bonding between the glass particles leading to porosities and lower density (50% of theoretical). After a process parameter optimization, it is feasible to use this method for AM of glass. However, the parameter variation window remains to be quite small. Laser melting is possible in this process to achieve suitable densification, but in such a case, the chances of distortions and warpages are quite high leading to loss of geometry.

4. Conclusions

From the review of the scholarly articles, it can be deduced that currently, photo-curing methods in the form of SLA/DLP are better suitable for additive manufacturing of glass in comparison to SLS and molten glass extrusion. All three methods mentioned above can produce fully transparent, high-quality glass components with negligible porosity. Methods 1, 3 are better suited for producing multiple components whereas 2 can be used for prototyping or complex components. From Table 1, it can be concluded that method 3 is most suitable for processing pure silica glass parts through 3D printing. Method 1 is suitable if multi-component glass parts are to be manufactured. SLS and molten glass extrusion methods cannot be neglected completely as they have certain capabilities which cannot be attained with SLA technology. However, more research with regards to energy efficiency, process tolerance needs to be completed to make this process better suited for commercial production. The study does not consider the characterization methods involved in deducing the component properties. All the research instances made use of different geometries for evaluating their processes. This is a grey area since for accurate comparison between the processes, characteristics of benchmark geometries printed using the different methods should be compared.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Technologies for improving the accuracy and mechanical properties of additively manufactured parts†

Aswin Narasimhan Srinivasa Raghavan [1],*

[1] Technische Universität Chemnitz; Chemnitz; Germany

* Correspondence: aswin.narasimhan-srinivasa-raghavan@s2020.tu-chemnitz.de

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Abstract: Additive manufacturing is a fast-growing field in modern manufacturing and can be used in various industries due to its advantages, but various limitations also exist for this technology such as inaccuracy in shapes, weak bonding and inefficient process cycle. Several technologies to overcome this are briefly explained in this article. The technologies such as usage of a laser system to predict the path of the printing robot, a substrate plate system for entire process cycle, bio-inspired designs for composite materials fabrication and optimization through simulation and machine learning. Also, the scope and drawbacks along with the future research possibilities are summarized through this work.

Keywords: 3D triangulation; substrate plate; multi-axis toolpath; sonotrode horn; interlocking sutures.

1. Introduction

Additive manufacturing was initially limited to only concept modeling and rapid prototyping but it has proven to have great potential in the aerospace, automotive, defense and medical industries due to its capability of producing complex shaped products which are difficult to manufacture in the conventional methods due to the difficulty in producing the molds and it opens the possibility of experimenting with unconventional designs and different material combinations while also reducing the tooling. Additively manufactured components also reduce the material waste greatly when compared to the conventional subtractive method, which becomes another compelling reason for companies to utilize this technology more for a sustainable and economic reasons. These factors make additive manufacturing an important part of Industry 4.0.

Various methods for additive manufacturing such as Laser Metal Deposition (LMD), Selective Laser Sintering (SLS), Laser powder bed fusion (L-PBF), Ultrasonic additive manufacturing (UAM), Digital Light Synthesis (DLS) and Multi-Jet Fusion (MJF), are discussed in this article. Each method mentioned above has its unique advantage and challenges. But additive manufacturing has its limitations such as difficulty in maintaining the geometrical accuracy due to the distortions created by the thermal stresses and also weak bonding between the layers due to the low duration of crystallization temperature. This often requires post processing with some additional subtractive processes. This article covers some of the technologies that are helpful in overcoming these limitations and improving the process time and the part's properties

2. Methods

The research papers discussed in this review article were obtained from renowned publications and journals such as Elsevier, Springer, and IOP publishing. The search strategy was aimed at finding the research works performed in reputed universities and research institutes during the last three years which are focused on optimizing the process and results of additive manufacturing. The search engines such as scopus and google scholar were also used. The key search terms were "additive manufacturing" along with "improvement and optimization". A total of 4263 and 2292 articles were obtained respectively and the following seven articles were selected on the basis of their significance and suitability of those works with this review article.

3. Procedure and Results

The LMD method works by deposition of layers of laser cladding to develop the part layer by layer but it also has problems mentioned above to overcome this, Castro et al. (2015) developed a process for laser deposition by optimizing

the process parameters (laser power, beam size, processing speed etc.) by printing different specimens and measuring their metallurgical and mechanical properties. The parameters values were chosen from the specimen with the desirable result. Along with this a three-dimensional control system capable of generating trajectories which are suitable for the buildup of the required part. It is made possible using a 3D vision system for monitoring the geometry of the part during the buildup process, the system will therefore be able to detect any deviations and correct it in each deposited layer to ensure the accuracy of the final desired geometry. The materials used for this study are S355 JR structural steel and AISI 4040 powder. A deposition strategy (V20) which has alternate direction of the layer formation gives better result and it was used. The three-dimensional control system works on the principle of 3D triangulation and the setup consists of a camera and laser stripe. The laser stripe is projected on to the workpiece under construction and the camera is used to detect the laser stripe, and the 2D image is converted to 3D points which is then compared with the required geometry, by this method the robot coordinates are continuously adjusted for a better result without distortions. This system might require some prior calibration and it was found to increase the accuracy of the workpiece.

The orientation of the layers within a printed part plays a crucial role in the load bearing capacity of that part, in the real world application the part needs to withstand multiple loads in different planes and from different direction, there is no possibility of orienting the layers in the typical 3-DoF (Degree of freedom) deposition. Kubalak, Wicks, and Williams (2019) developed an algorithm to generate multi axis toolpath for the product in a 6-DoF machine, this facilitates the fabrication of tensile specimens at different global orientation. Suitable support materials must also be designed as there is a risk of the deposited material interfering with the tool path. The study was done by printing three types of specimens at different orientations (XYZ, 45°, and ZYX) and measuring the strength in different directions. The tensile modulus is same for XYZ axis specimens, as both have identical layer orientation. The specimen with 45° alignment which is printed with multi-axis toolpath and layer orientation towards the tensile loads displayed a 23% increase in the tensile modulus value and same is the case for the ZYX axis specimens the layer-oriented specimen shows a 31% increase. The multi-axis machine printed specimen shows better yield tensile strength, with the 45° specimen showing 30% higher and ZYX axis specimen being 153% higher strength values. The multi-axis printing certainly proves to be beneficial but it additionally requires careful planning of clearance, support and tool head dimensions to avoid the collision between tool and the printed part.
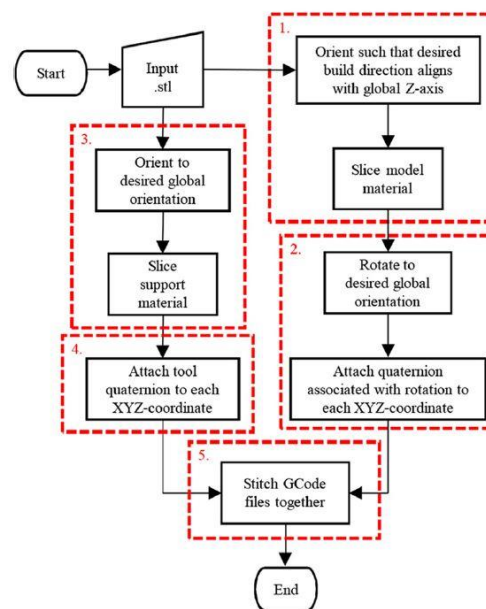
Figure 1. Description of the Multi-axis toolpath planning algorithm used for printing as a flow chart (Kubalak et al., 2019)

The post processing of the buildup parts is mandatory for most industrial applications, the existing procedure for post processing of parts produced through Laser Powder Bed Fusion (L-PBF) require several preparation steps and involves the risk of workpiece deformation due to multiple cut off and reclamping, which results in lack of automation to the process and results in additional lead time. To avoid this a continuous flow of workpiece is essential for the industrialization of the process, the Wollbrink et al. (2020) developed a substrate plate system that is capable of withstanding the L-PBF process and able to fit in most of the L-PBF machines, the new substrate plate is designed to continue

the same substrate plate for the entire process chain with an easy removal of the part and increased life of the substrate plate. The plate is fabricated using AISI 446 steel material. The substrate plate system consists of four layers i.e., the base plate which is mounted to the machine table, the collet plate in which the collets to fix the pins are screwed in, the clamping plate opens and closes the collets, and the substrate plate on top where the part is built up. The substrate plate consists of circular matrix of slots for the pins and this matrix pattern is updated to the part building software, this enables the construction of the support elements to the part design. The conventional method involves the disposal of the plate after a defined number of applications due to the thermally induced stress, but the new substrate system designed can maintain its stiffness over time. With this concept of releasable pins new process chain design opportunities are possibilities. A part of turbo machinery was built to test the substrate plate system and the post processing was done successfully using a milling operation.

Another approach used by Borovkov et al. (2020) for improving the accuracy of the product is by using computer aided engineering to model the process directly, the research was performed by creating a digital twin for the entire process and running a simulation of the layer by layer development of the part. The material used for this study was AlSi10Mg and the part was a service bracket used in the jet engine. The finite element modeling software Amphion was used for the modeling of the part and simulation of the process along with the support structure generation. The mechanical properties and deflection of the trial specimen was updated to this software for the preparation of the digital twin. Prior to the step-by-step simulation of the process done by the software several parameters such as scanning strategy for printing, post processing and heat treatment of the part are added to the software. The aim of this simulation is to get the data about the deformed shape and predeformed shape of the part, the deformed shape gives us the deviations of the printed object to the required one and the predeformed shape in printing allows us to get the original part with nominal geometry. To evaluate the effect of these simulations several brackets were printed with nominal geometry, predeformed geometry with and without optimized support structures. It was concluded that the print with predeformed geometry with optimized support structures were the most accurate one to the required dimension, hence simulation of the process before additive manufacturing can be an effective method to improve the quality and reduce the costs.

Ultrasonic additive manufacturing (UAM) is an effective technique for solid state processing of thin metal layers and joining them by application of ultrasonic vibrations and compressive normal force. Levy et al. (2018) used UAM for fabrication of laminated low-alloy carbon steel, the advantage of this method is that the defects associated with melting and solidification are eliminated as the layers are formed in solid state. This technology is based on the application of the ultrasonic vibrations (20 kHz) through a sonotrode horn. Levy et al. (2018) welded nine SAE4130 grade steel foils of 0.127 mm thickness and 25.4 mm width on to a steel substrate with 12.7 mm thickness , the process parameters such as vibration amplitude, weld speed, weld force, base plate temperature were varied for several specimens and only the parameters in which the initial steel foiled did not peel off from the substrate and welded properly were considered. After all the layers were welded the interface between the parts exhibited numerous defects affecting the bond quality and this was confirmed through cross section microstructure analysis. To improve the properties of the welded parts heat treatment of the specimens was performed through Spark Plasma Sintering (SPS) at 950°C for thirty minutes and under uniaxial pressure of 25 MPa, the Hot Isostatic Pressing (HIP) was also performed at 950°C for thirty minutes under 100 MPa argon pressure. After the treatment the shear strength test was performed in the specimen and it was found that the shear strength of the SPS treated specimen was three times higher than that of the as printed specimen and the hardness of the material improved uniformly in the HIP specimen. Hence both these processes can be useful in industries for the improvement of the properties of the UAM workpiece.

Machine learning can play a great role in optimizing the additive manufacturing process. Osswald et al. (2020) used machine learning to predict the cooling phase in the multi-jet fusion technology. This technology was developed by HP Inc., the system consists of three main parts, the printer, a processing station, and one or more trolleys which are the build units. These components communicate via internet. The printing process is done in multiple steps, first the material powders is placed inside the processing unit, generally thermoplastic powder, next an ink jet array disperses a fusing agent and a detailing agent over the powder bed. The area coated by the fusing agent can absorb the energy, allowing that particular region to melt and fuse that portion together while the rest of the powder in that layer is not melted. By this method each layer of the part is built inside the trolleys. The advantage of this multi jet system is multiple pieces can be designed to fit inside the trolleys and can be built together. After the part is built, it is allowed to cool down generally for 24 hours followed by cleaning and post processing. In the entire process 66% of the time is spent in the cooling process and this is undesirable for the mass production in industries. There is no accurate method of determining the cooling time, the manufacturer of the multi jet system provide a generalized guide value for cooling but it is often overshot and this affects the process planning and operation of the trolleys with printed products. Osswald et

al. (2020) used gaussian process regression to create a model to predict the cooling time. The internet of things based MIOTY developed by Fraunhofer IIS is an integral part of the communication system in this research. The measurements of the temperature during the cooling phase were measured in an interval of five minutes through a type K thermocouple inserted into the trolley through the opening on the top lid along with the housing and measuring system mounted on top. It is inserted in such a way that temperature for all the possible job heights from 40 – 350 mm can be measured.   Cooling curves of various build jobs were recorded for four months along with variable parameters such as build job height, packing density, number of layers, number of parts in the build and environment influences such as temperature and humidity. The machine learning model was built in Matlab software and monitored learning procedures was implemented. The gaussian process regression model is trained with the different parameters to predict the cooling time of the build till it reaches 50° C as the output. The model is most accurate when the 30 data points are measured the error value determined used the root mean square error was the lowest for 30 data points.   The optimized cooling time prediction was closer to the actual measured value than the manufacturer provided values and this model was implemented in BMW's additive manufacturing production facility for a leaner production and planning.

The additive manufacturing process can also be used for composite materials, Selvam et al. (2020) used 3D printing for the fabrication of Carbon Fiber reinforced Polylactic acid (CFRPLA) and applied the bioinspired interlock sutures. PLA is bio-degradable in nature so it was selected, the PLA pellets were mixed with 5% of CF for twenty minutes and were extruded by a customized filament setup with a nozzle of 1.7 mm diameter. PLA has lower strength than other materials like Acrylnitril-Butadien-Styrol (ABS) hence reinforcements are required. Forty-eight identical T joints were fabricated using this method, sixteen each for the three interlocking sutures spline, triangle and rectangle. The process parameters such as extruder temperature, layer thickness and speed influenced the strength of the specimen greatly, hence sixteen sets of parameters were chosen for each of the designs and all the forty-eight specimens were subjected to the bending load. Using the test value, a regression model was built for each interlock joint. The design with a spline interlock suture had the highest bending load strength, the best regression equation of spline model was hence used for the particle swarm optimization (PSO), this is done to optimize the process parameters value that gives us the maximum bending strength of the T joint. The PSO code was written in Matlab and result was evaluated with the experimental result. The extruder temperature of 190° C, layer thickness of 0.1 mm and speed of 60mm/s was the PSO optimized parameters and the predicted result of bending load was 345.68 N and the experimental result is 344 N. It was found that PSO technique is an effective method for predicting the optimum parameters for the 3D printing process of CFRPLA and can hence be applied for several other researches and industrial requirements.

4. Discussion

In this review article the technologies and researches that was applied to improve the accuracy, mechanical properties and process optimization of additive manufacturing were highlighted and the core aim of these works is to utilize the potential of additive manufacturing in fabrication of complex designs with minimal material usage. The researches mentioned above do tend to have few limitations, the laser assisted 3D vision system might cause distortion to the accuracy due to the additional heat generated by the laser, to counter this a monitoring system without laser for the robot's path prediction can be one of the future fields of research. In the case of multi-axis material extrusion future technologies must be focused on developing algorithms for the orientation of layers for complex structures with loading in multiple directions. The machine learning model developed for determining the optimum cooling temperature in multi-jet systems is already implemented and based on the performance further data must be added to the model for more accurate prediction. To increase the stability in the additive manufacturing simulations can be used for all future works. The PSO method works as an effective tool for predicting the optimum process parameter that affect the strength of the printed part and this paves way for the fabrication of bio degradable polymers with CF reinforcements. The future work can be done for bio inspired sutures design of glass fiber reinforced filament to improve their tensile strength. It can be summarized that with the help of these technologies in overcoming the limitations, the process of additive manufacturing can be further utilized in advanced product manufacturing.

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Review article

Cold Spray as a means of Additive Manufacturing technology for the generation and repair of components†

Sankhya Bhattacharya [1,*]

[1]   Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: sankhya.bhattacharya@s2019.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: In this review article the latest trend in the field of Additive Manufacturing has been presented. The name of the process is Cold Spray Additive Manufacturing (CSAM). This process has gained immense popularity in the recent years because of its ability to produce near net shaped parts or repair of damaged parts with high accuracy and precision for multi material systems. In this review article the detailed study of the process including its construction and components have been illustrated. An understanding of the bonding mechanism by studying the spray materials and substrate properties have been gathered. A brief inspection on the powder and coating characteristics have been touched upon. The review article is concluded with the major advantages and disadvantages of the process and subsequent solutions have been provided along with its applications and further scopes for future enhancements.

1. Introduction

Cold Spray Additive Manufacturing (CSAM) is a highly efficient and dependable method for the application of various high quality coatings made up of metals, alloys, composites, refractory materials, etc. Cold Spray (CS) technology was firstly introduced in the early 1980s at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences in Novosibirsk. In this process the starting powder is accelerated to the supersonic flow of working gas with the help of a supersonic converging-diverging nozzle to extremely high velocities of approximately 300-1200 m/s at a temperature much lower than the melting point of starting feedstock materials. The oxide layer on the surface are broken down by the accelerated particles and a strong bond is formed with the chemically active surface of substrate (Sova, Grigoriev, Okunkova, Smurov. 2013). The working gases are Helium, Argon or Nitrogen. The performance and property of a CS coating significantly depend on the bonding state of particle-substrate and particle-particle interfaces.

The compaction, deformation and plastic flow of sprayed particles with a very high velocity results in the elimination of the oxide layer from the surface of the substrate and formation of a strong bond. Due to the nature of this method of deposition process at a low processing temperature, the adverse effects of oxidation, decomposition, grain growth, phase transformation and other problems can be prevented. This method is widely utilized for the generation of new coating or possible repair of the damaged parts leading to a reduction in lead time, labor and other costs. It is considered as a legitimate repair method to a wide range of parts such as turbine blades, valves, cylinders, pump elements, pistons, bearing parts, rings, etc.

2. Methods

All the reviewed literature such as journal, articles, e-books and conference paper were obtained from Google Scholar, Scopus, ScienceDirect databases via TU Chemnitz University Library access. In order to finalize a topic a comprehensive research was done in the field of 'Technologies and Applications in the field of Additive Manufacturing' and 12 papers were shortlisted. The search was filtered on the basis of recent study articles no earlier than 2013 to focus on the recent trends in the field of Additive Manufacturing. When a particular topic was shortlisted based on keywords 'trends in additive manufacturing, 3D printing, Coating technologies', etc. the most relevant ones were considered along with the maximum number of citations. This narrowed down the search from 12, and thus 8 papers were finalized. Citavi 6 was used for citations adhering to the APA (6th edition) format. Preliminary assistance was obtained from websites such as Research Gate, Springer, Springer Professional, Mdpi, etc.

3. Results

3.1 Construction

The typical Cold Spray Additive Manufacturing (CSAM) system had been divided into five modules (Wu et al. 2021): spray module, robot module, in situ measurement module, inter-process module and post-process module (Figure 1).

3.1.1 Spray module

There were majorly two types of CS system which were used. They were the portable CS system, and the robotic CS system. The various apparatus of spray module were – A high-pressure compressed gas source, a powder feeder, power sources, and a spray gun with a de Laval nozzle. The gas source was Air, Argon, Nitrogen, and Helium.

The various factors which affected the spray performance were the nozzle design, gas stagnation temperature, gas stagnation pressure, particles density and the type of working gas.

3.1.2 Robot arm

This involved an industrial robot arm (ABB IRB 2400), a robot control cabinet and a computer (Wu et al. 2021). Such a process mainly used industrial robots due to their high accuracy, repeatability, and flexibility. The most common role of an industrial robot in CS was to hold the spray gun to spray materials, while the substrate was statically fixed.

3.1.3 In situ measurement module

The in-situ measurement module consisted of a 3D scanning system with a 3D scanner, a computer and software. The 3D scanner may use an optical laser or contact systems (Wu et al. 2021). According to the study, a high-speed 3D laser profiler (LJV7060, Keyence, Japan) was used to perform contour scanning, data acquisition and processing, which were connected to the robot control cabinet via a computer. The 3D Scanning system had been used for CAD modelling, monitor the Cold Spray deposition process and measurement of coating thickness.

3.1.4 Inter process module

This module was used to analysis and realize the combinations of Cold Spray Additive Manufacturing processes and other machining processes such as milling, drilling, etc. which were characterized by a relative interaction with the actual CSAM process. This module allowed combinations of CSAM with other subtractive manufacturing processes, making it a hybrid Additive Manufacturing process.

3.1.5 Post processing module

The parts produced by CSAM process required high amount of post-processing to overcome various challenges after spraying. Therefore, the post-process module was designed to conform to the required properties and geometry. Post-treatment process primarily depended on the material and its application which further assisted in the repair process.
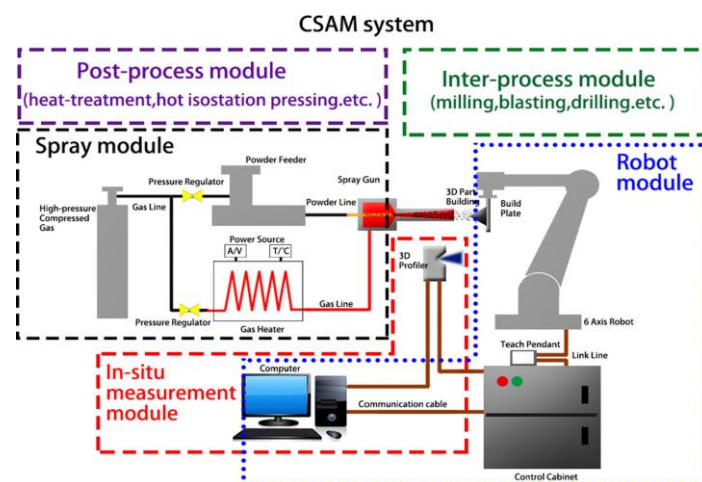
Figure 1. Schematic diagram of CSAM System.

3.2 Process

3.2.1 First step

A 3D geometric model was to be acquired. Be it spraying as a coating on a complex surface, or accumulating material over a damaged contour or developing a freestanding shape component, the corresponding CAD model was essential.

3.2.2 Second step

The work piece was analyzed and effective related manufacturing strategies were formulated (Wu et al. 2021). The most desirable solutions were provided by the advanced robot offline programming technology. The graphical simulation of the robot and its work cell, motion planning and programming for the manufacturing process, kinematic models of the robot, was provided by RobotStudio™.

3.2.3 Third step

The work piece had to be pre-processed such as blasting or other machining and bound at a position in the work spot.

3.2.4 Fourth step

The spray program was scanned and run.

3.2.5 Fifth step

Post-processing done to reach the desired performance and precision. They included residual stress, failure mechanisms, micro hardness, microstructure, determination of mechanical properties, etc. to detect subsurface (internal) potential flaws such as cracks, delamination, porosity, contaminants, and weak bond interface.

3.3 Spray Materials

This process can be used with a plethora of particle materials, such as ceramics, metals, polymers, and composite materials. In this study of CSAM, the basic properties of Aluminium, Titanium, alloys and Cermet had been studied. Aluminium (Monette, Kasar, Daroonparvar, Menezes, Pradeep. 2020) showed a high specific strength, good wear resistance, good thermal stability, and superior seizure resistance. Such spray coatings could be widely developed and tested in marine, nuclear, military applications (Petráčková, Kondás, Guagliano. 2017). The process when used with Titanium powder resulted in a compact coating with a high dimensional tolerance, high deposition rate, and minimal heat-affected zones (Monette et al. 2020). Deposition of alloys such as Stellite 6, Waspaloy, Inconel 625, Inconel 718 (Monette et al. 2020) resulted in microstructure compactness and hardness of the coating (Pathak and Saha 2017). Materials when reinforced with Cermets (Pathak and Saha 2017) had various advantages such as improved physical, chemical, mechanical, tribological, optical properties and high deposition efficiency. Cermets also kept the nozzle clean.

3.4 Bonding Mechanism

- In the first stage, a thin layer of material (monolayer) was deposited on the substrate (Prashar and Vasudev 2021). This stage (Figure 2) was characterized by substrate and particle direct interaction and depended on the properties of the substrate and the degree of preparation of the substrate surface (Sova et al. 2013);
- In the second stage, a layer of finite thickness was built up by particle deformation and realignment (Pathak and Saha 2017). With the development of densification, there was displacement of the material at the point of contact, the contact area enlarged in size and the inner particle voids were filled with the material, which could be termed similar to the peening effect. (Figure 3);
- In the third stage there was formation of a metallurgical bond between the particles and subsequent reduction in voids (Sova et al. 2013). Thus, a new component could be produced or a damaged component could be repaired;
- In the final stage there was further work hardening and densification due to the peening effect of the coating.
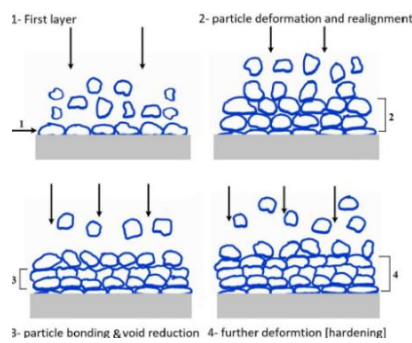
Figure 2. Plastic deformation stages for ductile materials.
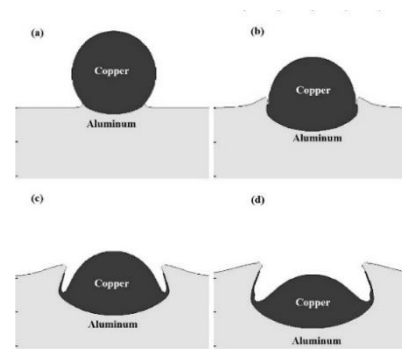
Figure 3. Impact of Cu on Al substrate at 5,20,35,50 ns.

3.5 Powder and Coating characteristics

The powder characteristics of Stainless Steel (Brewer, Schielb, Menon, Woo. 2018) had been studied and was found that there was successful cold spray deposition of austenitic stainless steels, i.e. SS304 and SS316, within a range of different spray conditions. By keeping a temperature range of 320-1000°C, pressure range of 0.6-4 MPa and gas types as Nitrogen and Helium, the deposition efficiencies ranged from 19% to 100%. By the use of mixed particle sizes, the addition of Aluminium oxide powders and increase in the temperature and spray pressure during the spraying process, the measured particle velocities were found to be in the range of 625-800 m/s. The greater particle velocities corresponded with increased deposition efficiencies and increased density of the coating. The hardness of the cold-sprayed coatings was expected to be very large mainly because of the intense strain hardening experienced by particles upon impact (Brewer et al. 2018). The Vickers hardness values were reported to be in the range of HV200-437. The higher hardness values were observed when Helium was used as spray gas, instead of Nitrogen. The main explanation for this was the higher spray velocity of the Helium gas, which imparted greater velocity and kinetic energy to the steel particles, resulting in a denser coating with high plastic deformation, thereby enhancing the hardness.

Tests had been carried out with commercially available inert gas atomized A357 Aluminium alloy powder (Petráčková et al. 2017), with particle size distribution of 15-63 micrometer by varying gas temperature (200-550 C), spray angle (60-90 degrees) , pressure (20-57 bar), and stand of distance (10-50 mm). The deposition efficiency was compared by measuring the thickness of the coatings using the Keyence VHX-5000 digital microscope; the optimum spray parameters were chosen based on lowest porosity and highest deposition efficiency (Wu et al. 2021). Highest deposition efficiency and tensile stress were achieved when sprayed at 550 °C in presence of Nitrogen without altering the residual stresses.

4. Discussion

The Cold Spray Additive Manufacturing is a solid-state coating technology in which a coating is generated by plastic deformation of the substrate with the colliding feedstock powder below its melting point unlike in conventional Additive Manufacturing technologies like Selective Laser Melting (SLM) where the coating is generated by fusion of the powder with the substrate at high temperatures, therefore, (Sova et al. 2013; Monette et al. 2020) while comparing with SLM, creation of multi layered objects using materials with different coefficient of thermal conductivity and thermal expansion lead to technological problems. The process set up and bonding mechanism is simple yet highly effective. CSAM is a relatively young technology in the field of Additive Manufacturing (Prashar and Vasudev 2021), but with a plethora of applications in the field of aerospace (example - actuator barrels of aircraft nose wheel steering fabricated with Nickel alloy), marine (example - antifouling of artificial underwater maritime structures), military (Pathak and Saha 2017), repair, and many more which are yet to be explored. One of the main mottos of this process is 'Repair rather than Replace', due to high deposition efficiency and material recovery rates without the need of protective atmosphere.

5. Conclusion

The coatings generated by the process of CSAM showed several advantages like wear and corrosion resistance, increased deposition efficiency, improved electrical conductivity. This method can be used for restoration and repair of damaged parts of expensive materials such as Titanium. Since the greatest advantage of the CSAM process is its ability to fabricate functionally graded and multi material components, therefore, new developments in the application of

micro nozzles for enhancing the spatial resolution and enhancing the precision with optimized spraying strategy can be a scope for the future research. Since the bonding mechanism in the process of CSAM is through plastic deformation, therefore the problems due to the presence of micro pores in the deposits can be overcome by increasing the impact velocity of the feedstock powder and peening effect as a method of post processing. This technology is not abruptly cost intensive; however, efforts should be made to shift to air and Nitrogen as the carrier gas instead of Helium for future commercial use in the industry. As one of the main motto of this process is 'Repair rather than Replace', therefore efforts should be made for proper installation and selection of the components and educating the technicians. The CSAM technology holds the capability of transforming the entire industrial system in terms of product life and resource efficiency.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Comparing Return Loss of Horn Antennas Produced by Laser Beam Melting & Stereolithography†

Dakshil Kirtikumar Prajapati [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: dakshil-kirtikumar.prajapati@s2020.tu-chemnitz.de
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Abstract: With the inherent advances of rapid prototyping, design flexibility, and cost-efficient applications, Additive Manufacturing (AM) technology has emerged as a successful alternative in recent years for prototyping complex Radio Frequency (RF) antennas. The purpose of this review is to focus on the S11 (or return loss) and the impact of surface roughness on the S11 of the horn antennas which are manufactured with metal and polymer-based materials. This review compares the return loss of horn antennas produced using advanced AM technologies such as Stereolithography (SLA) (polymer) and Laser Beam Melting (LBM) (metal). The results reveal that the return losses for the antenna made of metals are more efficient as compared to the antenna made of polymers and also the return loss is unaffected by the roughness of the surface.

Keywords: Additive Manufacturing; horn antennas; Stereolithography; Laser Beam Melting; return loss.

1. Introduction

Additive Manufacturing has a wide range of applications in the field of space technology. Due to its simplicity, low cost of manufacturing, and rapid prototyping, we can produce components ranging from small antennas to entire rocket engines. Additive Manufacturing, also known as 3D printing, can print an object in three dimensions with high accuracy. The recent advancement in AM technologies helped in the development of High Throughput Satellites (HTS). HTS provides high bandwidth connectivity as compared to traditional satellites. AM plays an important role in the manufacturing of horn antennas which are used in satellites for transmitting and receiving signals from various sources on earth. Among the other antenna elements which are used for HTS operating in Ku band, the feed horns, Orthomode Transducer (OMT), and waveguide are designed mostly with AM technology because of low cost and the ability to print the antenna in one single piece, reducing the assembly time as well as increasing the performance of the antenna (Kilian et al., 2019).

Horn antennas are commonly used for broadcasting signals and operate at microwave frequencies. It is a type of directional antenna, so it can be utilized for long-distance communications. There are different types of horn antennas categorized based on their shape and capacity to transmit energy. Some examples are sectoral horn, spline horn, pyramidal horn, conical horn, and corrugated horn. Traditionally, casting or forming sheet metal processes are used for the manufacturing of horn antennas, but now these antennas can be developed with different AM techniques such as SLA (Kilian et al., 2019), Direct Metal Laser Sintering (DMLS) (Kilian et al., 2019), LBM (Cailloce et al., 2018), Direct Digital Manufacturing (DDM) (Kacar et al., 2017), etc. The main challenge for the application of AM techniques in the development of antenna models is to have good accuracy, surface roughness, and electrical conductivity.

There are different types of printing materials available for space applications, every material has its special characteristic, strengths, and limitations. The commonly used material for AM is a polymer-based material, which shows good results in RF applications. SLA is one of the 3D printing processes which uses ultraviolet light to cure polymer and produce parts with extremely high precision. Earlier, SLA was a strong candidate for printing horn antennas because it offers some of the finest resolution and greatest surface qualities compared to other AM techniques (Van der Vorst & Gumpinger, 2016). A ring focus dual reflector and spline profiled smooth horn antenna manufactured by the SWISSto12 company was reported at European Conference on Antennas and Propagation (EuCAP) in 2016 (Van der Vorst & Gumpinger, 2016). Polymer-based material has certain drawbacks as it requires copper or gold coating which are overcome by metallic materials.

The Additive Manufacturing industry has been growing rapidly and with the development of new machines and methods, printers are now capable of printing metal-based materials. 3D printing technologies that use metallic materials are Laser Beam Melting and Direct Metal Laser Sintering. LBM is a newly developed process in which 3D objects are divided into 2D layers in software and a high-power laser is used to melt and fuse the metal powder. Two spline profiled horn antennas are manufactured with the LBM process using two metal materials, one with titanium (Ti6V) and another with aluminium (AlSi7Mg06) (Cailloce et al., 2018). DMLS is a rapid prototyping technology that uses a high-power laser beam to melt and fuse the metallic material, hence building a model layer-by-layer. An entire Ku band feed cluster manufactured with the DMLS method containing horns, OMT, and a waveguide was reported in 2019 at EuCAP (Schneider et al., 2019).

2. Methods

First, a short search was conducted using the term "additive manufacturing". Four databases were selected, including Google Scholar, IEEE Xplore, Springer link, and Research Gate. After reviewing some of the recently published literature on AM applications from 2013 to 2021 on all four databases, one of the most recent advancements in AM in space technology was chosen for this review. Next, the term "Additive Manufacturing for space" was searched in the IEEE Xplore and it showed around 248 results consisting of 183 conference papers, 49 journals, 11 Books, 3 early access articles, and 2 magazines. Judging from some of the recent space applications, most conference documents were related to antennas. The antenna types mentioned in the database were different, so to further narrow down the subject area, different keywords such as "Additive Manufacturing of antenna", "3D printed antenna horn" and "Additive manufacturing of RF antenna" were used. A detailed review was carried out on the various types of antennas operating at different frequencies. After analyzing 21 conference papers and 1 journal, the antenna operating at Ku band was selected. Next, the keyword "3D printed horn antenna for Ku band" was searched and all the relevant data related to the horn antenna for Ku band was available in the IEEE Xplore. It has 10 conference papers and 3 journals. The relevant data based on metal and polymer printed horn antennas were selected from 2 conference papers after evaluating 10 conference papers. After reading 2 conference papers, the return loss of the horn antennas, which were made utilizing the LBM and SLA methods, was carefully examined and the other 5 papers based on SLA, DDM, and LBM processes were chosen after that. Finally, 5 conference papers including LBM and SLA procedures with return loss, 1 conference paper with data related to the calculation of return loss in horn antenna, and 1 paper with DDM process were chosen, and all information was gathered and analyzed.

3. Results

To check the efficiency of the antenna, some of the RF performance of horn antenna such as return loss, gain, directivity, and radiation patterns are measured. Horn antennas are designed in different shapes and with different materials depending on their application. While designing the antennas, Scattering or S-parameters are analyzed which show the relationship between the input and output ports of an antenna and are is measured by using a Vector Network Analyzer (VNA). The return loss, also known as the S11 reflection coefficient, is a measurement of how much power is reflected from an antenna port and it is expressed in decibels (dB). The S11 reflection coefficient of different materials such as polymer and metal are compared in this review paper. S11 is an important parameter because it helps in understanding the signal performance and is taken into account where impedance matching is important. It is observed that the range for the return loss is from -10 dB to -20 dB (-10 dB means 10% power reflected and 97% transmitted and -20 dB means 1% power reflected and 99% transmitted) (Makam & Kulkarni, 2013). The measurements were done in the Ku band range (12 GHz -14.5 GHz). The value below -10 dB is the recommended value of return loss for antenna design and above -10 dB indicates design failure because most of the power is reflected and a very low amount of power is transmitted.

Firstly, with the help of the LBM process, two different spline horn antennas are created and their results were compared with simulation (Cailloce et al., 2018). The FEKO simulation software developed by Altair Engineering was used to calculate and compare the S11 parameter for both titanium (manufactured with ProX320) in Figure 1**(a)** and aluminium (manufactured with SLM500) in Figure 1**(b)** and the results were quite similar to the simulation results (Cailloce et al., 2018). The red line represents the results of the FEKO simulation, whereas the blue line depicts actual measured data from prototypes. The measured value is below -18.5 dB from the starting value of 11 GHz. The return loss is gradually decreasing below -18.5 dB (as shown in Figure 1**(a)** and **(b)**) and at 14.5 GHz it is below -45 dB which indicates that the antennas are capable of transmitting power with very low return loss.

Secondly, with the help of SLA technology, a spline profiled smooth horn antenna is created with polymer and coated with copper, and then the return loss is measured by using CHAMP 3D software developed by Ticra (Van der Vorst & Gumpinger, 2016). The prototype is manufactured with an advanced plastic material by the SWISSto12 company (Van der Vorst & Gumpinger, 2016). The results (shown in Figure 2) are not satisfactory for the return loss as per the graphs. At 12 GHz the return loss is above -10 dB which indicates a problem in antenna design. The results are not accurate probably due to two reasons, either the shape of the waveguide is changed from circular to rectangular or it needs further development in the interface (Van der Vorst & Gumpinger, 2016). The values shown with the blue line are based on simulations only.
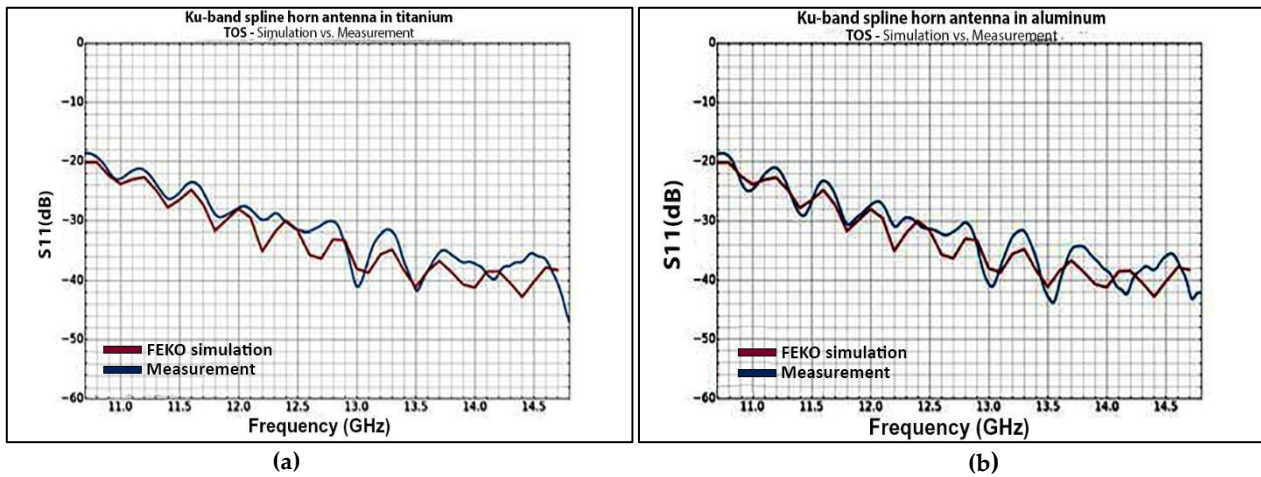
Figure 1. Simulation vs measurement of S11 reflection coefficient: **(a)** Ku band spline horn antenna in titanium; **(b)** Ku band spline-horn antenna in aluminium (Cailloce et al., 2018).
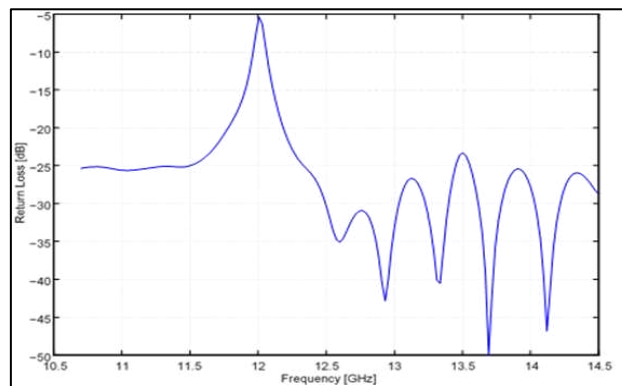
Figure 2. Return Loss or S11 of Spline-Profiled Smooth Horn Antenna made of polymer (Van der Vorst & Gumpinger, 2016).
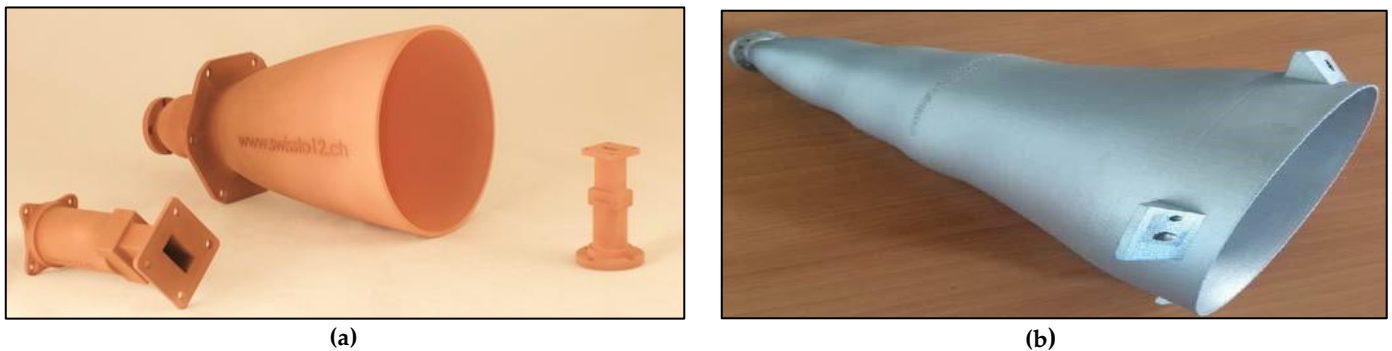
Figure 3. Image of the actual spline horn antennas manufactured with different materials and methods: (a) polymer using SLAprocess (Van der Vorst & Gumpinger, 2016); (b) aluminium with LBM process (Cailloce et al., 2018).

Figure 3 shows actual horn antenna prototypes with smooth surfaces produced using SLA and EBM techniques. Smooth wall spline-shaped horn antennas are easier to build than other shapes, such as corrugated shaped spline horn antennas, and they also have the advantage of being lightweight (the weight of corrugated shape antenna is much higher). As illustrated in Figure 3**(a)**, the copper coating was applied on the surface of the polymer horn antenna to provide a clean surface finish, and after coating different results were calculated. Surface roughness is one of the disadvantages of the metal AM process, and it is not always possible to provide a suitable surface quality due to complex structures. The horns manufactured with Al as shown in Figure 3**(b)** using the conventional milling method has a low surface roughness of fewer than 1 μm, whereas, in the case of 3D printed horns the surface roughness is 16 μm and after postprocessing, the surface roughness is reduced to around 3.4 μm for the Aluminum (Cailloce et al., 2018). It can be noted from Figure 1 and Figure 2 that the surface roughness does not have any impact on the return loss of the metal printed horns as well as polymer printed horns. Other RF performances, such as conductor loss, may be affected without sufficient coating for polymer antenna or polishing for metal antenna, although the effects will be minimal for the return loss.

4. Discussion

The results show that the return losses of the horn antennas created with Ti and Al are around -20 dB which shows better performance of the antennas. The return loss comparison between polymer and metal horn antennas is analyzed in order to show the advantage of the advanced metal AM process over the polymer AM process. The findings for polymers are unsatisfactory since numerous aspects were not taken into consideration, and as a result, it does not represent the best achievable antenna performance (Van der Vorst & Gumpinger, 2016). Another important RF parameter to consider while building a horn antenna is the radiation pattern. The radiation patterns of spline horn antennas made of Ti and Al (Cailloce et al., 2018) and spline profiled smooth horn antennas (Van der Vorst & Gumpinger, 2016) are compared, and the findings reveal that the horn antennas made with both AM techniques have a greater performance. Although the use of polymers reduces the weight and increases the thermal insulation of the antenna, the author suggests that a copper coating is required for the antenna to function properly in space (Cailloce et al., 2018). The overall cost of the polymer antenna is increased because of the conventional coating method which is necessary to improve electrical conductivity. To reduce the cost, the process of manufacturing polymer antennas can be improved by combining two different AM techniques into one, first prints the antenna with polymer and second for providing a metal coating on the antenna.

Due to the drawbacks associated with polymer-based materials, metal AM methods are fast gaining prominence for the production of complex space antenna structures. This is mainly due to the fact that structures produced by this method do not require additional coating. Furthermore, there has also been an emergence of new materials such as scalmalloy, a recently created aluminium alloy by Apworks which possesses greater strength than the commonly used aluminium (AlSi10Mg) powder for metal 3D printing (Kilian et al., 2017). Also, owing to its strength and lightweight characteristics, scalmalloy is even stronger than titanium, thus resulting in it being poised as the future of horn antenna manufacturing.

The use of metal Additive Manufacturing in the space industry is still in its early stages, and more development of these techniques will be necessary before they can be fully embraced. Although both metal and polymer AM techniques used for antenna production have associated limitations such as the need for polishing and coating respectively, they possess several advantages over traditional methods. In conclusion, metal AM technology is the most effective technique for RF applications because it produces good results for return loss and also provides cost-efficient solutions.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Microstructure and mechanical properties produced by Hybrid Additive Manufacturing†

Jean Damascene Nirere [1],*

[1] Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: Jean-damascene.nirere@s2020.tu-chemnitz.de
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Abstract: For the last decades, Additive Manufacturing (AM) has been adopted by industry. However, certain limitations are still hindering its full exploitation. Recently, there has been an approach to alleviate some of its drawbacks by integrating AM with conventional manufacturing techniques through what is called "Hybrid Additive Manufacturing (HAM)". In this paper, the HAM that combines powder bed fusion with sheet metal forming using 316L steel is reviewed by focusing on the microstructure analysis, geometry and hardness of the resultant material. It was found that the hybrid part indicated improved mechanical properties with little geometric deviations to the target compared to the conventional formed material. Furthermore, current challenges and future research work in the field are highlighted.

Keywords: Hybrid additive manufacturing, Additive manufacturing; Metal forming, Conventional manufacturing.

1. Introduction

Additive Manufacturing(AM) has a great potential for the future industrial age due to its benefits such as part complexity, flexibility, product customization and high efficiency(DebRoy et al. 2018; Tofail et al. 2018). AM consists of building components by a layer by layer approach(Tofail et al. 2018). For metallic components, powder bed fusion and direct energy deposition are among the well-known AM techniques(Pragana et al. 2021). On the other side, AM has disadvantages such as high manufacturing cost and long process time for large size products to name a few (Bambach et al. 2020). One of approaches to mitigate these challenges is to integrated AM with a second conventional production technique through Hybrid Additive Manufacturing (HAM)(Dilberoglu et al. 2021). Hybrid manufacturing can be defined as the combination of two or more established manufacturing processes into a set -up that synergically exploit advantages of each discrete process(Zhu et al. 2013). HAM can typically be used for the manufacturing of complex end use geometries such as EV connectors, switch boxes and duct shape core. It is also used to repair dies and other components that are expensive to replace(Jiménez et al. 2021). The process combination of AM and some conventional manufacturing techniques such machining was studied. On the other side, the study of the combination of AM with forming has not been intensively investigated (Merklein, Schulte, and Papke 2021). This paper reviews the microstructure, mechanical properties and geometry that results from the combination of powder bed fusion with metal forming using 316L steel.

2. Methods

To acquire relevant literature, numerous scientific databases including Science Direct, Mendeley, Google Scholar, Scopus and Web of Science were consulted. Different papers were found using keywords such as, hybrid manufacturing, hybrid additive manufacturing, hybrid manufacturing and forming. The obtained articles were sorted according to the date of their publication. Most of them were published only within the last 3 years (2019, 2020 and 2021). However, papers from early 2010s were also used depending on the relevance of the content. The relevant litterature from ten papers was summarised in a separate word document and the articles were stored in a Mendeley desktop folder for later consultation and citation.

3. Results

The reviewed papers are concerned with HAM. However, many of them do not specifically focus on the combination of AM and metal forming. The selected papers which pay a particular attention on forming are based on the

manufacturing of a gear with teeth geometry by depositing steel powder on a sheet of the same material followed by forming.

3.1. Microstructure and Mechanical properties

A gear with teeth geometry was manufactured by depositing 316L steel powder on a sheet of the same material followed by forming. Conventionally, this geometry can be produced by sheet metal forming process chain which consists of orbital forming, deep drawing and upsetting. In the case of HAM, the orbital forming process to form the teeth is not required (Figure 1a and b) (Merklein et al. 2021). The microstructure of the AM part and interaction zone between the AM and base material consists of large beads aligned in the build direction (Figure 2). The measured hardness profile shows the increase from the base material (215 ± 9HV) to the AM part (256 ± 6HV) (Merklein et al. 2021). The incresed hardness profile from the base material agrees with the study carried out on the forged Ti-6Al-4V alloy by depositing the same material. For the later case, the tensile testing indicated that the interaction zone did not have any detrimental effect on the mechanical properties (Bambach et al. 2020).
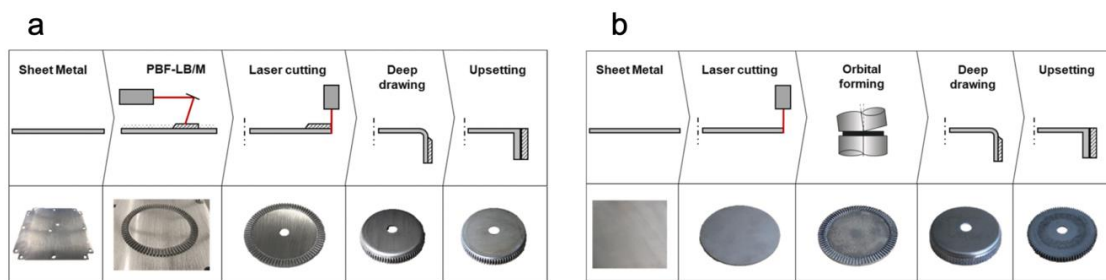
Figure 1. a) HAM process chain b) Conventional Manufacturing process chain (Merklein et al. 2021)
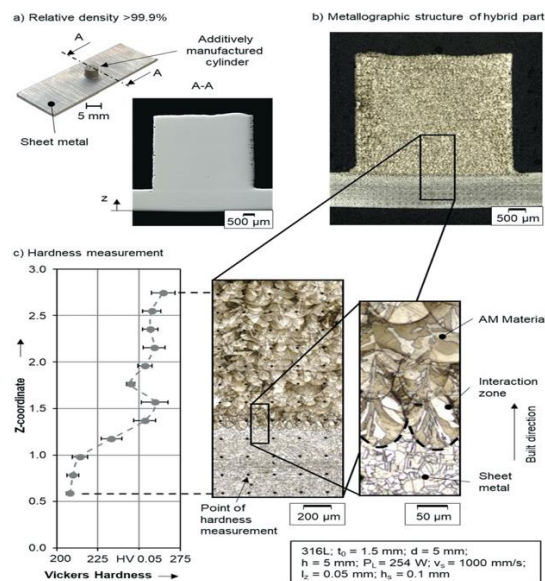
Figure 2. Microstructure and hardness distribution of the HAM part (Merklein et al. 2021)

3.2. Geometry and formability of the HAM part.

The overall geometrical deviation of 0.10 mm from the target geometry for the AM part was indicated considering the upper side of the teeth. However, compared to the deviation of the orbital formed part at the flank of the teeth, the AM teeth were much closer to the target geometry (Figure 3)(Merklein et al. 2021). The mechanical properties of the deep drown HAM part were found to depend on the position of the teeth relative to the outer radius of the geometry. The situation is indicated by two cases, R40 where the teeth are 40 mm from the centre and R35.2 where they are at 35.2 mm. After drawing and upsetting, it was indicated that for R35.2 the AM material terminates at the radius of the cup bottom and showed necking whereas for R40 the material was not at the bottom and no necking was observed (Figure 4). The hardness of the metal sheet was found to increase from 211± 2HV to 300HV for the R35.2, whereas the hardness

of the AM part did not change from 256±6 HV except from highly stressed part. For the R40, only the sheet metal hardness changed. Furthermore, the similar study on a stainless steel blank indicated the possibility of cracking which can be prevented by increasing the AM material thickness in the bending area (Figure 5) (Schulte et al. 2020).
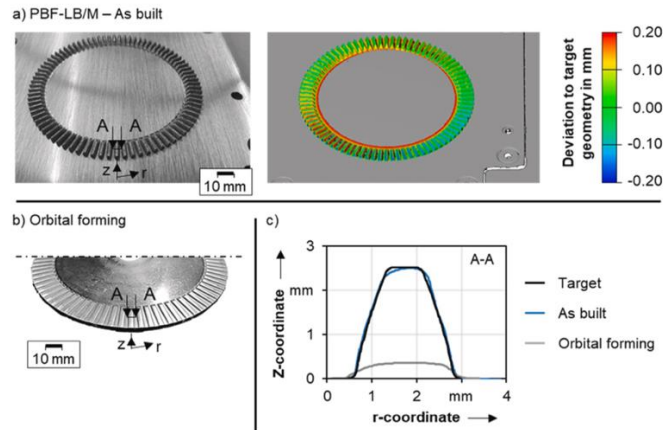
Figure 3. Geometry of a) hybrid part and b) conventional part and c) geometric deviation from the target(Merklein et al. 2021).
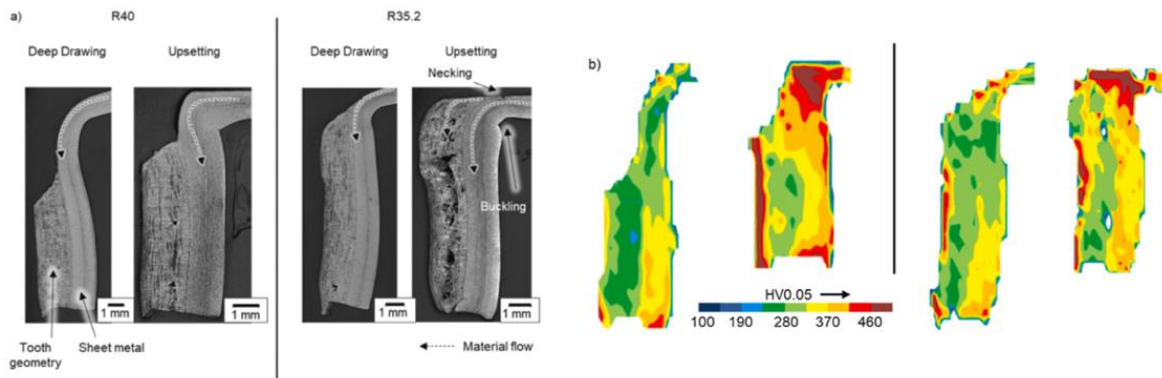
Figure 4. a) Cross section of the HAM part b) Hardness mapping after drawing and upsetting (Merklein et al. 2021).
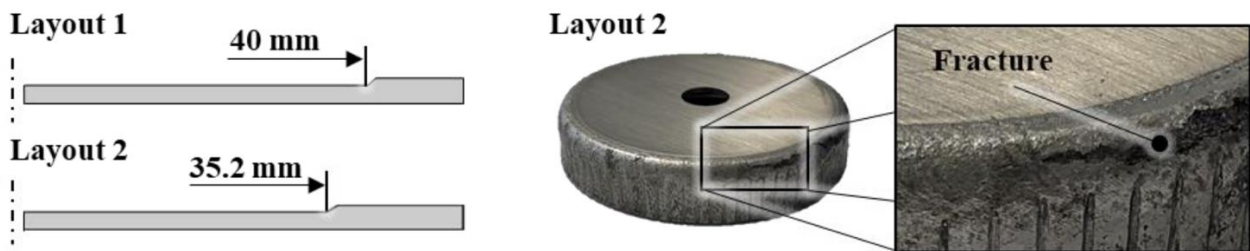
Figure 5. Material failure after deep drawing(Schulte et al. 2020).

4. Discussion

According to the result of the microstructure of the HAM part (Figure2), the base material microstructure was found to be consistent with that of 316L steel suggesting that it was not affected by heating and therefore no change in microstructure which is commonly known for some joining techniques (Shakerin and Mohsen 2020). The interaction zone results from the partial melting region which solidifies, coarsen and acts as nucleation site for the AM solidification grains that grow in the build direction. According to the hardness profile, the lower hardness from the base materials may be attributed to the annealing prior to deposition. The increase in hardness from the interaction zone to the AM

part is due to the high cooling rate. According to Figure 4, the rise in hardness of the base and AM material is caused by the work hardening due to forming. In the case of R35.2 where the AM material terminates at the bottom, higher bending stresses are expected, putting the AM part in tension however, no failure in the bending zone was observed in the study. On the other side, the possibility of cracking in the bending area which can be prevented by thicker AM matrial was indicated (Schulte et al. 2020). The incraese of crack resistance due to incresed thickness can be attributed to the higher volume of functional material material on the wall accomodating deformation. The necking of the R35.2 is caused by the flow behaviour difference between the AM part and the sheet metal where the yield stress of the sheet is lower than that of the AM part therefore, the sheet starts to flow before the AM material (Merklein et al. 2021). In summary, the feasibility of process combination between powder bed fusion (AM) and forming was examined. It can be concluded that: The hardness was found to increse from the base matetial to the AM part. The interaction zone between the base and the AM material did not show any detrimental effect to the mechanical properties after deposition. The HAM part showed little geometric deviations to the target compared to the part manufactured by the conventional process chain. The forming and upsetting processes did not cause failure in the bending zone for large material volume of the AM part suggesting that HAM has a high potential for the suggested applications. The possibility of cracking for a small volume of AM material in bending zone indicates that it is important to analyse the stress state in that region to understand the fracture behaviour. The future work should focus on the effect of geometry on stress state in the bending zones in case AM and metal forming because these zones can have a complex stress state which can promote failure of the AM part. The effect of surface preparation before material deposition is equally important as it can be the source of defects in the interaction zone.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

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Review article

3D Printed Titanium Brake Caliper in High-Performance Vehicles†

Krunalkumar Patil [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: patil.krunalkumar@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: With the advancement of Additive Manufacturing (AM) technologies, automobile manufacturers can manufacture new components with complicated designs and structures to achieve lighter and highly efficient components. The Bugatti titanium brake caliper is the world's largest working titanium component generated using 3D printing technology. This study analyzes mechanical properties such as tensile and fatigue properties of Ti-6Al-4V (commonly known as TC4 or Ti64) parts manufactured by two different AM technologies, Electron Beam Melting (EBM) and Selective Laser Melting (SLM). The findings indicate that the SLM method has better outcomes than the EBM method for the fabrication of titanium brake calipers.

1. Introduction

The market for AM has grown significantly during the last few years. Fabricating complex lightweight structures while maintaining adequate strength is a key element of AM techniques. As a result, AM technologies have a wide range of applications in the automotive, aerospace, and medical industries. Additionally, 3D printed parts require no or minimal machining before use. Therefore, with the help of AM, the overall production costs and carbon emissions are reduced. By using a post-processing process (e.g., heat treatment), properties of AM manufactured materials such as strength, hardness, as well as ductility can be improved (Wischeropp et al., 2019).

High loads are applied to braking systems in high-performance vehicles over short time intervals. A vehicle's deceleration is controlled by the braking system, which is an important aspect of the driver's safety (Farias et al., 2015). The brake caliper is an essential part of a disc brake. When you step on the brakes, the brake pads of the caliper press against the rotor of the wheel, preventing the wheel from rotating. Brake pads are a pair of metal plates found inside each caliper. Calipers must meet certain technical requirements, such as being stiff, lightweight, and heat resistant (Tyflopoulos et al., 2021). The vehicle's performance is improved by reducing its mass. Therefore, reducing the mass of the brake caliper becomes critical.

One of the most commonly used titanium alloys is Ti-6Al-4V due to its excellent corrosion resistance and high specific strength. As a result, Ti-6Al-4V alloy is an ideal material for the manufacturing of brake calipers (Dalpadulo et al., 2021; Tyflopoulos et al., 2021). The chemical composition of Ti-6Al-4V alloy is around : 6.0Al, 4.0V, 0.10Fe, 0.14O, 0.012N, 0.0042H and 0.01C in mass % (Borisov et al., 2015; Mohammadhosseini et al., 2013). Powder-based AM methods such as EBM and SLM are commonly used in the development of Ti64 alloy when it comes to the fabrication of dense metallic structures (Rafi et al., 2013). Part is formed during the SLM process by selectively melting successive layers of powder using a laser beam. In EBM, the metal powder is put in a vacuum environment and heated with an electron beam to fuse it together. These AM processes provide many benefits over conventional manufacturing methods. Some of the significant advantages of AM technologies include the potential to produce complex geometries, optimal material consumption, and the elimination of expensive tooling. This research aims to compare the fatigue properties and tensile properties of EBM and SLM methods for Ti64.

2. Methods

For this review, conference papers and journal articles published between 2013 and 2021 were used in order to get relevant information on the state of the art in the field of AM of the titanium brake caliper. Databases that used for this research were IEEE Xplore, Google Scholar, ResearchGate, and Springer Link. Firstly, the keyword "Additive

Manufacturing" and "3D printing" were searched in all four databases. Detailed research was carried out on the AM applications. Next, the term "application of additive manufacturing in automotive industries" was searched. A total of 8,266 results were found on the Springer link. After reading few publications related to that topic, one of the most recent developments of AM in the automotive sector was additive manufactured titanium brake caliper and to further narrow down the subject area, different keywords such as "additive manufacturing of titanium brake calipers", "selective laser melting of titanium alloy" and "electron beam melting of titanium alloy" were used. After analyzing few conference papers and articles, many publications based on the microstructure and mechanical properties of Ti64 parts manufactured by EBM and SLM were found in the result. Finally, 4 articles and 3 conference papers were selected for this review paper which were primarily focused on mechanical properties.

3. Results

The external surfaces of Ti64 parts produced by EBM and SLM processes have varying surface textures due to the differences in layer thickness, scan speed, and powder particle size. When compared to EBM fabricated components, the surfaces of SLM fabricated components are comparatively smoother, because of finer powder particle sizes, slower scan speeds, and thinner layers. Many applications require machining of the components to achieve the desired surface finish. The EBM and SLM methods generated differing microstructures for Ti64 (Rafi et al., 2013). This implies that the mechanical properties of EBM-fabricated and SLM-fabricated parts are different. Table 1 shows the comparison of mechanical properties for titanium alloy samples manufactured by EBM and SLM.

Table 1. Results for EBM-generated and SLM-generated Ti-6Al-4V alloy parts (Borisov et al., 2015; Mohammadhosseini et al., 2013; Rafi et al., 2013).

	Tensile Strength, MPa	Yield Strength, MPa	Elongation, %
EBM, as built	978. 5 ± 11.5	881.5 ± 12.5	10. 7 ± 1.5
EBM, hot isostatic pressed	978 ± 9.5	876. 5 ± 12.5	13. 5 ± 1.5
SLM, before heat treatment	1269 ± 9	1195 ± 19	2.4
SLM, after heat treatment	1090	1000	8.3

The tensile properties of the Ti64 parts which are produced by EBM and SLM parts differ significantly. The mechanical properties of SLM-produced samples were characterized by low ductility and high hardness, limiting their usage in heavy load applications. Heat treatment is commonly used to enhance mechanical behaviour. The specimen's ductility and elongation increased significantly after heat treatment, whereas its strength reduced slightly due to the phase change (Borisov et al., 2015; Rafi et al., 2013). The obtained ductility level showed that SLM products can be used in high-loaded components. The yield strength of the hot isostatic pressed sample in EBM was lower than the fabricated sample (before heat treatment), while tensile strength was almost same and the elongation was slightly higher. Hot isostatic pressing (HIP) is a technique for reducing metal porosity and increasing material density. After the HIP process, the material's mechanical properties and workability are improved as a result. The microstructure is fundamentally changed during the HIP process, which might cause a lower yield strength. On the other hand, it reduces porosity, which explains the slight increase in ductility. The variations in the microstructures were responsible for the tensile findings. EBM-manufactured parts have lamellar structure, as compared to SLM-manufactured parts which have martensitic structure. Thus, this was responsible for the increased tensile strength (Mohammadhosseini et al., 2013; Rafi et al., 2013).

Table 2 represents the hardness of EBM-processed and SLM-processed Ti-6Al-4V samples. Heat treatment of specimens resulted in a slight decrease in hardness due to the development of different phases; However, it is important to note that the changes in hardness values are minimal and vary from 2 to 3 Hardness Rockwell C (HRC). The hot isostatic pressed parts have a lower hardness than the as-built parts. This can be attributed to microstructural coarsening (Borisov et al., 2015; Mohammadhosseini et al., 2013).

Table 2. The hardness of the Ti-6Al-4V alloy samples generated by EBM and SLM (Borisov et al., 2015; Mohammadhosseini et al., 2013).

	Hardness, HRC
EBM, as-built	37.8
EBM, hot isostatic pressed	35.7
SLM, before heat treatment	37.9
SLM, after heat treatment	39.2

(**a**) (**b**)
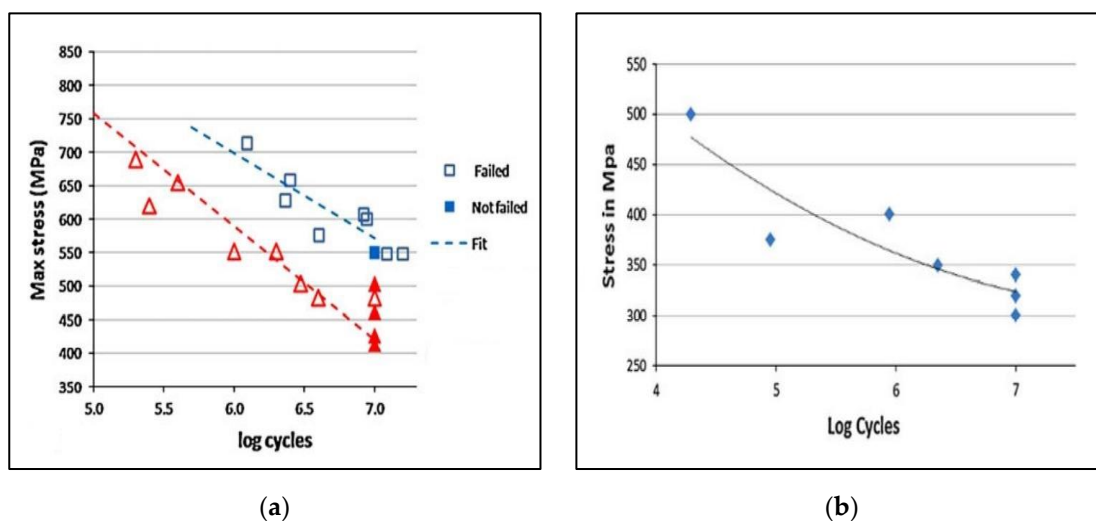
Figure 1. S-N curve represents fatigue behaviour of Ti-6Al-4V parts: (**a**) SLM; (**b**) EBM (Rafi et al., 2013)**.**

Stress-life (S-N) approaches are commonly used to estimate fatigue performance, where N denotes the number of failure cycles. Figure 1 shows S-N curves which demonstrate the fatigue behavior of Ti64 produced by EBM and SLM. One of the most common failure modes is fatigue failure, which is generated by cyclic loads. Fatigue limits of 550 MPa (Fig. 1a) and 340 MPa (Fig. 1b) were observed for SLM manufactured Ti64 and EBM manufactured Ti64 (Rafi et al., 2013). When compared to SLM-produced samples, EBM-produced samples had a lower fatigue behavior. The fatigue characteristics of Ti-6Al-4V alloy are affected by heat treatment, although parts fabricated by EBM have both small and large porosities in the fabricated sample. The fracture surface of the hot isostatic pressed samples showed no porosity, resulting in improved fatigue qualities (Mohammadhosseini et al., 2013; Rafi et al., 2013).

Figure 2. Titanium brake caliper produced by 3D printing (Wischeropp et al., 2019).

Figure 2 demonstrates a newly developed titanium brake caliper for the Bugatti Chiron, which was made by 3D printing (Dalpadulo et al., 2021; Wischeropp et al., 2019). The Bugatti Chiron's brakes are the world's most powerful serial brakes, posing high expectations in terms of performance at minimal weight. The conventional brake caliper is

made of high-strength aluminium and weighs around 4.9 kg. Therefore, the Ti-6Al-4V alloy was selected for the new design because of its good strength-to-weight ratio and weight is only 2.9 kg (Wischeropp et al., 2019). By using the new part, Bugatti reduced the weight of the brake caliper by around 40% while maintaining even higher strength. Now it is the world's largest working titanium component created with the help of 3D printing technology.

4. Conclusions

High-performance automotive components are frequently subjected to a variety of stresses, and in particular brake systems may experience problems because they must operate with heavy loads at high temperatures. To meet these requirements, the material must have high stiffness at elevated temperatures and light in weight, allowing high-performance cars to perform better. While aluminium has been the primary material utilized for AM of automotive components so far, the mechanical qualities of aluminium alloy degrade significantly at high temperatures. Ti-6Al-4V alloy is used instead of aluminium alloy because it has better heat resistance at high temperatures and is comparatively lighter (Dalpadulo et al., 2021; Wischeropp et al., 2019). Samples generated by SLM have a better surface finish than those produced by EBM. However, all EBM samples are machined to increase the surface finish. For fabricated samples, surface machining is required because surface defects would decrease fatigue performance. SLM products do not require any additional machining processes. Therefore, this technique is recommended for reducing manufacturing costs and time.

SLM-generated samples have better tensile and yield strength than EBM-generated samples but EBM-produced samples are more ductile. The heat treatment allows for the material to get excellent mechanical properties, such as increased ductility. Because of the martensitic microstructure, SLM samples have a higher tensile strength, whereas EBM samples have a higher ductility due to the lamellar structure (Mohammadhosseini et al., 2013; Rafi et al., 2013). However, the fatigue performance of Ti64 samples generated via EBM was unsatisfactory. SLM-generated parts have a higher hardness than EBM-generated parts. One of the most significant advantages of the SLM manufacturing technique is the ability to customize products. As a result, SLM is the best-suited method for the production of 3D printed heavily loaded components like brake calipers. Bugatti's fully developed 3D printed titanium brake caliper shows how titanium alloy can be used and lead to performance improvements in the automotive industry (Dalpadulo et al., 2021).

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Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Path planning strategies are for better infill distribution quality and material efficiency with wire and arc additive manufacturing[†]

Prince Prafulchandra Tandel [1],*

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: prince-prafulchandra.tandel@s2019.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: The Wire and Arc Additive Manufacturing (WAAM) process has considering in most Industrial friendly processes due to their unique advantage as a high deposition rate. However, these advantages come with the complexity of material deposition, path planning, heat flow, residual stresses, and properties of the workpiece. Path planning has a crucial role in surface quality, material and time saving, and achieving the objective of properties. This review paper focused on path planning strategies for better deposition of the material without void and material efficiency with WAAM. All the path planning strategies process have considered were Medial Axis Transformation (MAT) path planning, Adaptive MAT path Planning, Modular Path Planning (MPP), Optimal build direction, Composite Path Planning (CPP), Revised Layers-Overlapping Model (R-LOM), and Continuous three-dimensional path planning (CTPP). All the strategies have used the combination or specific path pattern. MPP and CPP have considered the combination of path patterns. MAT has better results with a thin-walled structure which can be more generalized with Adaptive MAT path Planning. CPP perform best for sharp edge object while R-LOS and CTPP have more consideration of multilayer deposition. All the path planning strategies are fulfilling the desired objective with some limitations and for specific geometry only.

Keywords: Path planning strategies; Material efficiency; Path pattern; Wir and Arc Additive Manufacturing; Complex geometry.

1. Introduction

Additive Manufacturing (AM) has been developed for the past 30 years and continuously evolving because of the numerous advantages over traditional material removal manufacturing. Among all AM processes, Wir and Arc Additive Manufacturing (WAAM) is stand out due to the number of advantages like high deposition rate, cost-competitiveness, capable of deposit of various metals, and environmental friendliness (Ding et al. 2015; Ding et al. 2016). WAAM has a high deposition rate due to which deposition height can be varying based on the specific parameters. This property makes the process having difficulties with dimensional accuracy, surface roughness, and the properties of the workpiece. Path planning strategies have a considerable effect on the mentioned problem. However, path planning strategies of the traditional AM process cannot be capable of many topologies as the energy balance is disturbed (Ding et al. 2016). Path planning in AM is a strategy of designing the paths for a single layer, and layer paths have been used for deposition layer after layer to manufacture the whole structure. In this review paper, the considered path planning strategies focused on better distribution of material to create void-free workpieces and improvement in dimension accuracy (material efficiency). Path planning strategies were based on path patterns such as raster path, zig-zag path, contour offset path, and spiral path. A combination of path patterns is used in the planning strategies as it uses the advantages of all the patterns in one.

Because the contour path follows from outside to inside possibility of having a gap in the middle is high. (Medial Axis Transformation) MAT path planning methodology follows the medial line of the component in 2D space from inside towards outside (Ding et al. 2015). Adaptive MAT path Planning uses an artificial neural network (ANN) model, which predicts accurately predicts the bead geometry from welding parameters input. These reduce the discontinuities (Ding et al. 2016). It is harder to create a path planning for the complex components because it will create a path with more discontinuity. Dividing components into each section that uses for a specific set of parameters make the complex geometry simpler. Modular Path Planning (MPP) partitions the complex surface contour of a structural component, and each partition path has generated separately based on the geometric characteristic (Michel et al. 2019).

Based on the geometric structure, it oriented that works better for path planning could be best generated without voids. Considering Optimal build direction to minimize the overhang, and maximum try to remove the support (Kumar and Maji 2019). The Sharpe edge will be more prone to less material efficiency. That can solve by combing the path patterns near the corner with contour offset path and middle area by any other patterns. The Composite Path Planning (CPP) method uses a zigzag path planning and contour offset path, which has later connected properly (Liu et al. 2020). WAAM is a layer-by-layer deposition process. So, the final structure has a significant effect on layers-overlapping. The model for consecutive layers will strongly depend on the cooling rate and previous layer surface quality. Revised Layers-Overlapping Model (R-LOM) also considers the counter height problem, which has usually reduced (Li et al. 2018). If considering a thin path, controlling the supply of energy and matter is complex with 2.5 D (the traditional practice of dividing the model into multiple layers). Continuous three-dimensional path planning (CTPP) modulates the deposition height by controlling parameters (Diourté et al. 2021).

2. Methods

The basic idea of the topic was the WAAM process path planning. Google Scholar had used first to get an understanding regarding the topic and the current trend of research. The data-based used are Science Direct, Scientific.net, and Springer. In the beginning, search terms used are Wire and Arc Additive manufacturing, path planning strategies and also included the synonyms like Wire + Arc Additive Manufacturing, path planning solution, path planning methodology. Narrow down the search more the focus had given to improve printed qualities. More search teams added are Infill distribution quality, surface quality, material efficiency, and shape accuracy. All searched team had used with AND command. These made around 35 papers, including all data-based I used.

More narrow search teams added are solid components, complex geometry, and Thin wall parts. Most research papers that were considering complex geometry were from 2015 to 2021. Some research paper with revised strategy was considered instead of the old one for example Revised Layers-Overlapping Model. Even after all the search teams, some unwanted research papers had excluded. Which have based on microstructure, residual stress, and slicing algorithm as it was not the focus of the main topic. For better citation, Zotero software had used.

3. Results

Path planning strategies are based on a path pattern, where the contour path has advantages of proper filling of the material without void as it avoiding extra material around the boundary as it follows the contour. MAT-based path planning with contour path patterns has focused on avoiding gaps in middle areas for geometries like thin-wall, solid structure, and with or without internal holes in the structure. Firstly, the medial axis of the sliced layer has defined as it is represented as a skeleton or as loci of the centers of locally maximal balls inside an object. Path planning has differentiated into 3 cases such as single branch, multi branches, and with holes. The path has been defined based on these cases around the medial line. However, the loop has a different direction for multi branches and with holes. Secondly, creating several loops from the medial line towards the boundary, and the basics of the directions were path cases. Loops have been created until they reach the geometry boundary. Finally, the path which is going out of the geometry is trimmed. Many discontinuous paths are formed near the boundary as it just following the medial line. This path is followed for deposition of material step by step. From the experiments of 5 types of samples. It's observed that the thin-walled structure has better material efficiency than a solid structure. It has shown no void in middle (Ding et al. 2015).

Till the defining medial line of the individual layer Adaptive MAT path planning has similar to the MAT-based path. After that, the loop formation has adaptivity according to the boundary. Considering this step over distance (d) and weld bead width of a single deposition (w) should be ($d = 0.738w$) to make sure the flattest of the layer. This relation will ensure the overlapping of beads to ensure the proper height. However, adaptivity at the boundary improves the ability of the WAAM process. WAAM process can have the same layer height with varying travel speed and wire-feed rate. It will ensure material efficiency at the boundary and removes discontinuity. Optimal Parameters of WAAM for the same layer height with improved material efficiency were selected using the database of the ANN model, which has been defined based on experiments. Instead of better material efficiency and improved continuity, this strategy lag when the parameters will not have integer values from the relation $d = 0.738w$ (Ding et al. 2016).

It can be solved if parameters are defined based on the different similar zones in the layer geometry. MPP has based on this idea. It also has a similar step till slicing, and then segmentation of a given layer has performed. Segmentation will create sub-parts called sections which are differentiated based on the geometry in the particular selected layer. After that, path palling of all sections and combining the paths of all sections. The zoning of specific sections is based on similar parameters. All these steps have been repeated for all layers one by one, as shown in Building Strategy

(BS) flowchart in figure 1 (a). This strategy results in void-free geometry with better material efficiency. However, welding process parameters have to be manually set (Michel et al. 2019). The path palling strategy becomes more difficult with a more complex geometry layer formed after slicing. Alternatively, the optimal build direction has a significant impact on the layered complexity after the slicing. Optimal build direction is decided based on the minimum structure support and overhang by comparing three build directions. The bead geometry modeling for width, height, and cross-section are deposition with Response surface methodology (RSM) based on experiments. The parameter has defined as voltage, current, and wire feed rate increases with layer size. The final result from the experiment was without any void, but the extra material around the boundary has not considered (Kumar and Maji 2019).

(a)

(b)
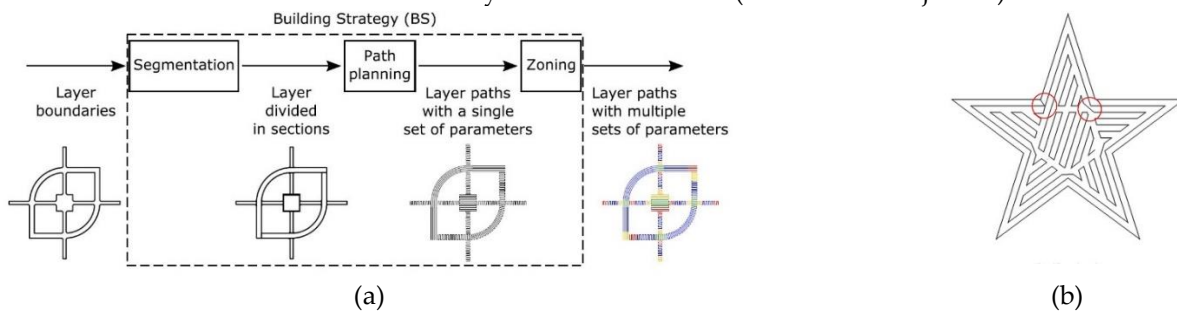
Figure 1. (a) Building Strategy (SB) flowchart (Michel et al. 2019); (b) Closed path after connection of patterns (Liu et al. 2020).

All the above strategies are difficult to implement for the sharp edge geometry as it was more prone to deposit extra material with poor path planning. These were solved by combing the path patterns done by CPP as explained in Section Introduction. Path pattern was selected based on the convex or concave polygon. Geometry has divided into convex and concave polygons. All convex polygon has a path planned with a zig-zag pattern, and all concave polygons are path planned by contour offset near boundaries, and zig-zag path pattern has used in the middle area. Contour offset has been used near boundaries of concave polygon because they have sharp edges; Furthermore, the zig-zag pattern starting point should be the minimum vertical distance from each vertex from the proper void-free filling of material. The next step is to connect the path of both the pattern, where the shortest path pattern can be selected to maintain the better surface forming quality, as shown in figure 1 (b). As the liner distance between the two adjacent inflection points at the sharp edge increases, the lap joint angle of the corner decreases. The critical angle $\beta = 58.65°$ at which the overlapping of the deposition path start and height start increase than overall surface height. Smaller than this angle will change the deposition height, and overall material efficiency will get compromised (Liu et al. 2020).

Compromise in corner height will affect the overall deposition height of the geometry, which can solve with proper layers-overlapping strategy (LOS). A recent study has revised the LOS to R-LOS. R-LOS has focused on maintaining the same height throughout the surface. R-LOS made possible with deposition of the material shortage of the previous layer by consecutive layers. Moreover, this can be more effective if the consulate layer is deposited towards the edge with an offset distance. The final result does not give good geometry accuracy, which may be because of the assumption of neglecting the deformation of the component and temperature field (Li et al. 2018). The layers-overlapping strategy for complex thin parts has the advantage of considering the deformation of the component as it has better heat transfer. CTPP used the modulation of the height layer by layer to overcome the disturbing height due to discontinuity. Modulation of height is performed by controlling the parameters like wire feed speed and robot travel speed.

Modulation made possible because this process in 3D path planning instead of 2.5 D in which deposition has not been done only at the particular layer. So, the discontinuity decrease as no need to stop and start the deposition process for the next layer. Starting of deposition will create the height discontinuity, which has to eliminate by consecutive layers. This is done by always compare the height from the Computer-Aided Design (CAD) model. So every layer deposition will reduce the deposition height until the desired overall height has reached. It compares the CAD model for overall height. This process repeats 7 to 8 times but strongly depends on the geometry. The experimental result confirms, the reduction of discontinuity which improves the material efficiency and defect link to these phenomena for thin parts geometry (Diourté et al. 2021).

4. Discussion

MAT path planning and adaptive MAT path planning both have the same basic concept. However, the outcome shows that adaptive path planning is better for controlling the material efficiency around the corners and drastically reduce the number of starts and stops. As the number of starts and stop increases, the discontinuity increases as the

deposition start with gradual to high deposition. MAT path planning limitation of discontinuity makes the adaptive MAT path planning a preferred choice. This limitation has shown, in figure 3 where figure 2 (a) shows more path which stopes at boundary and figure 2 (b) shows the path followed the boundary (Ding et al. 2015, 2016).

(a)(b)
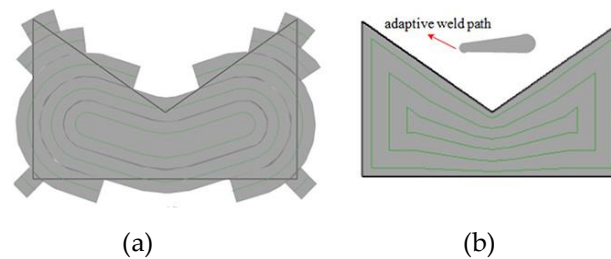
Figure 2. (a) Extra material deposited along the boundary (Ding et al. 2015, 2016) ; (b) Void-free deposition with high accuracy at the boundary through using adaptive MAT path (Ding et al. 2015, 2016).

MPP and CPP are the path planning for more complex parts, which both are fulfilling the main focus on proper material filling and material efficiency. However, the limitations of MPP required the process parameters for a particular zone manually while CPP reduces the material efficiency for the corner angle less the critical value and discontinuities for connection the different path pattern (Liu et al. 2020; Michel et al. 2019). Optimal building direction has selected, which has only based on a few orientations, which could not consider optimum if the more complex body is included (Michel et al. 2019). R-LOS has improved the surface quality with improved material efficiency, but the deformation of the component is neglected. So, the final geometry was not accurate (Li et al. 2018). CTPP has also fulfilled the desired output. However, it requires a specific number of layers to eliminate the height difference. This may be not the case for many of the small-height geometries.

5. Conclusions

All the strategies consider in review fulfilled the main object of proper filling of material without void and improvement in material efficiency. However, all of them are specified for particular geometry and work best with some limitations explained in section 4 (Discussion). MAT path planning can use for all types of geometry, but better results are found with thin-walled structures. Adaptive MAT path planning considers an improved version of MAT path planning which can also be used for more complex structures, but with little extra material deposition around the boundary for some geometry. MPP strategies tried to reduce the complexity by creating segments, but they only used oscillator path patterns, whereas CPP considered combining more patterns to reach all the sharp corners of the complex geometry. If the optimal build direction has combined with all the above strategies, then the capability of complex geometry can increase. Considering multi-bead deposition, R-LOS and CTPP are effective, but R-LOS can improve by considering the deformation of the component, and CTPP can implement on even solid geometry. Finally, there are no strategies that can handle all types of geometry. Suggestion for further study where the focus should be the strategies can work for all complex geometry.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

On tensile strength of 3D printed continuous fiber reinforced thermoplastic composites manufactured by Fused Deposition Modeling process†

Vivek Niel Jason Kanaparthy [1],*

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: vivek-niel-jason.kanaparthy@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: This review evaluates the tensile strengths of 3D printed specimens reinforced with synthetic and natural continuous fibers manufactured using Fused Deposition Modeling (FDM) process. The continuous fibers considered were carbon, glass, Kevlar, jute, flax and pineapple leaf fibers. The reinforcements aided in increasing the tensile strength of the specimens for all fibers and the percentage increase of the tensile strength was determined by comparing with specimens without any reinforcements. In all specimens, the main fracture behavior was observed to be fiber pullout due to bad fiber-matrix adhesion. This emphasizes that moving forward, there is a need to incorporate pre and postprocessing steps to solve this problem.

1. Introduction

3D printing (3DP) works on the principle of additive manufacturing and is the process of creating complex structures through layer-by-layer deposition. It is rapidly increasing in the aviation, automobile, medical and many more industries. Fused deposition modeling (FDM) is one of the variants of 3DP process, that is used a lot as it is easy to use, cheap and can handle a wide range of polymers. Though this method offers significant advantages as complex geometries with extremely good material utilization can be manufactured in short times, the parts produced show poor mechanical properties and cannot be used for structural applications. This presented the need to strengthen the printed structures by using reinforcements.

Reinforcing materials like short or continuous fibers were used to print fiber reinforced structures to increase their mechanical properties of that layer. Short carbon fibers were previously used as reinforcement for acrylonitrile butadiene styrene (ABS) by Ning, Cong, Qiu, Wei, and Wang (2015) and a meagre increase of tensile strength was observed, when compared to a pure ABS printed sample. This showed that short fibers were incapable of reinforcing the printed part to the required level which led to the consideration of continuous fibers as reinforcements. Following this, Matsuzaki et al. (2016) used continuous carbon and jute fibers for reinforcing 3D printed components.

Since continuous fibers are fed in along with the thermoplastic filaments, filaments of thermoplastic matrix material and continuous fiber or pre-embedded filaments of continuous fiber reinforced thermoplastic matrix material are fed into a nozzle by a feeder where the thermoplastic filament is melted in the heated nozzle. The continuous fibers are wetted by the thermoplastic melt material and are subsequently deposited onto a plate through the X-Y motion of the extrusion head and layer upon layer through the movement of the building platform along the Z axis as shown in Figure 1. In this review, synthetic continuous fibers like carbon, glass and Kevlar have been considered as they are the preferred choices for high strength applications and natural continuous fibers have also been considered as there is an increasing focus on producing biodegradable components. Ultimately, this review aims to compare the tensile strengths of the 3D printed continuous fiber reinforced components to that of pure thermoplastic specimens and thereby know the current limits of the said components.
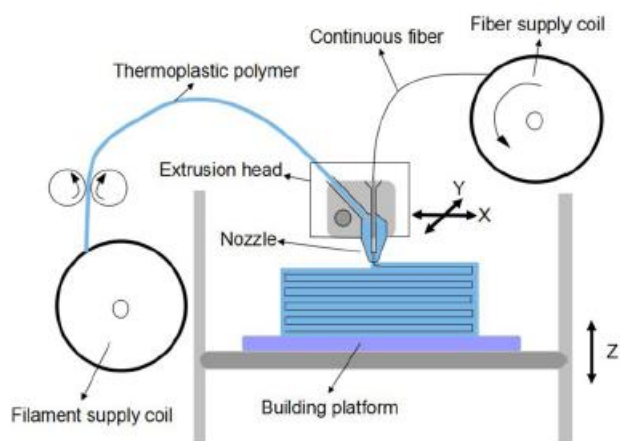
Figure 1. A schematic representation of manufacturing continuous fiber reinforced 3D printed specimens using FDM process; adapted from Yang, Tian, Liu, Cao, and Li (2017)

2. Methods

The information required for this review was obtained by using Google Scholar, Elsevier databases, Rapid Proto-typing Journal of Emerald Inside database, Nature journal and SAGE journals. In all databases, the necessary papers were found by using the advanced search option. The search terms used to for this purpose were, "3D printing" AND "continuous" AND "fibers" AND "Fused Deposition Modeling". Additional papers were also found by looking through the references of the papers that matched the conditions stated above. No further filters in the form of a specific time-period, particular authors, etc. were applied as not a lot of research was conducted on this very same topic.

Furthermore, of the various papers selected by the initial conditions, only those which explored the tensile strength of the 3D printed parts were considered as that is the primary focus of this review paper. Subsequently, the required papers were found and the relevant data from within each paper was used.

3. Findings

3.1. Synthetic Fibers

In general, the tensile strengths of all the synthetic continuous fibers reinforced 3D printed specimens showed a good increase in the longitudinal direction, due to the presence of the reinforcing fibers, which were longitudinal with respect to the specimen, within the thermoplastic matrix. Heidari-Rarani, Rafiee-Afarani, and Zahedi (2019) (Study 1) used continuous carbon fibers (CCF) to reinforce PLA matrix. Since the sizing applied to the CCF would only be compatible for thermosetting polymers, a preprocessing step was carried out in which the existing sizing was removed and a new sizing, which was compatible with PLA, was deposited onto the CCF. This increased the tensile strength by 37% when compared to pure PLA specimens. Li, Li, and Liu (2016) (Study 2) also chose CCF as reinforcing material and PLA as the thermoplastic matrix. The CCF was pretreated to modify its surface characteristics and so that its interfacial strength might be improved. The pre-treated the CCF before embedding them within PLA filaments which showed an increase of 225% when compared to pure PLA components and 13.75% when compared to untreated CCF reinforced PLA specimens at a fiber volume fraction of 34%. This increase in tensile strength was directly linked to the pretreatment of the CCF which greatly reduced the voids in the composite and led to higher tensile strength. Yang et al. (2017) (Study 3) also evaluated the tensile strength of CCF, albeit used ABS instead of PLA as the thermoplastic matrix and recorded a tensile strength of 147MegaPascals (Mpa) with a fiber weight fraction of about 10%. This study found out that though the tensile strength of the components increased by more than two times, it was still lesser than that of specimens having the same fiber volume ratio but prepared by injection molding. The reason behind this behavior was identified to be fiber pull out and fiber rupture, which limited the tensile strength of the printed composite. Moham-madizadeh, Imeri, Fidan, and Elkelany (2019) (Study 4) prepared continuous carbon, glass and Kevlar fibers reinforced nylon composite samples using FDM using two different infill patterns. The tensile strength was higher for specimens which were prepared with the concentric and isotropic infill type as specimens prepared according to this infill type had higher fiber volume content. Additionally, specimens prepared out of continuous glass and Kevlar fibers showed good but lesser tensile strength when compared to specimens prepared out of CCF. Though the fiber volume fraction

remained the same, the tensile strength was observed to fluctuate due to a change in fiber orientation. In all the studies, fiber pullout was determined to be the main reason for fracture mechanism while performing tensile strength tests on the 3D printed specimen. This further led to the finding that the fiber pullout was a direct consequence of the fibers not being wetted completely by the matrix. An overview of the tensile strengths and the percentage increase when compared to pure specimens with no reinforcing elements has been given in Table 1 below.

Table 1. Tensile strength and net increase when synthetic fibers were used.

Study	Fiber	Matrix	Tensile strength (MPa)	Net increase
Study 1	Carbon	PLA	61.4	36.8%
Study 2	Carbon	PLA	91	225%
Study 3	Carbon	ABS	147	194%
Study 4	Glass	Nylon	372.1	N.A [1]
Study 4	Kevlar	Nylon	309.14	N.A [1]

[1] N.A is used as the author of the study did not provide tensile strength of pure specimens to evaluate the net increase.

3.2. Natural Fibers

Research has also been conducted with natural fibers with a view to make 3D printed parts more environmental friendly. Matsuzaki et al. (2016)(Study 1), Suteja, Firmanto, Soesanti, and Christian (2020)(Study 2), Le Duigou, Barbé, Guillou, and Castro (2019) (Study 3) and Zhang, Di Liu, Huang, Hu, and Lammer (2020)(Study 4) conducted studies of 3D printing using natural fibers as the reinforcing element within a PLA matrix. Since PLA is a biopolymer, the composites produced through these raw materials were completely biodegradable. Matsuzaki et al. (2016) produced 3D printed fiber reinforced polymer composites using continuous jute fibers as reinforcements within the PLA matrix. It has been reported that since no pretension was applied in straightening the fibers before the printing, it resulted in creation of weak points within the 3D printed composite specimen. Furthermore, it was also reported that fiber pull out was the main reason of failure of the 3D printed composite speciemens which could again be traced back to the presence of voids. Le Duigou et al. (2019) carried out tensile strength tests using continuous flax fibers, having a linear density of 68 Tex, as the reinforcing elements within a PLA matrix. Instead of feeding flax fibers and PLA filaments separately, the fibers were embedded within the PLA filaments and this composite filament was used to for printing the specimens using the FDM process. Doing so ensured optimum wetting of the flax fibers with the PLA matrix and greatly increased the tensile strength of the speciemens, about 4.5 times compared to pure PLA specimens. Zhang et al. (2020) also conducted tensile strength assessment using continuous flax fibers of two-ply yarn of 68 Tex, albeit changed the printing method by using a five-axis machine. Flax fiber reinforced PLA composite filaments were first prepared which were later used for manufacturing the 3D printed specimen. The corresponding increase in tensile strength was reported to be slightly less than two times in this study. The reason for this was observed to be the incomplete coating of the fibers by PLA while the composite filament was being formed. Suteja et al. (2020) prepared continuous fiber reinforced 3D printed parts using pineapple leaf fibers. The study noted that since the pineapple leaf fibers have good tensile strength, they can be used as reinforcing elements. Consequently, tensile tests were conducted which revealed that pineapple leaf fiber reinforced PLA specimens had a tensile strength of 96.8 Mpa. The results obtained through the above four studies have been summarised in Table 2 below.

Table 2. Tensile strength and net increase when natural fibers were used.

Study	Fiber	Matrix	Tensile strength (MPa)	Net increase
Study 1	Jute	PLA	185.2	435%
Study 2	Flax	PLA	253.7	450%
Study 3	Flax	PLA	89	89%
Study 4	Pineapple Leaf	PLA	96.8	8.2%

It has further been pointed out that the twisted nature of the natural fibers led to the formation of fiber rich zones (Figure 3.a) within the composites, which subsequently lead to the formation of voids and limited the tensile strength of the specimens. Eventually this led to failure due to fiber pullout (Figure 3.b).

(a)   (b)
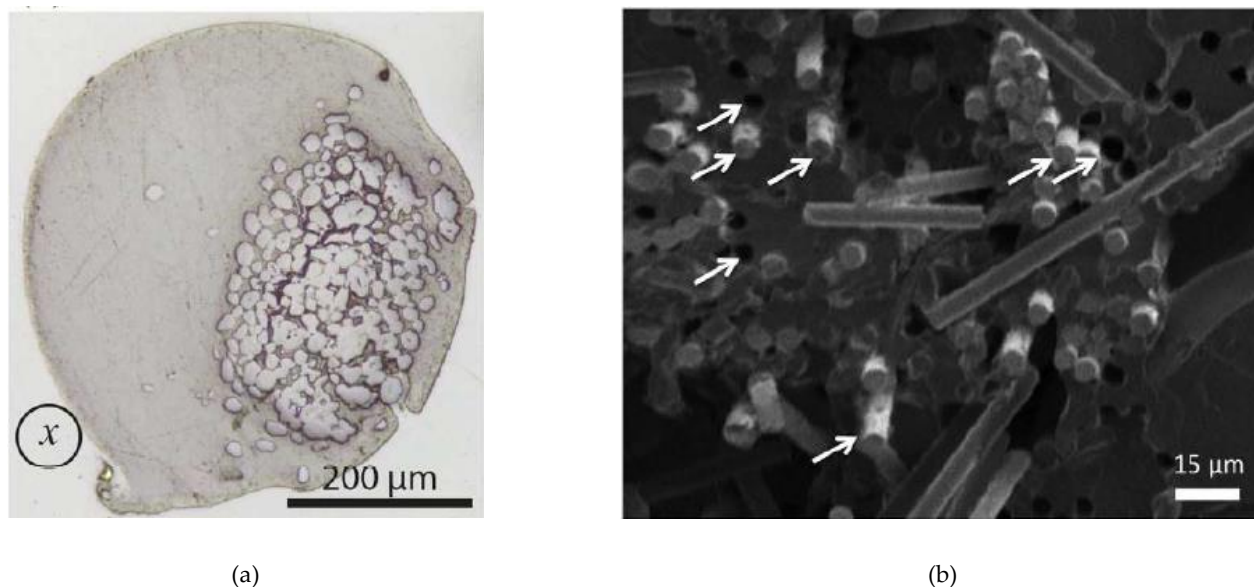
Figure 3. (**a**) Fiber rich zones within the composite filament; adapted from Le Duigou et al. (2019) (**b**) Fiber pullout in jute fibers; adapted from Matsuzaki et al. (2016)

4. Discussion

The tensile strength of the 3D printed specimens reinforced with synthetic and natural continuous fibers was evaluated in this review. Overall, all the specimens showed an increase in their tensile strength in the longitudinal direction when compared to specimens made of pure matrix material. But strength comparison for the specimens made of different studies could not be made as there were many other parameters that were different from each other. This therefore highlights the need for more studies and analysis to be performed so that the strengths of specimens can be compared based on single parameters while keeping everything else constant or uniform between studies.

Fiber pullout was the dominant failure behavior of all the studies, when the tensile tests were conducted in the longitudinal direction, due to improper wetting of the fibers with the thermoplastic matrix which suggested that there was an intrinsic need to strengthen the fiber-matrix adhesion for all the samples. This would require preprocessing steps like using ultrasonic waves to increase the roughness of fibers and thereby increase the surface area. Alternatively, post processing steps can also be employed to increase the wetting of fibers and decrease the void content within the composite. Therefore, further investigations and studies in this field are absolutely necessary.

In conclusion, the studies carried out so far showed that, continuous fibers can to an extent, reinforce 3D printed components to be used in load bearing applications, but also that they cannot yet replace composites created by conventional methods using thermosetting matrix.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Review of defects in additively manufactured lattice structures†

Yogesh Chandra Chandrashekar [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: yogesh-chandra.chandrashekar@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Additively manufactured lattice structures are well known for their desirable properties such as high surface area and high specific stiffness are being explored for several applications, including aerospace components, heat exchangers, and biomedical implants. Metallic additive manufacturing techniques, in particular the powder bed fusion process, are capable of fabricating strong, lightweight, and complex metallic lattice structures. However, they still face certain process limitations due to the complex geometry. Thus, lattices are particularly vulnerable to manufacturing defects. This paper provides a review of defects in lattice structures manufactured by powder bed fusion processes. The review focuses on the ramifications of lattice design on dimensional inaccuracies, porosity, and surface defects. The information in this paper contributes towards a comprehensive understanding of defects in lattice structures to improve the quality and performance of future lattice structure designs.

Keywords: Lattice structures; Powder bed fusion (PBF); Manufacturing defects; Additive Manufacturing.

1. Introduction

Lattice structures typically refer to a form of cellular solid where an interconnected network of struts forms a unit cell's faces and edges. A lattice's physical behavior is governed by its design parameters, such as unit cell topology, unit cell geometry, and strut diameter. Lattice structure designs are described by their unit cell, which falls into one of two categories: strut and surface-based (Fig.1). Full control over these design parameters has recently been established by developments in additive manufacturing (AM) processes, particularly powder bed fusion (PBF). This review focuses on the literature regarding manufacturing defects in non-stochastic, metallic lattice structures produced by PBF. The produced lattice structures are prone to defects due to their numerous overhanging, often millimeter-scale features, which challenge the performance limits.

Lattice structure defects are categorized into the following groups: dimensional inaccuracies, surface texture, and porosity. Dimensional inaccuracies result on the identical scale as the lattice features, such as a deviation in the length or overall geometry. Surface defects refer to any discrepancy from the ideal surface and are measured through surface texture parameters. Porosity denotes the lack of material, where a pore describes a closed void within the part of a surface void.
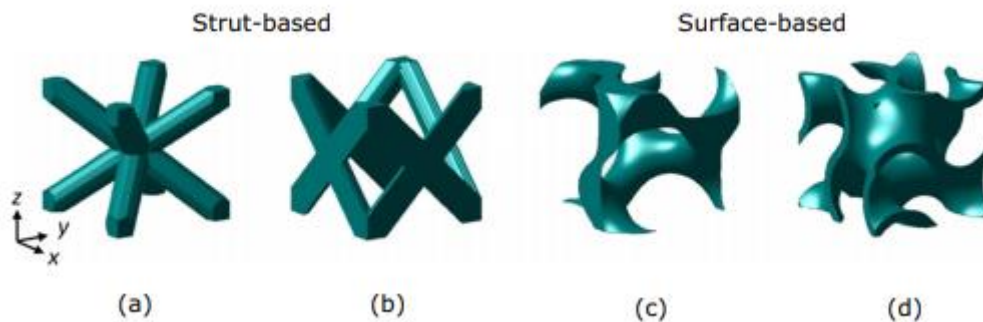
Figure 1. Types of unit cells: (**a**) body-centered cubic, (**b**) face-centered cubic, (**c**) gyroid, and (**d**) double gyroid from (Panesar et al. 2018).

2. Methods

This literature review was undertaken using the main scientific databases such as Scopus and Google Scholar for publication dates ranging from 1995 to 2019. Searching keywords on Scopus such as 'additive manufacturing,' 'stochastic,' 'lattice structures,' 'laser melting,' and considering the most recent results in 2019, displayed 85% (of 13 results) related to the non-stochastic lattice structure. Papers for the review were selected if the contents of the study helped in answering any of the below questions:

1. How do defects form in powder bed fusion processes?
2. What are the types of defects formed in lattice structures?

3. Results

This section provides a brief overview of the defects often formed in the production of lattice structures by powder bed fusion (PBF) processes. The initial heating, melting, and cooling mechanisms within the powder bed fusion process are at the core of the final quality of the produced parts. Manufacturing defects are any measurable deviations between an initial design and the final manufactured product, which can significantly hinder the required operating performance of AM parts, for example, through the resulting stress concentrations causing a drastic reduction in fatigue strength. Therefore, considering the load-bearing applications of AM lattice structures, a thorough understanding of manufacturing defects is required.

3.1. Dimensional Inaccuracies

It is often helpful to initially assess a lattice structure's general conformity to CAD data, where the outcomes generally show a reasonable adherence to CAD data. However, dimensional inaccuracies can be found out via a local analysis of specific lattice features, such as nodes, struts, designed pores, and wall thicknesses. Struts are frequently observed to deviate from circular cross-sections to ellipsoidal in references, as stated in (Zhang et al. 2018). (Ataee et al. 2018) show that ellipsoidal deviations are to a greater degree in horizontal struts due to over melting and particularly note the effect to be strongest at the ends of the struts. (Cuadrado et al. 2017) and (Ataee et al. 2018) states strut diameter to be significantly affected by strut orientation, where horizontal struts were over-sized by over 100%, and vertically oriented struts were under-sized by up to 45%.
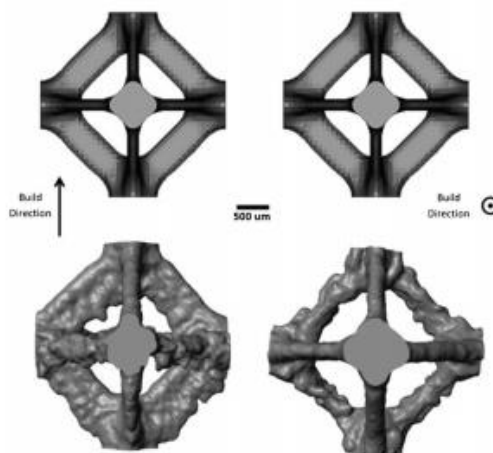
Figure 2. Example of strut orientation dependency. CAD representation of a unit cell (Top). The 3D rendering of an X-ray computed tomography model (Bottom) from (Sercombe et al. 2015).

3.2. Surface Defects

The highly complex surfaces are produced using PBF processes, and surface defects are frequent due to melt pool instabilities. The most predominant surface defects in lattice structures can be noticed when comparing down-skin and up-skin surfaces. Local over-heating in down-skin surfaces is often detected due to the many overhanging features in lattice structures. (Al-Ketan et al. 2018) compared the surfaces formed of a strut- and surface-based unit cells and noticed the stair-stepping effect to be less pronounced in surface-based unit cells—as shown in Fig. 3. A reduced stair-stepping effect has been due to the continuous change in the inclination angle of surface-based design. (Leary et al. 2016) calculated Ra and Rz values for downskin and up-skin surfaces in BCC and FCC struts, which had inclination angles to the

build bed of approximately 35° and 45°, respectively. Leary et al. (2016) calculated a Ra value of downskin BCC struts to be almost three times that of FCC. Also, the Rz values for BCC down-skin surfaces were significantly larger.
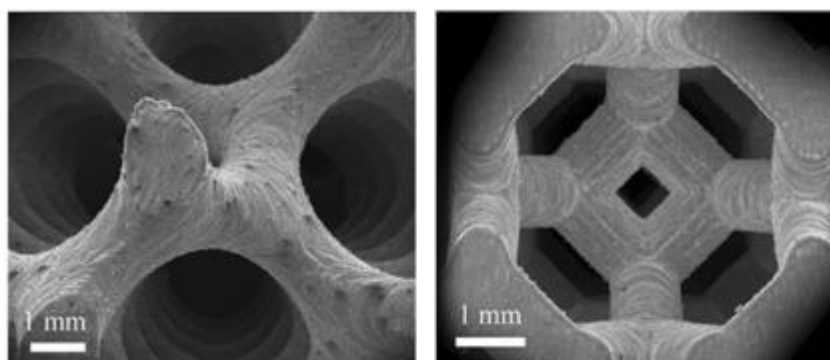
Figure 3. SEM micrograph of two-unit cells, surface-based gyroid (Left) and strut-based structure (Right). A more noticeable stair-stepping effect can be seen in the strut-based structure from (Al Khetan et al. 2018).

3.3. Porosity Defects

The pores are typically referred to as enclosed voids beneath the part's surface; however, frequent regular, hemispherical voids can be recognized as surface pores. Under load, pores establish stress concentrations which can significantly affect fatigue properties. In addition, process parameters are often the cause of porosity. However, in lattice design, (Yan et al. 2012) observed porosity to increase up to 10% upon increasing the size of gyroid unit cells from 2 mm to 8 mm. This can be ascribed to the longer scanning paths needed for bigger unit cells which enables a higher period of time for pores to form in between adjacent scanning tracks.

(Dong et al. 2019) investigated the impact of strut orientation on porosity for AlSi10Mg lattices. Struts were fabricated at varying inclination angles from the build bed, and each strut was categorized into the upper and lower region (A and B as presented in Fig. 4). The results (Fig. 4) showed overall porosity to increase as the inclination angle decreased.
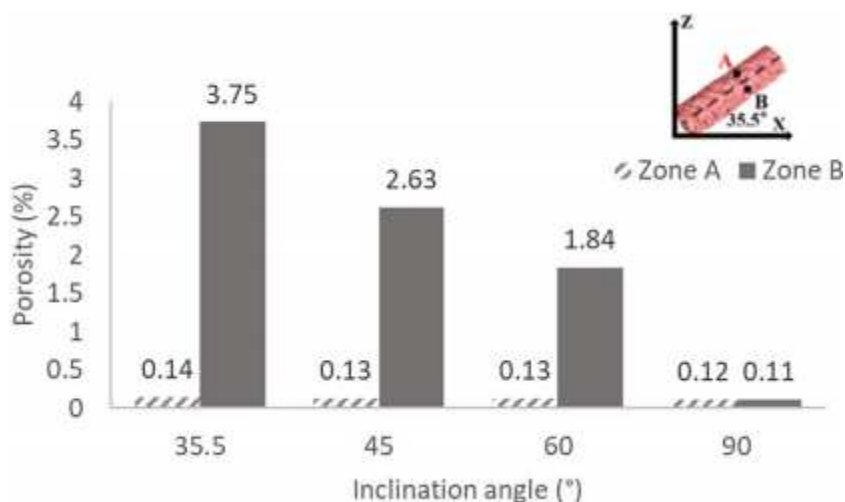
Figure 4. Results from (Dong et al. 2019) showing the effects of strut inclination on porosity in AlSi10Mg lattice struts.

Table 1. summarizes the methods that have been used in the studies discussed in this review to inspect defects in lattice structures.

Table 1. Defect measurement methods

Defect	Method	Quantitative characterizing techniques
Dimensional inaccuracies	XCT	• Comparison with CAD by maximum deviation • Calculate the total volume • Measure strut diameter (largest circle/sphere inscribed) • Elliptical strut cross-section
	SEM	Dimensional measurements (length, diameter, etc.)
	Optical microscopy	
Surface texture	XCT	Calculate Ra value from strut profile or cross-sectional area
	Optical microscopy	Ra value from strut profile
Porosity	Archimedes' method	Infer porosity from weight in two fluids
	XCT	Calculate total porosity

4. Discussion

This review intends to serve as a resource on manufacturing defects in lattice structures produced by PBF. The most cited papers on lattice structures using additive manufacturing were consistently focused on non-stochastic metallic forms. Defects within strut-based lattices were significantly more documented in the literature than those found in surface-based lattices. The dimensional inaccuracies are often documented for strut-based designs, with defects such as strut waviness, varying diameter, material accumulation, and critical orientation dependency within the struts.

- The surface defects have been observed to be highly dependent on orientation, with down-skin surfaces resulting in rougher surfaces, verified by extracted surface texture parameters. The stair-stepping effect was observed to be less effective in surface-based designs, considering the continuously varying inclination angles on the surfaces.
- The porosity has been specially documented in several strut-based designs, where larger pores have been observed in nodal areas. Orientation of the strut has also been documented to influence porosity, with lower inclination angles yielding higher porosity and the pore distribution grouping towards the lower region of the struts.
- Sample preparation can affect measurement results through process actions such as removing parts from the build bed. (Sing et al. 2016) found lattice height to be reduced upon removal through electrical discharge machining. Also, data processing has a strong influence on measurement results.
- Finally, working within the smaller measurement volume, sample preparation was often required to be destroyed. Moreover, to carry out porosity measurements, the sample is destroyed upon sectioning to evaluate the pores, and this may modify the pore morphology. Pores can also easily be undetected as only those exposed upon sectioning contribute towards the calculation.
- Looking forward to further research, including a more in-depth characterization of defects in surface-based lattice structures are necessary, as the literature based for the review was heavily skewed towards strut-based.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Comparison of 3D Printing Techniques with Subtractive Manufacturing Methods used in Dentistry†

Ajinkya Goray [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: ajinkya.goray@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Additive Manufacturing (AM) technology, by virtue of its advances in rapid prototyping, cost-effectiveness and design flexibility, has found widespread applications within Dentistry, mainly in the fabrication of prostheses (Prosthodontics). The primary additive manufacturing processes used in the production of dental implants, bridges, prostheses and mandibles are Stereolithography (SLA) and Selective Laser Melting (SLM). This review focuses on the advantages of these processes over more conventional subtractive manufacturing methods, the materials utilized in the fabrication of the aforementioned components and the factors considered in the evaluation of the final product. It also briefly examines the limitations associated with certain rapid prototyping techniques and the need for their refinement before application in clinical practice as well the future of Additive Manufacturing technologies within the field.

Keywords: Additive Manufacturing; Dental Prostheses; Prosthodontics; Stereolithography; Selective Laser Melting.

1. Introduction

Additive Manufacturing is fundamentally described as process used for the creation of 3D objects by deposition of material, usually in layers. The earliest AM techniques were developed in the 1980s, with SLA being the first recorded AM process. Following this, several new methods were developed and patented but it wasn't until 1999 that they found application within the field of medicine.

Dentistry is a branch of medicine that deals with the study, diagnosis, prevention and treatment of diseases, disorders and conditions of the oral cavity. It is commonly associated with, but not restricted to teeth, and also includes other aspects of the craniofacial complex (i.e., parts of the head enclosing the brain and the face). The field also offers several specializations, one of which is Prosthodontics, i.e., pertaining to the replacement of missing teeth and the associated soft and hard tissues by prostheses which may be fixed or removable, or may be supported and retained by implants. These implants are described as artificial structures inserted by a dental surgeon into a person's jawbone due to a loss of one, more or all teeth, referred to as whole or partial edentulism. It acts as an anchor for a custom-made tooth, referred to as a crown, which is connected to the implant by means of a device known as an abutment.

Dental prostheses are traditionally manufactured by using conventional subtractive manufacturing methods wherein the data from the patient is collected in the form of images, molds and x-ray scans which are then compiled and sent to a group of highly skilled lab technicians. The most widely used subtractive manufacturing method within the Dental Industry is 5-axis milling, which offers a large number of possibilities with respect to part sizes and shapes. The term "5-axis" refers to the number of directions that the cutting tool can move in, i.e., linear motion across the X, Y and Z axes and rotational motion on the A and B axes in order to approach the workpiece from any direction. The prostheses are fabricated from materials such as zirconia and wax (example: DWX-50; Roland DG Corp.) (Bae, Jeong, Kim & Kim, 2017). This process involves cutting of the desired product from a block of raw material, leading to a high probability of the formation of micro-cracks which have adverse effects on the mechanical properties of the finished product (Lian, Sui, Wu, Yang & Yang, 2018). Similarly, dental implants are also manufactured using Electric Discharge Machining (EDM), which is a subtractive fabrication technique. EDM, in tandem with laser scanning and CAD-CAM technologies has been shown to produce accurate restorations directly from a raw ingot. Computer controlled operations such as milling also produce implants with a high degree of accuracy. However, studies have shown that the material loss incurred due to the subtractive nature of the machining processes is about 80%. Furthermore, the tooling cost associated with this operation is significantly high (Nasr, Kamrani, Al-Ahmari & Moiduddin, 2014).

Stereolithography (SLA) is one of the main AM processes used for manufacturing dental restorations, implants and bridges. It involves the curing of a photopolymerizing resin under ultraviolet light to produce high precision parts. It is widely applied in the production of dental restorations as it can be used to fabricate both casts (i.e., replicas of a patient's teeth) as well as restorations (i.e., bridges, implants or dentures). The specimens fabricated using SLA are also observed to have a higher accuracy than the ones produced using subtractive methods (Bae et al, 2017). In another study, zirconia, which is traditionally used to produce restorations by conventional subtractive techniques, was used to manufacture dental bridges using SLA. For this purpose, a zirconia ceramic suspension was prepared and subjected to UV laser as a light source for curing. This process was chosen over other processes such as Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) as it provides good dimensional accuracy with minimal shrinkage and a high relative density (Lian et al, 2018). SLA has also successfully been applied on Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) slurries for the fabrication of dental ceramics with positive results (Li, Son, Sung, Ma & Shen, 2019).

Another popular AM process for manufacturing dental prostheses and implants is Selective Laser Melting (SLM). A study based on this process talks about how the process traditionally relied heavily on voluminous and consequently expensive machines which required well-trained staff to run, thus effectively keeping smaller companies away from the field and then shifts the focus to the Realiser Desktop SLM Machine ©, specifically targeted at dental labs that produce a large variety of small parts. Traditional processes like casting and CNC milling pose stiff competition as they too provide a high degree of accuracy. However, SLM possesses the advantage of being able to process any metal powder and even powder blends. It is more cost-effective due to zero chipping compared to milling and minimal material wastage compared to casting. Secondly, SLM can be used to manufacture significantly complicated parts, which is challenging to achieve with casting and milling (Gebhardt, Schmidt, Hötter, Sokalla & Sokalla, 2010). In certain cases, both SLA and SLM can be combined for the production of parts with hybrid materials in order to effectively utilize the individual advantages provided by both the processes (Silva, Felismina, Mateus, Parreira & Malça, 2017).

2. Methods

Since its advent, AM technology has grown rapidly and now finds applications in a diverse variety of fields. There is a large amount of literature pertaining to AM available in the public domain through various journals, research papers, scientific articles and conferences. Certain keywords such as "additive manufacturing", "3D printing" and "dental" were defined in order to keep the search broad yet relevant. Four databases, i.e., Google Scholar, IEEE Xplore, Science Direct and Elsevier were selected and searched with all possible logical iterations of these keywords. The results were kept restricted to within the last 5 years apart from some exceptional cases in order to reference the latest advancements within a relatively nascent field. 4 papers were chosen from among these results on the basis of their abstracts and conclusions following which the search terms were modified to include more specific keywords such as "subtractive manufacturing", "stereolithography" and "selective laser melting" to further narrow down the search field. 3 more relevant papers were then selected from this updated search list and thus, all 7 shortlisted papers were then reviewed in detail. Having no prior knowledge of Dentistry, the official websites of the American Dental Association (ADA) and European Prosthodontic Association (EPA) were referred in order to gain familiarity with key technical terms from the field and insights about the subject as a whole. Working professionals/peers from the dental industry (India) were also contacted to understand the commonly used methods for manufacturing prostheses and implant and the problems associated with them.

3. Results

In order to evaluate the effectiveness of AM methods over conventionally practiced techniques in Dentistry, it is necessary to draw comparisons between the two based on parameters such as accuracy, finish, grain structure and mechanical properties. Accuracy and finish have been considered as the primary factors for evaluation due to the highly aesthetic and precision-based nature of the field. Owing to the extremely fine margins involved in dental work, it is imperative that the generated implant or prosthesis be almost exactly replicated from the dental scan or generated CAD model within the bounds of the specified deviations or margins of error. Furthermore, the final product must also be visually appealing and devoid of any surface defects or blemishes.

For the purpose of evaluating the accuracy of the restorations, a distal-occlusal inlay utilized in clinical trials was first generated with the aid of a CAD software. The dimensions along the x, y and z axes were decided and a taper was added at the bottom with an angle of roughly 8 degrees to replicate the retention used in clinical practice. Four methods were considered: two subtractive (5-axis machining on zirconia and wax) and two AM (SLA for a UV polymerizable polymer and SLM for a cobalt-chromium alloy). A total of 40 specimens, i.e., 10 specimens per group, were fabricated

preceding which a random sample from each group was scanned using a digital dental scanner to compare the deviation from the original data. The spectrum of the laser was divided into 15 colour segments; maximum/minimum critical values were set to ± 100 μm and the nominal values were set to ± 5μm. The data was obtained as standard deviation mean average value, tolerance range and RMS (Root Mean Square) value for deviation. The RMS is calculated by the formula:

$$RMS = \frac{1}{\sqrt{n}} \sqrt{\sum_{i=1}^{n} (X_{1,i} - X_{2,i})^2} \tag{1}$$

where $X_{1,i}$ is the measuring point I on the reference data (CAD model), $X_{2,i}$ is the measuring point I on the scanned data (specimen) and n is the total number of measuring points (Bae et al, 2017). The resultant values were calculated using IBM SPSS Statistics v21 (IBM Corp.™) and have been tabulated below:

Table 1. Table comparing the Root Mean Square (RMS), Standard Deviation, Variance and Tolerance values of the 4 samples (Bae et al, 2017).

	SLA	SLS	Wax	Zirconia
RMS (μm)	106	113	116	119
Std. Dev. (μm)	99	105	109	112
Var. (μm)	11	12	13	13
In Tol. (%)	10.97	10.63	10.24	10.13

The 3D analysis conducted on the above components is inadequate for evaluating the local changes in shape. Hence, the samples were observed under a digital microscope to observe said changes, the results of which are as follows:

(a)   **(b)**

(c)   **(d)**
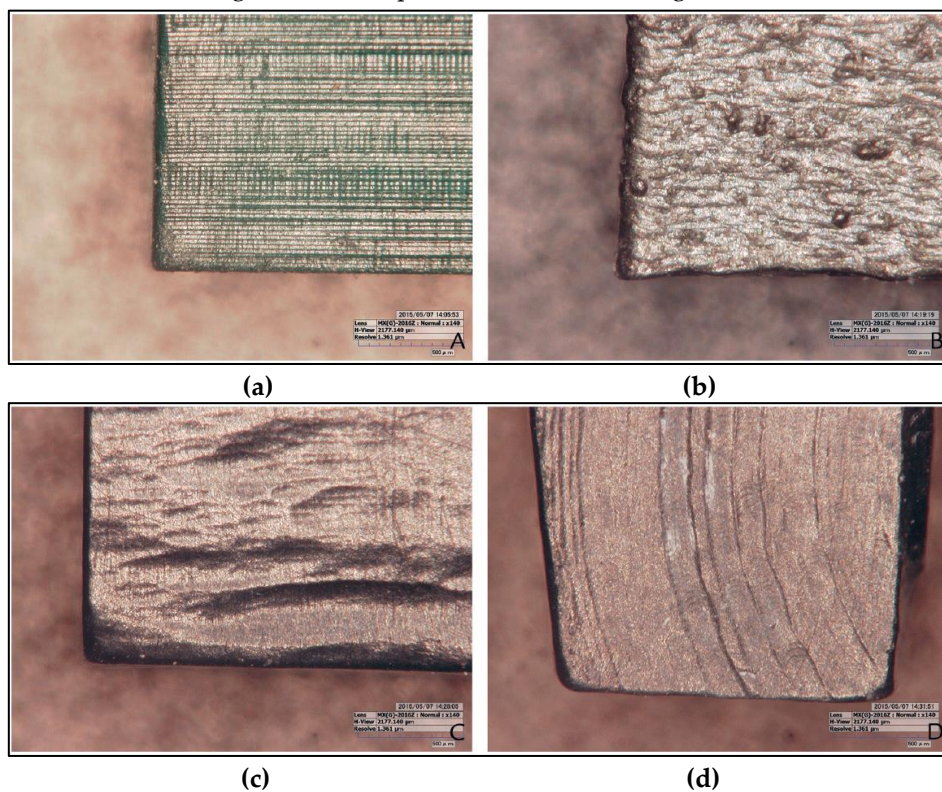
Figure 1. Specimen surfaces observed under a digital microscope: **(a)** Stereolithography image; **(b)** Selective laser sintering image; **(c)** Wax 5-axis machining image; **(d)** Zirconia 5-axis machining image (original magnification x 140) (Bae et al, 2017).

The microscopic images taken at 140x magnification display the final surface finish of the four samples and the singularities induced as a result of the employed manufacturing methods and materials (Figure 1). In the SLA sample, there was a clear distinction between the individual layers in a laminated fashion with a fine gap between each layer (Figure 1(**a**)). Conversely, the SLS sample has light circular depressions, the cause of which is unknown (Figure 1(**b**)). In the wax specimen, traces formed as a result of the end-mill cutting process were observed (Figure 1(**c**)). The ZIR

specimen also shows similar traces of end-mill cutting and chipping, albeit more prominently (Figure 1(**d**)) (Bae et al, 2017).

4. Discussion

The aforementioned results highlight a few differences between the values obtained for AM methods and subtractive methods respectively. The RMS value for the SLA group (106 μm) is significantly lower than that of SLS (113 μm), wax (116 μm) and Zirconia (119 μm). This low value indicates minimal deviation in the accuracy of the final product from the reference data. Similarly, the standard deviation denotes how far each value lies from the mean of the data set and variance signifies the degree of spread of data, with SLA having the lowest values and 5-axis machining of Zirconia having the highest values for each. Thus, this establishes SLA as the most accurate process followed by SLM, 5-axis machining of wax and lastly, 5-axis machining of zirconia. Furthermore, it also proves that the accuracy of AM methods is greater than that of subtractive methods. The error allowance for the restorations was set to ±5 μm, i.e., a total deviation of 10 μm. The values of ±5 μm (In Tol. %) obtained somewhere around the 10% mark signify the closeness in resemblance of the fabricated samples to the original data (Bae et al, 2017).

For all their advantages, AM methods also pose certain limitations which must be overcome before they can start being applied regularly in clinical practice. For instance, even though SLA is the most widely used AM process in Dentistry, it still poses certain challenges such as possible structural inhomogeneity due to aggregation of nanoparticles, the need for an extra support structure to hold impending sections, formation of cracks due to layer by layer fabrication and microscopic defects such as formation of pores (Li et al, 2019). The application of AM methods in the dental industry is still in its nascent stage and further optimization of these processes will be required before they can be completely adopted. There have, however, been attempts to improve certain aspects of these processes or to combine one or more processes to work in unison. One such study utilizes a polymeric mixture of polymethylmethacrylate (PMMA) and polyethylmethacrylate with 0.6% TiO_2 nanoparticles (optimum amount) for the fabrication of dental prostheses by SLA. This PMMA polymeric matrix with nanoparticles was observed to show better mechanical properties than the commonly used PMMA with a photoinitiator for UV curing (Totu, Stanciu, Butnăraşu, Isildak and Cristache, 2017). In another study, both SLM and SLA techniques were used for the fabrication of the interior metal mesh and the external polymer coating of a dental bridge in order to achieve a high mechanical strength and/or gradient of physical and mechanical properties (Silva et al, 2017). Such endeavors, along with process optimization, improved mechanical properties of products and support/investments from AM equipment manufacturers can contribute significantly towards the already bright future of AM in Dentistry.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Continuous Liquid Interface Production Technology: Benefits and Potential in the Field of Mainstream Manufacturing[†]

Aayush Mohta [1,*]

[1]   Technische Universität Chemnitz; Chemnitz; Germany
[*]   Correspondence: mohta.aayush@s2020.tu-chemnitz.de
[†]   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: With the onset of the 4th Industrial revolution, the application of additive manufacturing (AM) is expanding into the realms of mainstream manufacturing. Although the scope of application is vast, several limitations of traditional three-dimensional printers (3D printers) have put a check on its gaining popularity. The main cause of these limitations is the discontinuous layer-by-layer approach of traditional printers. To provide layer-less and continuous fabrication, Continuous Liquid Interface Production (CLIP) technology has been introduced. CLIP technology has the potential to fabricate parts that are ready for end use. Thus, in this paper pros and cons of CLIP technology have been reviewed and its potential in the field of mass manufacturing has also been checked.

Keywords: 3D printing; Additive manufacturing; Continuous Liquid Interface Production; Rapid manufacturing; Layer-less printing.

1. Introduction

3D printing has been around for decades but as we now move into the 21st century, however, costs have decreased drastically, allowing a substantial increase in the application of 3D printing technologies in different industries (Attaran, 2017). The reason for such rapid increase in its application can be credited to various factors such as unlimited design flexibility, the possibility to generate complex geometries, removal of tooling process and related costs, and wastage reduction. Although the popularity of 3D printing is increasing, its application has not developed beyond the realm of rapid prototyping (Janusziewicz et al., 2016). This confinement of the field can be attributed to layer-by-layer printing leading to anisotropic mechanical properties depending on the direction of print (Janusziewicz et al., 2016), and high fabrication time (Tumbleston et al., 2015). Also, the 3D printed components are mechanically weaker with limited material options as compared to components manufactured by traditional production processes, for example, injection moulding (Hu et al., 2019; Kuang et al., 2018). To overcome these limitations, CLIP technology of AM was developed.

CLIP method allows for layer-less and monolithic fabrication resulting in continuous production. The process harnesses UV light (promotes curing) and oxygen (inhibits curing) to rapidly grow parts. The process utilizes the principle of oxygen-inhibited photopolymerization of free radicals to generate a continuous liquid interface of uncured resin between the growing part and the exposed window (Janusziewicz et al., 2016). This is depicted in Figure 1(a). The window exposed to the UV projector is made from a transparent material that not only is transparent to UV light but also permeable to oxygen. The resin used is photocurable but due to the presence of oxygen, a liquid layer is produced between the polymerised (cured) part and the window which is called the "dead zone" (DZ). The DZ prevents the cured resin from sticking onto the window and thus, promotes continuous fabrication (Balli et al., 2017). Also, fabrication continuity is generated because of the constant lifting of the cured part out of the resin bath, thereby creating suction forces that cause constant renewal of reactive liquid resin. It should be noted that, since DZ formation is dynamically driven, its thickness depends on various factors such as light intensity, oxygen content, build speed, resin viscosity, the weight percentage of UV absorber and so on (Janusziewicz et al., 2016). Figure 1(b) indicates the architecture and operation of a CLIP-assisted 3D Printer. The build platform continuously moves upward at a defined speed (200-500 mm/hr) to pull the solid part out of the pool of UV curable resin exposed to the UV projector through the special oxygen-permeable window (Balli et al., 2017). The working of a CLIP-assisted 3D printer clearly depicts how this process circumvents the inherent obstacles and provides for continuous production.
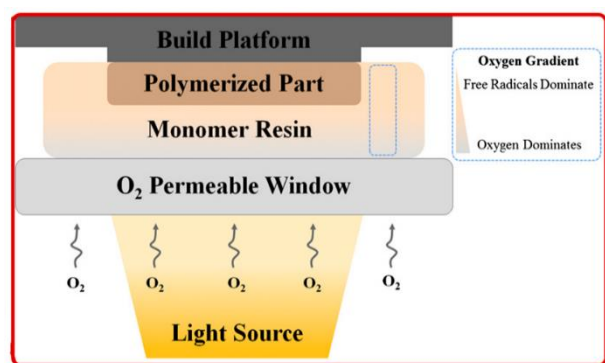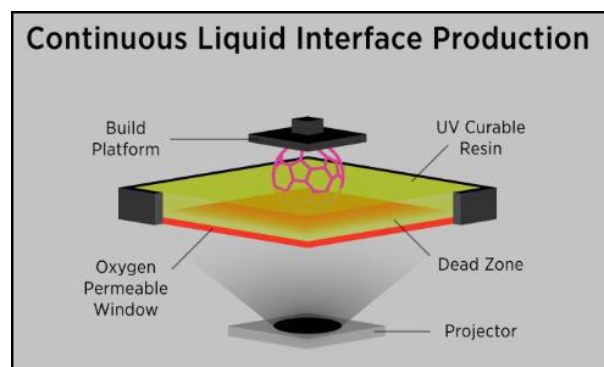
Figure 1. (a) Schematic of the dead zone produced by the presence of O2-permeable window and generation of free radicals upon UV exposure (Janusziewicz et al., 2016); **(b)** Architecture of CLIP assisted 3D Printer (Balli et al., 2017).

The solutions to the limitations of conventional 3D printing method by fabrication continuity of CLIP technology and the possibility of its application in the field of rapid manufacturing have been reviewed in this paper.

2. Methods

For review, only published literature, scientific research, and review articles within the last six years (i.e., 2015-2021) were considered. The database used for research purposes were Google Scholar, Elsevier, Science Direct, and Springer Link.

Initially, according to the theme of the topic, the keywords used were '3D printing', 'rapid manufacturing', 'additive manufacturing', and 'continuous liquid interface production'. All logical combinations of the keywords were iterated. From the search results, five papers were shortlisted after skimming through the abstract and conclusion of at least fifteen papers related to the field of interest. The other papers were found in the references of the shortlisted papers and by searching for other synonyms that were encountered while reading these papers. These synonyms were 'layerless fabrication', 'continuous 3D printing', and 'photopolymerization printing'. Thus, in the end, a total of nine papers were shortlisted with the focus to describe CLIP process, how it overcomes the limitations of the traditional layered printing process, and the scope of its implementation in the field of rapid manufacturing.

3. Results and Findings

The major limitations of the layer-by-layer printing approach of traditional 3D printers are anisotropic mechanical behavior, layered structures leading to staircasing effect and lack of monotonicity, lack of available material variety, mechanically weak fabricated components, and a large trade-off between fabrication time and accuracy. The CLIP technology provides a solution to each of the above-mentioned drawbacks creating a pathway to mass production (Hu et al., 2019; Janusziewicz et al., 2016; Kuang et al., 2018; Tumbleston et al., 2015). The solutions to these limitations are explained in the following sections:

3.1. Creation of monolithic and isotropic components

In the CLIP method, material grows instead of layer addition, thereby eliminating the layers and resulting in a monolithic structure (Tumbleston et al., 2015). As the component does not have a layer-like structure, the mechanical properties are independent of the orientation of printing. As a result, the CLIP manufactured parts are monolithic with a smooth exterior and interior texture along with isotropic mechanical performance (Balli et al., 2017).

Janusziewicz et al. (2016) also carried out an experiment to demonstrate that the CLIP method results in monolithic part production. To conduct the experiment, an open book benchmark was designed. The parameters checked proved the claim that the CLIP method is a layer-less process. Also, the isotropic behavior of the finished part was checked. To check this, ASTM type V dog bones were printed along the three axes (X, Y, and Z), and each of these dog bones were built with three different slicing thicknesses. Tests were conducted in accordance with ASTM D638 and the resulting tensile strengths and Young's modulus showed no difference with respect to slice thickness or orientation. The test results are better depicted in Figure 2. The tests provide enough evidence that CLIP parts are monolithic, layer-less and isotropic unlike the other conventional 3D printed parts. Detailed study of the experiment can be found in (Janusziewicz et al., 2016)
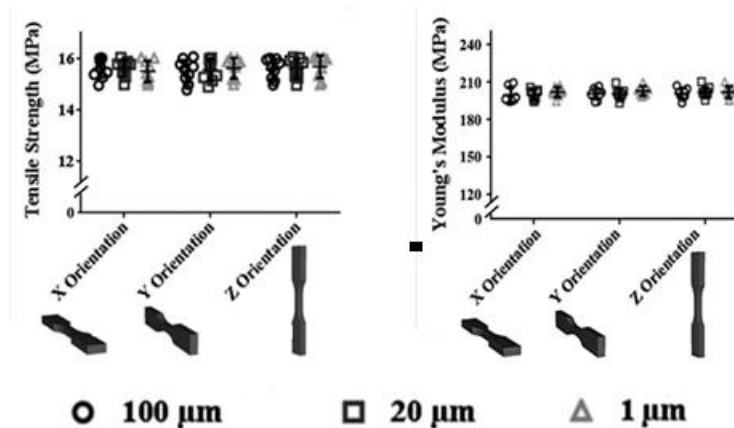
Figure 2. Results of ASTM D638 tests. Each dog bone was built in three different orientations with three different slicing thickness for each orientation (Janusziewicz et al.,2016).

3.2. High material flexibility and possibility to create mechanically strong components

"Carbon3D" has been one of the pioneer companies in the development of CLIP technology. The company provides a range of materials that can be broadly classified into prototyping resin and manufacturing resin. Currently, it provides six different types of resin for production purposes with material properties comparable to that of the engineering polymers available on the market. CLIP products are tough, chemical and wear resistant, resilient, thermally stable with high strength and strain values. The tensile strength and strain of 4 CLIP compatible materials, namely: cyanate ester (CE), rigid polyurethane (RPU), elastic polyurethane (EPU), and flexible polyurethane (FPU) have been compared with commonly used engineering polymers: acrylonitrile butadiene styrene (ABS), polypropylene (PP) and oxidized polyethylene (OA6-15GF25M). The comparison has been shown in Figure 3 (Balli et al., 2017).
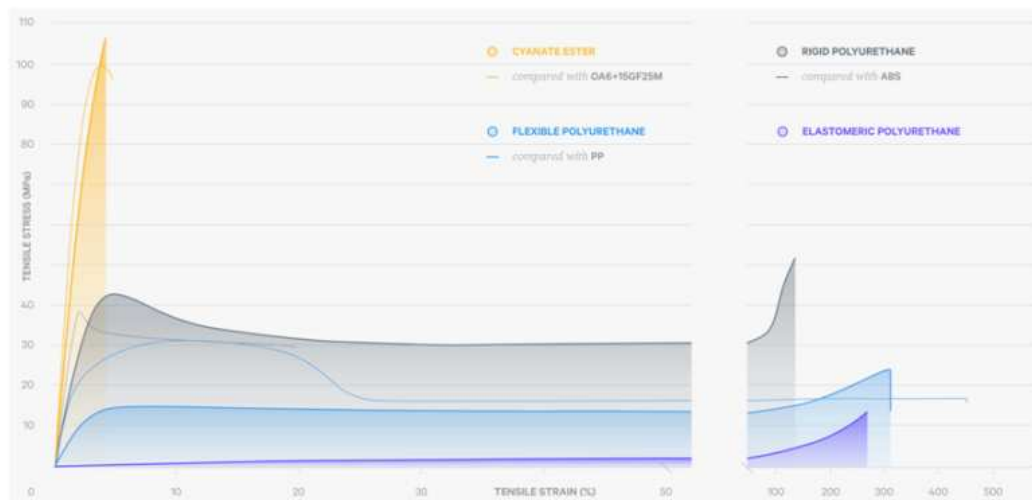
Figure 3. Tensile stress and strain behaviour of CE, RPU, FPU and EPU have been compared with standard engineering polymers used extensively in the industry (Balli et al., 2017).

To check the replicability of mechanical properties in components produced by the CLIP technology, McGregor et al. (2019) tested hexagonal lattice parts manufactured by CLIP-based AM. 84 parts were designed and tested, representing 4 designs and 3 materials. Across all the parts, the modulus was close to the desired value provided in the supplier datasheet while the strength deviated from the expected value by 7%. The results suggested that the mechanical values were close to expectations and hence proved that the components can be directly used for final applications rather than just as prototypes (McGregor et al., 2019).

Currently, new materials are developed to increase the scope of application of components produced by the CLIP-based technology. For example, Hu et al. (2019) developed a photocurable cellulose acetate butyrate resin compatible with CLIP technology and was able to construct components with excellent mechanical properties, high chemical

resistance, and thermal stability. Furthermore, some post-processing techniques have also been developed to enhance the mechanical properties of CLIP produced components. One such instance is the development of two stage curing process. In this process, the resin is first photocured and then thermally cured at elevated temperatures. The process combines the advantages of outstanding printing speed and resolution of photocuring process with high mechanical properties achieved after thermal curing. Post thermal curing, a significant increase in Young's modulus and strength was observed (Kuang et al., 2018). The observed mechanical properties are close to the engineering grade polymers. Such advancements are providing more opportunities for the application of CLIP technology in the rapid production field.

3.3. Enhanced production speed and accuracy

CLIP technology involves a continuous fabrication process in which various fabrication steps: UV exposure, resin renewal, and part movement occur simultaneously, unlike the conventional layer-by-layer 3D printing processes such as stereolithography (SLA) and digital light projection (DLP). Thus, the limiting factors for the print speed in a CLIP process are only resin cure rate and resin viscosity. As a result, a print speed of 500 mm/hr can be achieved by CLIP method which is close to a hundred times faster than the printing speed of conventional 3D printing methods (Tumbleston et al., 2015).

Another benefit of the continuous resin renewal mechanism of the CLIP method is that parts with different slice thicknesses can be created with the same build speed. This is not possible in a layer-by-layer type 3D printing process in which the printing speed reduces as the slice thickness reduces. Thus, there is no trade-off between printing speed (build time) and printing accuracy. Table 1 shows the comparison between the accuracy and print speed of various 3D printing methods (vat polymerization principle).

Table 1. Comparison between various vat polymerization processes based on printing speed and accuracy has been done. The maximum print size has also been compared to provide an insight on size limitations of the printed objects (Lan et al., 2018)

3D Printing Process	Printing Speed (mm/hr)	Lateral Resolution (μm)	Maximum print size (mm)
Laser -SLA	14	6-140	27-750
DLP	25-150	33-120	45-230
CLIP	500	50-100	80-320

4. Discussion

As seen earlier, due to various reasons, scope of application of CLIP technology is constantly increasing. Preliminary studies show that the features of the parts produced by CLIP are comparable to injection moulded (IM) parts. Since the quality of the parts are similar and various advantages of CLIP over IM like shorter product development lead time due to removal of tooling process, faster implementation of design change, feasibility to produce lightweight and high-strength geometries, and formation of a digital thread makes CLIP a better alternative to IM (Galantucci et al., 2019).

Although the advantages of the CLIP technology over traditional layer-by-layer approach have been highlighted in the previous section, there are still certain limitations that need to be addressed. A few are listed here:

- Limited build envelope: when compared with other conventional manufacturing technologies, the available build volume is low. A larger build envelope is required to compete with the traditional manufacturing methods.
- Limited pot life: engineering resins are two-part resins and once these two parts are mixed, their pot life gets limited to eight hours. Thus, resin with a higher pot-life is suitable as it allows for longer builds and higher production quantity. This helps in reducing production costs (Balli et al., 2017).

1. Despite these challenges, CLIP is a revolutionary technology that is slowly gaining its foothold in industrial applications. For example, Adidas is using this technology to create the first high performance footwear while many other automobile companies have also started to introduce this technology into their manufacturing system.

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Review article

The effects of using multi-axis additive manufacturing on the mechanical properties, surface finish, and support material of the printed part[†]

Osman Adil Osman Elbashir [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany

* Correspondence: osman-adil-osman.elbashir@s2020.tu-chemnitz.de

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Abstract: Material extrusion additive manufacturing technologies demand greater flexibility, creative design paradigms, and standards that fully utilize the available geometric and material freedoms. The goal of adopting robot-assisted additive manufacturing is to enable design options and to improve workpiece properties while eliminating process restrictions through utilizing extra degrees of freedom in the print head or the platform bed, and several design adjustments to the workpiece's internal and exterior geometry. The innovation has proven to affect the mechanical strength properties, surface quality and eliminates the need for supporting structures. This review paper examines nine scientific papers based on specific criteria to identify the effects of multi-axis AM on the printed part in comparison to conventional 3D printing.

1. Introduction

Additive manufacturing (AM) technologies involve technologies that fuse the material in order to build a 3-dimensional parts layer by layer, and because the part is being built up instead of being moulded or machined from outside, AM makes it possible to produce products and forms that are very complex and cannot be manufactured using traditional manufacturing methods, for instance, parts that have complex internal channels (Bhatt, Malhan, Shembekar, Yoon, & Gupta, 2019). Also, AM can eliminate a lot of assembly work because a part that might be assembled from a lot of small components could be created as a single piece instead.

Material extrusion (ME), which is also known as fused deposition modeling (FDM), is one of the most known techniques for AM. FDM extrudes the material in the form of filament wire using a stepper motor through a heated nozzle head that melts the material and moves within three degrees of freedom (DOF). The traditional FDM setup consists of planar layers that are used to create components. A huge number of planar layers are required to approximate a highly curved geometry (M. Bhatt, et al., 2019). When planar layers are stacked to make pieces, inferior anisotropic material properties can result, due to the inability to reorient the fibers in the desired position, which may result in a reduction of the part's strength. Staircase effects can also be caused via planar layer approximation and can result in a poor surface finish. In addition, one of the main disadvantages of this 3-DOF deposition method is the requirement for extra material in order to create support material for structures with overhangs (Wu, Dai, Fang, Liu, & Wang, 2017).

One of the approaches to resolve the current limitations and to further improve the traditional FDM 3-DOF deposition is by the introduction of robotic arms, which allows the application of multi-axis 3D printing. Multi-axis processes can provide higher DOF (e.g., four, five, or six), which enables the movement of the printing head or the printing platform in extra multiple axes. The multi-axis AM system allows for changes in build directions throughout the manufacturing process while maintaining planar layers. For instance, the staircase effect encountered in traditional AM can be mitigated by shifting the build directions across various levels. When necessary, parts can be printed with slanted orientations to prevent the staircase effect (Bhatt, Malhan, Shembekar, Yoon, & Gupta, 2019). Also in the traditional AM, the strength of the pieces along their construction direction is poor, and they may fail during usage owing to delamination under tensile or shear pressures. This issue may be prevented by adjusting the construction plane orientation according to the loading circumstances. Also, in some cases, multi-axis AM might eliminate the necessity for support structures; to handle such concerns, by tilting the part in the build direction or tilting the construction tool in the build

direction. In either situation, the system would require an additional DOF. An articulated robot arm can be used to provide this additional DOF to the system (M. Bhatt, et al., 2019). Therefore, this review paper investigates the effects of using multi-axis 3D printing on the mechanical properties, the surface finish, and the support-material requirements through the use of robotic arms in the FDM process.

2. Methods

The searching methodology for conducting this review paper was based on the examination of previously published papers in international conferences and scientific journals. This material was compiled utilizing well-known databases such as Google Scholar, Springer, Journal of Additive Manufacturing, Elsevier, and IEEE Journal. A total of 9 out of 13 papers were taken into account to conduct this review, the criteria for the acceptance were based on different factors such as if the paper had a high impact factor above 2.5 points, or if it's peer-reviewed, and the publishing date was within the last four years (2017-2021).

A synonym search terms for this topic include additive manufacturing, robotic arms, 6 degrees of freedom, mechanical properties, support-free 3D printing, and material extrusion were used for finding papers in the field of the topic, and then the papers were filtered thoroughly through the abstract and the results and findings sections. A citation and referencing software, Citavi, were used to keep track of selected papers and web pages, analyzing contents, structuring ideas, and writing the paper. The research was carried out utilizing the secondary quantitative research method to review past data based on the comparison of real experimental data, collected from different scientific papers and articles, to investigate the relationship between utilizing a multi-axis FDM and its impacts on the mechanical properties, surface finish, and the support material of the printed part.

3. Results

The main methodology followed to find the impacts of using multi-axis deposition, is to produce two parts identical to each other in shape, size, and thickness. The first one was produced using planar layer stacking (3-DOF) and the other one was produced using the non-planar or conformal layering (6-DOF) and then comparisons were made between them to conduct findings.

3.1. Effects

3.1.1. Mechanical properties

In a study work, two fabricated pieces were tested in loading configuration to examine potential changes in mechanical performance. The specimens were first put between compression platens in an electromechanical load frame. The 3-DOF Specimen A demonstrated a progressive rise in compressive load up to a maximum value of 1900 N at a displacement of 9 mm. The 6-DOF specimen B, on the other hand, resulted in a faster rate of load rise during compression, up to 2750 N at 9.5 mm (Alsharhan, Centea, & Gupta, 2017).

In an additional experiment, for tensile and yield strength, each specimen was tested in 3 different orientations, XYZ, 45 degrees and ZYX. Figure 1 depicts the tensile testing results for the 3-DoF and multi-axis printed items. The average modulus of the XYZ specimens was 2,322 MPa, and the average yield strength was 20.2 MPa. The average modulus and yield strength values for the 3-DoF 45° specimens were 1,871 and 16.4 MPa, respectively, whereas the multi-axis 45° specimens exhibited values of 2,304 and 21.4 MPa, exhibiting improvements of 23% and 30%, respectively. The 3-DoF ZYX specimens had average values of 1,665 and 8.1 MPa, respectively, while the multi-axis ZYX specimens exhibited average values of 2,179 and 20.4 MPa, exhibiting 31% and 153% improvement, respectively (Kubalak J. R., 2019). These two experiments above clearly depict the positive effects of using multi-axis deposition method in comparision to the conventional method in terms of enhancing the mechanical properties.
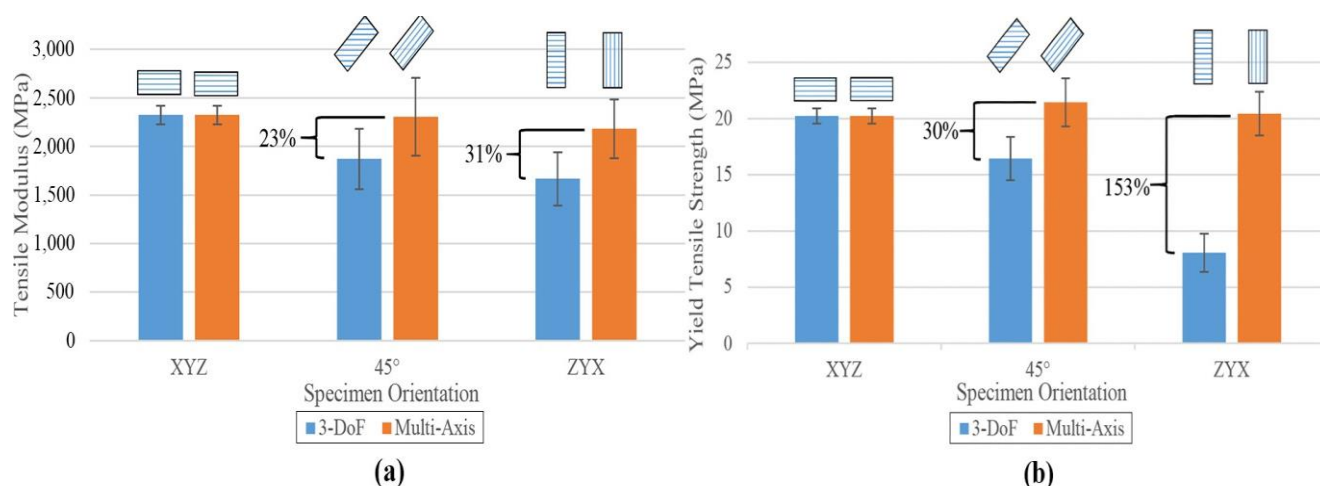
Figure 1. Results of tensile properties for each specimen orientation and deposition strategy (Kubalak J. R., 2019).

3.1.2. Surface Finish

As a preliminary investigation, the handle of a walking frame was created traditionally utilizing three axes and then multi-axis via workpiece decomposition. The preliminary tests aimed to improve the surface quality in terms of stair-step effects. As a result, the surface of the handle which was made by the multi-axis was smoother than in the traditional FDM method as shown in Figure 2. The 6-DOF proved that even with the same nozzle diameter, the multi-axis method prevents the stair-step effect (Wulle, et al., 2017).

Figure 2. 3-DOF FDM with strong stair-step effect (left), 6-DOF FDM with smooth surface properties (right) (Wulle, et al., 2017).

In another experiment, after printing two equivalent components with XY-planar layers, and then reinforcing one specimen using a 6-DoF robotic material extrusion platform with additional material placed along the surface (skinning process). The effect of this skinning approach was established by comparing skinned tensile bars to equivalent, un-skinned specimens, resulting in a smoother surface with an increased tensile modulus and yield strength by 9% and 59%, respectively (Kubalak, Wicks, & Williams, 2017).

3.1.3. Support material

Table 1 compares material waste and production time for three distinct manufacturing scenarios. It can be seen that using the 6-DOF for component fabrication (Case I) may minimize material waste percentage by 63.39% and 42.45%, respectively, when compared to Cases II and III, where 3-DOF were employed. In Case II, the support structure needed by the 3-DOF AM technique for producing the overhang feature accounts for about 62% of the overall material waste. The material waste in Case III, on the other hand, originates from the support structure, as the part is totally manufactured utilizing the AM technique (Li, Haghighi, & Yang, 2018).

Table 1. AM System's material waste comparison (Li, Haghighi, & Yang, 2018).

	Case I: Hybrid manufacturing (6-DOF capability)	Case II: Hybrid manufacturing (3-DOF capability)	Case III: Additive manufacturing (3-DOF capability)
PLA filament used (g)	32.08	34.60	91.33
PLA block used (g)	59.33	59.33	0
Material waste (g)	1.46	4.10	2.54
Waste percentage	1.60%	4.37%	2.78%

In another assessment, Figure 3 depicts a comparison of two rabbit models created by FDM system using different tool paths: The spatial tool path ways for 6-DOF printing platform system succeeded in creating the model without any support material, as shown in figure 3 it is noticeable the amount of the support material waste, which the planar paths system had to create in order to build the part (Dai, et al., 2018).
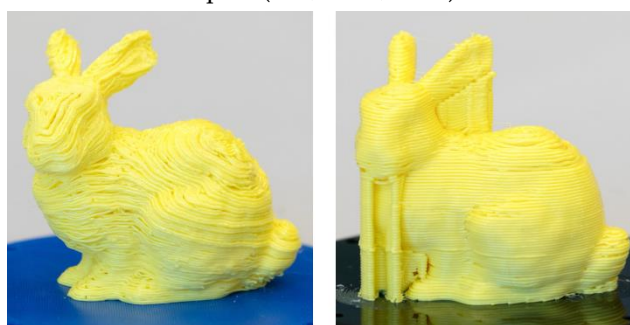
Figure 3. A comparison for a Bunny model printed by using different tool-paths: (left) non-planar layer stacking using 6-DOF, (right) planar layer stacking using 3-DOF (Dai, et al., 2018).

4. Discussion

Multi-axis FDM demonstrated in this review paper shows that it is capable of overcoming the limitations of existing three-axis FDM by reducing support structures, which saves manufacturing time and reduces material usage, resulting in cheaper prices. Also, reorienting the fibers in non-planar layers can lead to better mechanical properties and surface finish, which can prevent the extra processes that are done in traditional 3D printing to refine the surface.

Extra limitation of the traditional 3D printers is the low build volume and high installation costs, they are not suitable for large-scale applications. To manufacture a big-scale item using a typical 3D printer, the machine envelop must be large enough to hold the item, and the actuators that move the deposition head should be precise over the whole build plate. As a result, AM machines get larger and more expensive. Therefore, we can overcome the constraints of the gigantic-type print machines by utilizing robots in AM. One extra advantage of using robotics is the in-situ printing, which allows for the creation of AM parts at the site where they will be utilized. This method is useful when the part is too fragile or substantial to be transported from the point of manufacture to the point of application, or when transportation costs and time are too expensive.

In conclusion, using multi-axis AM has proved to have positive impacts on the printed part in comparison to conventional methods, yet, there are still a few difficulties to apply the multi-axis methods such as the collision avoidance between the tool head and the printed part which requires high accuracy and complex algorithms in the tool path planning.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Additive manufacturing of aluminium alloys using cold metal transfer process[†]

Ribhu Shashidhar [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany

[*] Correspondence: Ribhu.shashidhar@s2020.tu-chemnitz.de

[†] Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Aluminium alloys are used in various industries. The advancement in the field of Additive manufacturing (AM) has influenced the production of aluminium components using AM process, on a large scale. Wire arc additive manufacturing (WAAM) seems to be the best additive manufacturing process that can be used for aluminium alloys because of their good buy-to-fly ratio. Cold metal transfer (CMT) method, a modified version of Gas Metal Arc Welding is found to be the suitable WAAM process for aluminium alloys. However, the mechanical properties of the parts produced by CMT- based WAAM process is not satisfactory due to porosity in the produced parts. Porosity can be reduced to a great extent by using different arc-modes and inter-layer rolling. The surface quality of CMT-WAAM built part is better if good quality wire is used and when the arc length-voltage is of right value. The whole CMT-WAAM process is more beneficial if it is combined with advanced robotics.

Keywords: Aluminium alloys; Cold metal transfer (CMT); Wire arc additive manufacturing (WAAM); Process improvement.

1. Introduction

In the recent years, there has been rapid advancement in the field of Additive manufacturing (AM) of metals. AM uses technology to build parts by layer-by-layer addition of material. Initially created for the purpose of Rapid prototyping, AM is now being used in industries to create parts on a large scale. Using AM process is beneficial, as it is more sustainable and has a higher resource efficiency than the conventional processes. There are several methods for AM of metals, mainly classified by the state of filler material: liquid, powder, and wire (Cong et al. 2015).

Aluminium alloys find a wide range of applications in various industries, ranging from automotive to aerospace industries. Aluminium alloys are widely used in various industries because they have higher specific strength and good corrosion resistance. Although additive manufacturing is becoming increasingly popular to produce aluminum alloys, not all AM processes can be used for the manufacturing of aluminum alloy components (Derekar et al. 2020).

Wire based additive manufacturing (WBAM) is best suited for aluminium alloys because of its reduced production costs, high deposition rate and capability to produce large-scale components. As compared to the powder-based AM, it has higher material usage efficiency and buy-to-fly ratio. Aluminium alloys have a low absorption rate for laser and is therefore a slow process if laser-based AM is used. Therefore, arc based WBAM process is a much better option. (Köhler et al. 2019)

Wire arc additive manufacturing (WAAM) refers to AM technique that uses wire as a feedstock, and electric arc as the heat source. Different arc welding processes, such as Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW) and Plasma Arc Welding (PAW) can be used in WAAM. GMAW requires a consumable metal wire as electrode. GMAW based WAAM can directly deposit aluminum alloy wire using welding equipment without any need of auxiliary apparatus. GTAW and PAW require non-consumable electrodes and need separate equipment for the supply of wire. Therefore, it is easier to automate using GMAW than GTAW and PAW (Wu et al. 2018).

There are few limitations of using GMAW, as the process induces lot of heat and has poor arc stability, which affect the dimensional accuracy. Cold Metal Transfer (CMT) is a type of GMAW process, modified such that the motions of wire are combined with the process of welding. CMT process has well defined connection between the molten drop transfer and the wire feeding motion. In the CMT process, when the metal feed wire moves towards the substrate, an arc at the tip of the wire begins. There is a boost in the arc as the wire starts to get closer to the weld pool. As the tip of feed wire contacts the weld pool, there is a short circuit in the system. When there is a short circuit, the wire is retracted up to a certain height. During this retraction, droplet is detached from the tip of the feed wire and goes to the weld pool.

Due to the short circuit and consequent retraction of the wire, less heat is generated at the weld pool. The CMT-WAAM system consists of computer controller, wire feeding motor drive, robot and welding equipment as shown in Figure 1. There are different variants of CMT, which include conventional CMT, CMT pulse (CMT-P), CMT advanced (CMT-ADV), CMT pulse advanced (CMT-PADV) and variable polarity CMT (VP-CMT). (Schorghuber 2005)

The mechanical characteristics of the CMT-WAAMed part are not very good. Various modifications are to be made for improvement the mechanical characteristics, mainly by reducing the porosity content. The conventional CMT is also just capable of producing layer-by-layer, which is to be improved upon (Danielsen Evjemo et al. 2017).
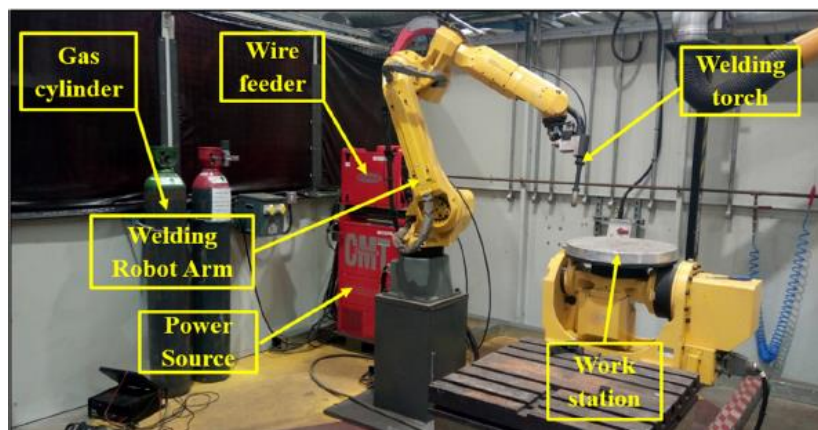
Figure 1. CMT-WAAM workstation (*Derekar et al. 2020*)

2. Methods

CMT is a relatively recent development in the field of welding. This technology is patented by Fronius International GmbH. The patent was searched on 'Google Patents' database and was found to be patented in the year 2005. This patent was the first reference that was chosen.

The database 'IEEE Xplore' was also used and searched for 'Cold metal transfer additive'. 1 paper was selected out of the search result based on the title of the paper.

A search on 'Google Scholar' and 'Scopus' for 'CMT aluminium alloy additive' was done. After skimming through the summaries of around 10 papers, it was found that surface quality and porosity were major concerns in CMT-WAAM.

Another search was performed on the same databases by using the terms 'CMT', 'aluminium', 'additive', 'WAAM' with possible relevant combinations. 16 papers which seemed to be relevant were selected based on the title. After studying the papers, 7 papers were found most relevant.

The total number of reference material selected were 9, including a patent. The papers were not filtered based on their publication year, as the CMT process was invented not too long ago. The chosen reference materials other than the patent were published between the years 2014 to 2020.

3. Findings

CMT based WAAM process for AM of aluminium is advantageous over other WAAM processes, as there is good dimensional accuracy and a greater heat control during the process. However, the mechanical properties and the surface finish were poor for the components manufactured by CMT method. Porosity was found to be the major reason for the poor mechanical properties. The surface quality of component was found to be affected by the process parameters and the quality of the wire being used (Cong et al. 2015; Derekar et al. 2020; Gu et al. 2016; Wu et al. 2018).

3.1. Porosity

Porosity in aluminium alloys is present mainly due to the undissolved hydrogen. The undissolved hydrogen is due to the solubility difference between the liquid and solid states. The porosity is also found to be related closely to the grain size. The alloying elements and process parameters are found to impact the porosity. Different arc modes, process such as interlayer rolling are found to be effective in reducing porosity (Derekar et al. 2020).

3.1.1. Arc mode

The kind of arc mode used for the CMT process had a significant impact on the porosity. VP-CMT was compared with the conventional CMT mode for Al-6Mg material, and it was found that VP-CMT produced superior quality product with fine equiaxed grains. Conventional CMT, CMT-ADV, CMT-P and CMT-PADV processes were tested with the same process parameters to find their impact on porosity on the aluminium alloy, Al-6.3%Cu. Figure 2 shows that there was significant reduction of number of pores by using different arc modes. Visible impact was seen in CMT-ADV and CMT-P modes. The CMT-PADV mode was observed to be best for reduction of pores for single layer, as well as multiple layers. CMT-PADV process produced the finest equiaxed grain structure and almost eliminated all the pores. The reason for porosity elimination by CMT-PADV was due to a low heat input and fine equiaxed grain structure (Zhang et al. 2018; Cong et al. 2015).
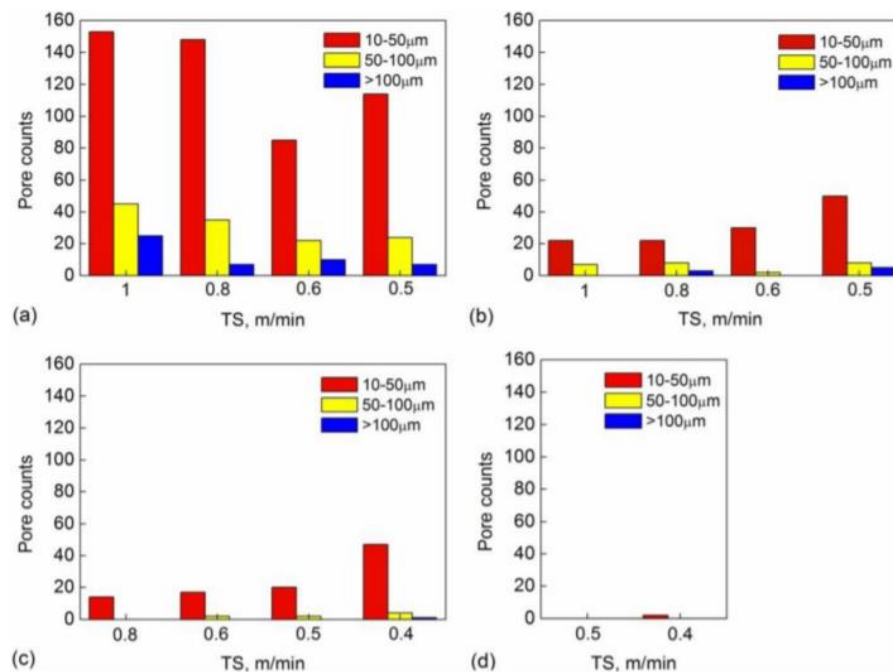
Figure 2. Pore counts of single layer sample deposit: (**a**) CMT, (**b**) CMT-P, (**c**) CMT-ADV and (**d**) CMT-PADV (Cong et al. 2015)

3.1.2. Inter-layer rolling

Inter-layer rolling was found to be effective in eliminating the pores. Two aluminium alloys, Al-Cu6 and Al-Mg4.5, were investigated by using inter-layer rolling process. Rollers were used to roll on the deposit after each layer is deposited, up to a height of 10mm. Loads of 15kN, 30kN and 45kN were applied on different samples. For the 15kN rolling load, there was decrease of pores by 68.7% for Al-Cu6 and about 26% for the Al-Mg4.5 alloy. However, it was found that all pores within the optical resolution were eliminated when the rolling load was increased to 45kN (Gu et al. 2016).

3.2. Surface waviness

The quality of the surface produced depends on several controllable parameters. The adjustable measures that affect the surface quality include quality of feed wire and the arc length (Köhler et al. 2019; Gu et al. 2014).

3.2.1 Arc length

The arc length is directly related to the heat input. The corrections made on the length of the arc affected the pulsed voltage and the retraction of the wire. Correction of arc length was made to have the best surface finish. The positive correction, by increasing the arc length, led to uneven of droplet transition. The surface waviness and drop transition were found to depend on the arc length (Köhler et al. 2019).

3.2.2 Quality of wire

Five wires of the same material (ER4043) were used to study their impact on the quality of deposition. Wires which were having the least scratches and pits were observed to have better quality of deposition. Wires that were exposed to

oxygen also did not perform well. Smooth and unoxidized wire was found to be having least surface waviness (Gu et al. 2014).

3.3. Robotic manipulator

To produce large-scale products, AM is beneficial if combined with robotics. Use of robotic manipulator in all the WAAM processes is difficult. CMT -WAAM is a feasible alternative, as it produces good quality of strings. Control programs were designed, trajectory path was designed and a proof-of-concept work for the CMT-WAAM by robotic manipulator to test various parameters. An Industrial robot with 6 degrees of freedom (DOF) was found better to produce large components. 6 DOF has an advantage over 3 DOF, that are used in traditional 3D printers, that there is more flexibility to build a part. This process would pave way for real-time compensation and repair. This flexibility to print in any direction combined with good path planning would mean faster production at lesser cost (Danielsen Evjemo et al. 2017).

4. Discussion

CMT is an advanced welding method that can be used for AM of metals, developed to overcome the drawbacks of the GMAW process in WAAM. The mechanical properties of CMT-WAAM manufactured parts was found to be low, and the major reason for this was found to be porosity. CMT-WAAM manufactured parts were also found to have surface waviness, some of the reasons being the undesirable arc length and poor quality of wire (Cong et al. 2015; Derekar et al. 2020; Gu et al. 2016; Wu et al. 2018).

Major reason for porosity in CMT produced WAAMed part was due to entrapment of hydrogen gas in the material. Varying the arc modes proved to be effective for reduction of porosity, and CMT-PADV mode was found to be the best arc-mode to reduce porosity. Interlayer rolling process also helped in reducing porosity to a great extent. The surface finish was best when the quality of wire used was good and the process parameters such as arc length was optimal (Derekar et al. 2020; Gu et al. 2014; Köhler et al. 2019).

Use of robotics combined with additive manufacturing helps build complex parts, more conveniently. Robotic manipulators with 6 degrees of freedom with proper path planning would benefit the CMT-WAAM process. Future research in the field of robotics for AM holds good scope (Danielsen Evjemo et al. 2017).

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct ([https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf](https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf)), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Cost-efficient prosthetic arm by using Fused Deposition Modeling†

Harsh Phaneendra Rao Vaddipartti [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: harsh-phaneendra-rao.vaddipartti@s2019.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: The objective is to investigate the cost efficient and light weight production process of prosthetic arms by using Fused Deposition Modeling (FDM). For writing this review paper, different research articles relevant to FDM technology and prosthetic arms were considered and it is found that multi-material 3D printing is much better than single material prosthetics when it comes to functional and ergonomic aspects. Better dimensional accuracy of the prosthetics can be achieved by computer tomography by scanning the body parts. For the future of lightweight prosthetics, Fused Deposition Modeling is a much better alternative as compared to the conventional production process.

1. Introduction

Due to increase in vehicle accidents and war like situation, people are losing their body parts. It is estimated that those who need prosthetic devices in developing countries are approximated to be 31 million individuals. The cost of conventionally produced externally powered prosthetic arms ranges from $25000 to $50000, which makes them difficult to afford by everyone (ten Kate et al., 2017). The conventional process for the prosthetic arm production requires higher lead time and it has low degree of customization. 3D printing especially Fused Deposition Modeling (FDM) comes into role to overcome the challenges faced in the conventional production process of prosthetic arms. It can be used to produce user customized prosthetics at very affordable price ranging from $300 to $2000 (Cabibihan et al., 2018). A sudden shift in the cost to produce prosthetic devices can be attributed to expiry of first patent on Fused Deposition Modeling in 2007 (Takagishi & Umezu, 2017).

Fused Deposition Modeling (FDM) is an Additive Manufacturing process in which a thermoplastic filament is heated above its melting point temperature and then deposited layer by layer through a nozzle to form a 3D object (Carneiro et al., 2015). FDM can be used to produce complex shape geometries with zero material wastage, which is not possible by the conventional production process. Body compatibility and ergonomic aspects of prosthetic arms are one of the major requirements of the amputee. Functional and compatible prosthetics can be produced by using multi-material 3D-printing. Wide range of filament materials in FDM technology make it suitable for multi material 3D printing. Material such as "Thermoplastic Elastomer" (TPE) is a class of elastomer that can be used to produce the soft functional components in prosthetic arms for better comfort (Bachtiar et al., 2020).

Conventional measurement methods for measuring the amputee body parts are time taking and less accurate. For accurate prosthetic dimensions, computed tomography (CT) scanning can be used to get accurate dimensional parameters of the affected and unaffected arms, based on which the prosthetic arms with the better dimensional accuracy can be 3D printed (Cabibihan et al., 2018). The patient does not have to get measured by the prosthetists or designers because the measurements are directly taken from the CT data. This approach allows the patient to be minimally exposed to the public. The **Figure 6** (a) shows the mirrored CT model of the patient's undamaged arm vs final prosthetic arm. To know the dimensional accuracy of the mirrored CT model of the patient's arm compared to final prosthetic arm, Boolean subtraction was carried out as shown in **Figure 6** (b). It was found that the proposed method has shown a high dice similarity coefficient of 0.96. Which implies that prosthetic arm is in close agreement with the mirrored image of the patient's injured arm (Cabibihan et al., 2018).
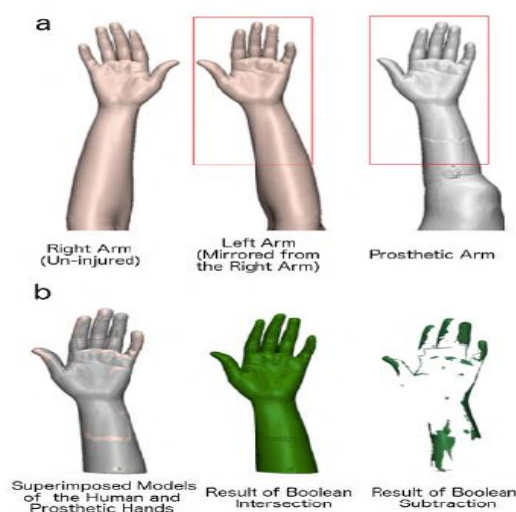
Figure 6. (a) Mirrored CT model of patient's undamaged arm vs prosthesis (b) Boolean intersection and subtraction of prosthetic arm vs mirrored CT model of human arm (Cabibihan et al., 2018)

2. Methods

To write this review article, database such as Research Gate, Science Direct, and Springer link were used. For selecting latest relevant articles, articles from 2015 to 2020 were considered. Search methodology for finding the research papers were as follows: key words such as "3D-printed prosthetic arm", "Fused Deposition Modeling", and "Prosthetic Arm" were searched in search database. After searching each keyword individually, first 10 search results were taken into consideration. From the searched articles, relevant content for the prosthetic arms was considered for the selection. Then from the most relevant articles, cross-referencing is done to get further relevant articles for writing this review paper. The literature search was carried out until the best 7 relevant articles were found for this review paper.

3. Results

3.1. Single-material 3D printed prosthetic arm

It is difficult to produce the cost efficient, light-weight prosthetic arms for individual patients by using the conventional manufacturing methods. These challenges can be overcome by using Fused Deposition Modeling. 3D printing provides high level of customization in the prosthetic arms as per the individual requirement and the production cost of the FDM printed prosthetic arms are much cheaper than the conventionally produced prosthetic arms. The 3D printed prosthetics cost one-tenth of the conventionally produced prosthetic arms (Cabibihan et al., 2018). The Figure 7 demonstrates the basic prosthetic hand produced by FDM process using Polylactic Acid (PLA) filament. The input data for designing the prosthetic arm is considered by measuring the unaffected body part of the patient. It is equipped with 5 motors for five-finger action and a motor for wrist rotation. Different parts of the prosthetic arm were joined by using nut and screws. There is significant weight reduction observed in this 3D printed prosthetic arm. It was developed for a person with a weight of 70 Kg, and it weigh only 750 grams whereas original arm weigh about 1610 to 2030 grams. It can be used by the patients to hold and place objects, food cutting and many more operations (Hagedorn-Hansen et al., 2018).

Figure 7. Single material 3D printed prosthetic arm (Hagedorn-Hansen et al., 2018)

3.2. Multi Material 3D printed prosthetic arm

One of the major barriers for adaption of the 3D printed prosthetic arm is limited compatible material for the use with the technology. Prosthetic arms produced by 3D printing of a single material have limited functionality, which leads to low active use and prosthetsis abandonment. However, there is a scope for improving capabilities of low-cost prosthetics by using multimaterials, which can add the functionality such as flexibility to the prosthetics (Bijadi et al., 2017). The Figure 8 demonstrates the multi-material prosthetic arm. The dimensions of the prosthetic arms were considered by manual measuring of the unaffected arm. Two classes of material: Polyacetic Acid (PLA) and Thermoplastic Elastomer (TPE) were investigated while building this prothetic arm. PLA is used for the 3D printing   of structural parts, whereas TPE is used for the flexible joint, which can join the structural parts. The TPE joints eliminates the need of the fasteners or pins required for assembly of different parts and facilitates more natural motion. TPE was further used to develop soft skins, grips, and custom paddings to improve ergonomics and tactile experience. As the major big components in this prosthetic arm were made from PLA material and only joints were made from the TPE material, due to which there was no significant change in the weight and cost as compared to single material prosthetics. But significant change in ergonomic comfort was observed by the patient in multi material prosthetics (Bijadi et al., 2017).
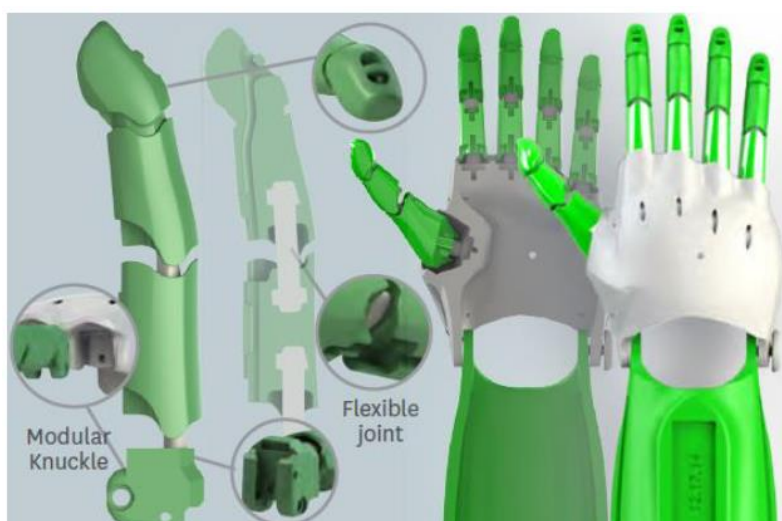
Figure 8. Multi-material (PLA body + TPE joints) prosthetic arm (Bijadi et al., 2017)

4. Discussion

Single material and multi-material prosthetic arms assisted by Fused Deposition Modeling are studied in this review paper. Prosthetic arms produced by Fused Deposition Modeling are up to 50% lighter than natural arm and by using single PLA filament material in FDM, up to 90% cost reduction can be achieved compared conventionally

produced prosthetics (Hagedorn-Hansen et al., n.d.-b). Multi-material prosthetics have better functional capabilities as compared to single material prosthetics. TPE joints in multi-material prosthetics helps to achieve more natural movement and it eliminates the need of fasteners and pin to join the different part. As in multi-material prosthetics TPE is only used in joints and rest is made of PLA, due to which no significant difference in terms of cost and weight was observed compared to single material (PLA) prosthetics (Bijadi et al., 2017; Hagedorn-Hansen et al., n.d.-b). CT scanning technology for measurement of the body parts is a better method to produce dimensionally accurate prosthetics (Cabibihan et al., 2018). Based on the mirrored CT scanned image of unaffected arm, CAD model of prosthetic arm can be developed, which can be further used for the 3D printing of prosthetics (Cabibihan et al., 2018). By using Fused Deposition Modeling with multi-material and CT scanning technology, a better patient specific cost-efficient prosthetic arm can be produced, which can provide better comfort to the amputee (Bijadi et al., 2017; Cabibihan et al., 2018; Hagedorn-Hansen et al., n.d.-b).

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

3D printing in the automotive market†

Abdalla Elhalwagy [1],*

[1] Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: abdalla.elhalwagy@s2020.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: this paper aims to enhance the industrial process in the automotive market and to provide more and more easy usage through the use of 3D printing. Since its beginnings, 3D printing has obtained great, industry-wide acceptance as a manufacturing technique in the automotive industry. By reading the results of this paper it can be seen that this technology already makes the processes of making cars are more quality with reduced costs. Turning to the discussion and conclusion, it can be also realized that as companies can test for a quality way before the production starts and also for some components, customized tools need to be made for certain designs which are time-consuming and expensive. AM takes away this dependency on OEMs.

1. Introduction

The concept "3D printing" can describe a range of procedures in which a needle is inserted, connected, or solidified via computer control to build a three-dimensional object, often layer by layer, with material (such as polymers, liquids, or powder grains) being placed together (Sharma & Garg, 2016). Previously, some automotive equipment, such as lighting, mirror brackets, and dashboard components, took a long time and a lot of effort to finish at the production line. The design of such elements considerably increased the amount of financial and human resources required to completely construct autos for retail (Jiménez, Romero, Espinosa, & Domínguez, 2019). today, People can utilize 3D printing to manufacture complicated automobile components that can be used for numerous manufacturing applications by using computer software to design items (ICHIDA, 2019). The automotive market is one of the fields that has profited greatly from the development of 3D technology. Nonetheless, by using 3D modeling on a wide scale, the automotive industry has drastically lowered total operating expenses (Manghnani, 2015). The expenses cited are the expenses of engaging teams of highly experienced individuals to make a single automotive part that can now be made by a single 3D machine. Now, 3D technology is being used by a variety of automotive manufacturers in various countries (Mpofu, Mawere, & Mukosera, 2018). The technology is still steadily getting prominence nowadays, and it is probable that in the future, all vehicle manufacturers will depend heavily on 3D printing to improve their automotive production process (Beiderbeck, Deradja, & Minshall, 2018).

3D printing can be employed as an effective intervention for optimizing the production process of cars in the car sector. In the car production process, 3D printing has also greatly shortened the time required to produce a single car (ICHIDA, 2019). 3D printers have enabled the production of sensitive car parts in a couple of hours (Beiderbeck, Deradja, & Minshall, 2018). As a result, the total time required to finish the assembling of a single unit in the automotive sector has decreased (ICHIDA, 2019). Companies that use 3D printing technology in the automotive manufacturing industry have significant market strategic advantages over their competitors. Also, by adopting 3D printing, automotive manufacturing companies may adapt to the complex shape and acquire distinct customization capability while producing different vehicle components for the worldwide market (Jiménez, Romero, Espinosa, & Domínguez, 2019). Furthermore, the ongoing utilization of 3D devices has helped automotive designers to make models and one-of-a-kind concept vehicles, which play an important role in shaping the future of autos and automotive technology development (Jiménez, Romero, Espinosa, & Domínguez, 2019). As a result, there is a need for a considerable study to be conducted to determine the influence of 3D printing on improving the business of the global automotive manufacturing industry nowadays (Jiménez, Romero, Espinosa, & Domínguez, 2019).

2. Methods

Only previously published papers, scientific, educational research, and review articles in journals published in 2015, 2017, 2018, and 2019 were investigated for the research project. This literature is gathered using recognized databases like Google Scholar, science direct, research gate, Hindawi journal, and international journal of research in aeronautical and mechanical Engineering

Synonym keywords used for searching for this topic are the auto sector, automotive industry, and rapid prototyping. When doing this research paper, many topics occupied especially relating to additive manufacturing with its easy influence to change or revise versions of a product in different fields including medicine, building, and automotive sector.

Before beginning to analyze and synthesize the articles that have been selected, each article was read quickly and skim through to get a sense of what they are about and also to know the most common between them and what is the difference between them and This will help ensure that this literature review is organized by subtopic, not by source. Also, help to define terms and variables for this area of research.

This paper is based on an interpretive approach that focuses on comprehending phenomena in a thorough, holistic manner. This study can detect the link between this new issue and its impact on the car industry. Because this interpretive technique relies more on subjective information, it necessitates cautious flexible interpretation. Also, to promote the efficacy of 3D technology in the automotive sector, a qualitative study was conducted. A study was used to conduct the research, which was aimed at vehicle part companies at Volkswagen, Toyota, Ford Motors, Kia, Honda Motor, Mercedes-Benz, and Bugatti.

3. Results

3.1. Background Research

The general finding of the conducted literature research was that the usage of 3D technology in the vehicle production sector has greatly reduced the expenditures or expenses previously incurred by automakers (Mpofu, Mawere, & Mukosera, 2018) (Sreehitha, 2017). As a result, carmakers have been able to reduce the cost of their products for clients, which is also a tactic used by such organizations to resist the market's fierce rivalry (ICHIDA, 2019) (Sreehitha, 2017), (Sharma & Garg, 2016). Besides, research has shown that using 3D printing in research has enhanced the value chain of vehicle retailing firms by raising the number of products manufactured and supplied to market clients (Mpofu, Mawere, & Mukosera, 2018). Furthermore, 3D printing has enabled innovative automotive and aircraft items to be created and supplied for market users faster than previously (Mpofu, Mawere, & Mukosera, 2018). The usage of additive manufacturing has also aided several car manufacturing companies in achieving widespread production of whole vehicles and replacement components (Reeves & Mendis, 2015).

3.2. Analysis

As it can be seen that, the percentages represent the views of the seven participants from the seven-car production firms (Table 1). The replies obtained indicated that the qualitative researchers realized the importance of additive manufacturing (3D printing) in improving the vehicle production process. Furthermore, the data collected of each element of the 3D printers had a higher proportion, indicating that the seven firms have already enjoyed the benefits of adopting 3D printing technology in their production process. The results demonstrated that using a 3D printer reduces the cost per unit of every car manufactured by a car industry firm. As a result, the cost per unit of all vehicles manufactured utilizing 3D technology is reduced. Furthermore, using 3D printing reduces the cost of manufacturing for auto manufacturing firms. Finally, this technology dramatically increases the net revenue and profitability of the overall market of car industrial companies. Automotive companies are now working on new metallic materials for 3D printing. Ford is developing lightweight cast materials for 3D printing which would replace metal casting and increase the fuel efficiency of the cars. GKN additives have prepared CuCr1Zr alloy which has 90% of copper's conductivity. However, the alloy has higher 3D printability and strength than copper.

Table 1. Data collections from different companies show the influence of using 3D printing in the automotive sector.

Element of 3d researched \ Company	Volkswagen	Toyota	Ford	Kia	Honda	Mercedes	Bugatti
Facilitate customization of car parts	%97	%98	%99	%94	%96	%98	%99
Cost manufacturing saves	%97	%96	%95	%99	%99	%98	%96
Allowance of creation of complex parts	%99	%99	%99	%99	%99	%99	%99
Revenues and profitability from using this technology	%99	%99	%99	%99	%99	%99	%99
Enhance the manufacturing cost/unit	%97	%98	%96	%98	%99	%99	%99
Average	%97.8	%98	%97.6	%97.8	%97.5	%98.6	%97.8

3.3. D Printing issues

The application of 3D printing in the automotive industry has been affected by a variety of issues, including the high cost of obtaining 3D printing materials and technological limits in production equipment (Mpofu, Mawere, & Mukosera, 2018). Other issues include scalability operations, a sufficient lack of experience in 3D programming, and constant modifications in 3D software programs due to innovation, resulting in the requirement to get new printing technology frequently (Mpofu, Mawere, & Mukosera, 2018). Nonetheless, despite such challenges, the 3D technique has been increasingly accepted by the auto industry and has considerably transformed the way automobiles are manufactured in today's modern civilization (ICHIDA, 2019). On the other hand, there is a scarcity of major published material objectives of this project of 3D technology used in the automobile sector (Yewale & Sarvankar, 2019). While 3D printing can manufacture products out of a variety of polymers and metals, raw material availability is limited. This is because not all metals or polymers can be thermally regulated to enable 3D printing. Furthermore, many of these printing materials are not recyclable, and only a small percentage of them are food-safe (Sreehitha, 2017). AM is still being used in the automotive industry by adding it into its current capacity. However, neither goods nor supply chain applications have seen considerable innovation. Vehicle firms should consider other options for generating long-term value. Auto manufacturers must adapt to the new norms of the market as the life cycle of new vehicle models shortens, and AM can help by reducing design-to-final production time and allowing the fabrication of complicated parts that meet high-performance criteria (ICHIDA, 2019).

4. Discussion

The usage of 3D printing in the automobile sector has grown dramatically over the last decade, hence it is likely to rise further in the following financial seasons. According to (Sreehitha, 2017) the 3D printing market in the auto sector is predicted to reach $2391 million before 2022. According to (Thryft, 2013), The 3D printing sector is expected to develop at an unprecedented rate, with market experts projecting an 18% increase year on year. The 3D printing technology part market is expected to develop to an $8.4 billion industry by 2025. Parts sales for automotive and airplanes are expected to be the highest. The increase in using 3D printing has already been related to the cost-saving advantages that the technology provides to automotive manufacturers in the production of high-quality vehicles. The application of 3D technology in the auto industry has also been confirmed by a study conducted by (Mpofu, Mawere, & Mukosera, 2018), which depicts its influence on improving an industry's production process. Based on the current research, 3D printing has enabled automotive and aircraft parts to be built more quickly and effectively, a phenomenon that has benefited the value chain (Mpofu, Mawere, & Mukosera, 2018).

According to the different studies done by (Reeves & Mendis, 2015), the usage of 3D technology has succeeded to revolutionize the industrial worldview. Furthermore, 3D in the automotive market has facilitated the accomplishment of the mass-manufacturing process in central plants, which were previously limited by tooling as well as massively cheap labor costs (Reeves & Mendis, 2015). According to various research studies by (Sharma & Garg, 2016), additive manufacturing technology (3D) is already being used by major auto companies such as BMW, Royce, and Bentley in the creation of sturdy and resilient automobile parts. Due to the increasing demand for cars in most regions around the world, the automotive sector has been characterized by strong rivalry during the last decade. Depend on a study

conducted by (Yewale & Sarvankar, 2019), The usage of 3D printing as an option for flexible manufacture of unique items has been used. That is, without having a substantial influence on the leading time and expenses spent by auto companies. As a result, such auto manufacturing businesses have been capable of producing high-quality products at cheaper costs, allowing the companies to compete successfully in the global market.

5. Conclusion

Finally, 3D software may be employed as an appropriate approach for optimizing the automotive production process in the automotive market. Furthermore, 3D printing began as a technology for generating solid structures by printing consecutive layers of materials. However, 3D technology is now widely used in the automobile industry as a low-cost and time-saving way of automobile development. Certain automobile elements, such as headlights, mirror brackets, and dash components, among others, may be easily made using 3D printing. Additionally, the usage of additive manufacturing has aided car companies in optimizing their value chain and assisting car businesses in securing mass production of automobiles for the accessible worldwide market. Furthermore, auto companies have been able to carry out huge manufacturing of spare components for cars using 3D printing. In addition, prominent vehicle manufacturers such as BMW, Bentley, and Rolls Royce have used 3D printing technology to create robust and long-lasting automotive parts. As a result, the use of 3D printing in most firms in the automotive sector has increased dramatically. As a result, all other vehicle manufacturers must use 3D technology to increase the size of their production processes.

Overall, it is clear that 3D printing has provided several benefits for the automotive industry today. As a result, all automakers should endeavor to integrate and implement additive manufacturing into their vehicle production processes. Furthermore, such 3D technological innovation should be included in the present and future goals of automotive manufacturers (ICHIDA, 2019). Also, it's likely that, in the long term, the whole vehicle production industry may use 3D technology to overcome the difficulties of generating undercuts and geometrically complicated designs of automobiles. in particular, those are the elements, that might be extremely difficult to produce using standard vehicle production processes (ICHIDA, 2019). Finally, based on the statistical data presented, evidence provided by vehicle manufacturers, and potential applications, it is clear that 3D printing, together with its technologies, will change the next industrial age.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

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Review article

Examining the scope to use real-time monitoring of Seam Geometry in Welding operations[†]

Nitin Kumar [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: nitin.kumar@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Weld seam is very important part of the welding process. The seam geometry influences the quality and reliability of the weld joint. In this paper, different methods of seam tracking are reviewed. This paper focuses on non-contact sensors for robotic seam tracking and its principles. Non-contact sensors are either based on electromagnetic or acoustic principles. In electromagnetic sensors, eddy currents are induced in the low-frequency domain for detection of surface irregularity. An offline programming technique for the path planning of the robot end manipulator from seam tracking devices is stressed upon and the laser-based vision sensor is discussed in detail which was fabricated based on the principle of laser triangulation. A Further idea of controlling seam geometry can be helpful in Wire Arc Additive Manufacturing process (WAAM), is presented.

Keywords: Welding; Laser triangulation; Seam tracking; Feature extraction.

1. Introduction

Additive Manufacturing has made significant developments and achieved new goals in recent years, the research of previous years has started to make into the industry and provided significant alternatives for manufacturing of different products ranging from plastics to polymer, metal and material combinations along with hybrid materials. Wire arc additive manufacturing process has also made good progress through scientific fields with more and more research directed towards this, which uses same principle as Gas Metal Arc Welding. One of the primary important parameters which are focused upon in welding processes is seam geometry and tracking of seam in real time to control the weld bead progression along with adapting to changes during the process that can produce a good quality weld. A weld seam is characterized by its profile which contains top bead, root widths, flank as well as convexities, concavities and undercuts. Seam tracking is critical to weld quality and productivity, is one of the key issues in the welding process. Around the world, research is in progress to develop general purpose sensor which can be used for automatic seam tracking along with adaptive control feature.

Many developments have been made in contact and non-contact seam tracking systems and a few have been made commercially available like Robo-find, Power-Trac; Servo Robot Inc. (Kah, Shrestha, Hiltunen & Markikainen, 2015). Nevertheless, none of these systems can be shown to meet all the requirements of the arc welding users. The following points have been contemplated as important for an automatic and adaptive seam tracking system for real-time control of seam geometry:

1. General Purpose: the same system should fulfill the requirements of different geometries.
2. Robustness: the same must function in an industrial environment (subject to harsh conditions around the arc).
3. The system should provide a three-dimensional information of the seam and fit up.
4. Sensing devices should be relatively small (in size), to operate with motion of welding torch.
5. The system should operate in real time: Positions and weld parameters can be adapted to situation during process.

Different types of approaches and methods are discussed in this paper ranging from tactile and non-tactile seam tracking systems. However, the attention here is towards non-tactile systems, fundamentally there are only two ways in which information can be transmitted in such systems: by acoustic waves or electromagnetic waves. A wide spectrum of frequencies is available, in which these sensors can operate. Magnetic sensors emit electromagnetic waves at a frequency between 10 to 100 KHz. Systems based on arrays of photodiodes, laser scanners, weld pool vision systems and

laser light stripe systems use frequencies for approximately 100 THz. The speed of sound and speed of light has a large difference between them, and this makes the basic difference in how geometric information can be obtained through acoustic and electromagnetic waves. The method of laser triangulation is used to compute the distance between the sensor and the surface of the object, used in optical systems operating at a few centimeters (Nayak, 1993). One another non-contacting seam tracking systems, arc sensing - which uses the principle of measuring change in welding current and arc voltage can also be used only if certain geometries conditions are met. There are many contact and non-contact sensors developed for seam tracking and with help of robotics, automatic seam tracking is possible to provide accurate data and produce a good quality joint.

Study of various seam tracing systems which are being currently used or in development stage and their principles have been reviewed. One method is also being specifically described for automatic seam tracking with laser-based vision sensor – designed and fabricated on principle of laser triangulation, image processing module and a multi axis motion control module to provide more understanding.

2. Methods

The vision of this work was agreeing with Aquino (2008), that the literature review needs to be addressed in a scientific way. A thorough study of the literatures underlined the search strategy. Earlier established work and conducted research presented comprehensive outline. The search was conducted specific keywords – 'seam geometry', 'robotic welding' and 'real time monitoring of weld'. Different data sources and research papers published by academicians found on Elsevier, Springer & google scholar. With the initial theoretical framework, the theme was delimited based on the research question (Perroni et al. 2014). The search strategy was defined with clear objective to find about different methods which was invented or discovered or devised to monitor the weld seam geometry in real time.

3. Findings

A no. of different seam tracking systems developed, and research is still in progress. Out of them a few of non-tactile systems have been presented here based on principle of acoustic and electromagnetic waves information.

1. **Systems based on vision and light** - A camera and structured light source are used in this, mounted on some arrangement moving ahead of welding torch. A pattern of lines or grid is projected from the light source at a certain angle onto to the object's surface. The angle between the optical axis of the camera and light source is constant. The 2D image from camera along with projected light stripe principally allows a 3D reconstruction of the welding joint or seam desired for process. Development of the improved vision system has been carried out in research and several improved systems proved to give better results than before. SRI (Chin, Madsen & Goodling, 1983) has developed a procedure for constructions of weld joints based on vision data and this system has been successfully used to control the motion of robot in welding of low carbon, hot rolled steels plates. Although the idea to use light stripe from laser or any other source seems interesting but there are a few drawbacks which cannot be overlooked and must be reduced to minimized in order to use this arrangement. The dimensions sensory equipment (camera and light source) normally moving ahead of the welding torch may prevent it to access the corners in complex geometry of the products. The distance of light stripe system, projecting light on the object and the welding torch limits the radius of trajectories. The long exposure of the camera and light source to the welding environment, dust and spatter, results in reduced intensity and decreased resolution. Interference of bright arc with the illuminating system represents a serious shielding and noise filtering problem. Both image and 3D image characterization by triangulation require significant computational support, which is a point to be of economic concern in the process. Figures 1 (Nayak, 1993) & 2 (Haung & Kovacevic, 2012) will help in better understanding with respect to above-described method. The noise due to arc can be handled using two pass filters, Gaussian filters help to take care of the desired frequencies. The camera performs the scan, locating and characterizing the seam, this information is required to adjust the nominal welding path. After completing the scans, the welding process starts with the information available and following the seam geometry while adjusting the torch points. The scan cycle is carried faster than the welding cycle. The problem of local distortions can be avoided in this and is of significant concern to avoid this by modifying the method as per the desired welding need and product geometry. Local distortions are caused by thermal expansions of the material. Also, focused laser beam can be used for scanning the object or required seam as compared to stationary light source.

2. **Acoustic Waves** - Acoustic waves can be utilised to characterize the dimensions of the workpiece surface. A pulse technique originally developed by Pellam and Galt (Pellam & Galt, 1982), to extract the range information. The sensing system utilises the piezoelectric transducer to convert electrical energy into ultrasonic energy and vice versa. The same sensor can be used as receiver and emitter. Ultrasonic waves propagated through air attenuated in proportion to the square of the frequency and a resonant frequency can be chosen for the purpose. Acoustic waves are temperature dependent on the speed of sound, which creates a problem while using this principle.

3. **Infrared** - Infrared Thermography can be used for arc misalignment, groove geometry faults, variations in penetrations and impurities in the weld pool as suggested by the study (Drews, Starke & Willms, 1980). To fully expedite the potential of this technique is still under research to make it useful for adaptive welding control.

4. **Arrays of Photodiodes** - P Drews (Drews, Starke & Willms, 1980), at the university of Aachen, developed at robust seam tracking system. A halogen light source is transmitted via fiber optics to the sensor system in this tracking system. An array of 256 photodiodes measures the reflected light intensity when an elliptical light spot is projected on to the joint. The recorded intensity pattern is then related to the actual geometry of the weld joint. The seam geometry is found by determining the relative intensity normal to the seam trajectory. Lower density indicates a longer distance between the sensor and the surface of the workpiece.

5. **Through the arc sensing** - The most common non-contacting seam tracking system uses arc feedback as the basic control signal. It has been shown with previous experiments and measurements the average welding current and average arc voltage is proportional to the distance between the electrode and the workpiece (Cook, 1983). With an execution of weaving motion with the welding torch normal to the seam trajectory reveals the surface of the joint. Weaving motion is obtained by simple mechanical oscillations or by having a plasma oscillate in an alternating magnetic field. Higher the oscillations, more precise the seam characterization can be accomplished with the alternating magnetic field. A space intrusion problem may be involved with this method as the magnetic field generator is mounted close to the welding torch tip. There can be two significant problems that may arise in this method, first – the dimensions of the joints must exceed some critical dimension and another, signal can be obtained only after the arc has been established. Hence this method cannot be used to find the starting point of the weld.

The concept of using vision and light sensors is demonstrated in above two. The system allows the seam information to be collected by the vision sensor to guide and control the welding torch in real time as well as position the sensor for the next scan. There are three main modules – a laser-based vision sensor module, an image processing module, and a multi – axis motion control module. The laser-based vision sensor is designed and fabricated based on the principle of laser triangulation. By using available platform such as LabVIEW, algorithms can be developed for image processing from the images captured by the vision sensor – identifying different types of weld joints and detecting feature points (Haung & Kovacevic, 2012). Based on the detected feature points, the position information for the welding torch and the geometrical features of the weld such as – depth, width, cross- sectional area can be obtained in a real time. This data can be fed to the multi-axis motion control module, a non-contact seam tracking is achieved by adaptively adjusting the position of the welding torch with respect to the depth and width of variations. A 3D profile of the weld joint can also be obtained for in-process monitoring and post-process quality inspection. (Nayak, Thompson, Ray & Vavreck) & (Huang & Kovacevic, 2012). Fig. (1) showing laser triangulation principle (Nayak, 1993).
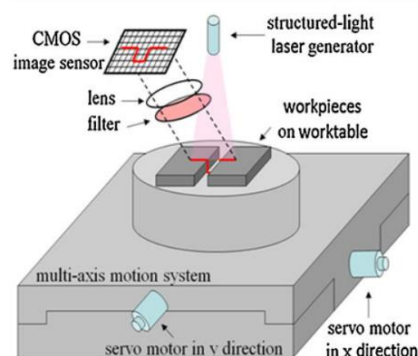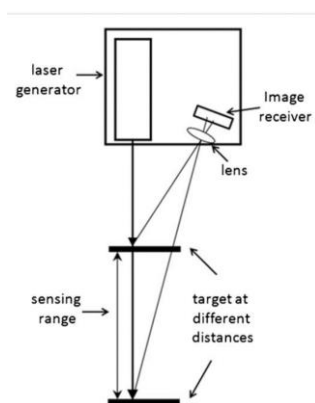
Figure 1. Principle of laser triangulation (Nayak, 1993).

Figure 2. Experimental setup of the laser-based machine vision system (Haung & Kovacevic, 2012).

4. Result/Discussion

With respect to real time seam geometry control, vision and light-based sensors can be proved to be more advantageous as developments has been in progress on these for the use in automatic welding process. This will fulfil two of the purpose namely:

1. Seam tracking meets the need to fully automate the welding process.

2. The requirement of seam tracking is necessary to compensate for the weld deformation (local) due to thermal distortion and gravity distortion. Proper attention should be given in design phase to minimise these distortions. An experimental setup of the laser-based machine vision system is shown in figure 2 (Haung & Kovacevic, 2012).

5. Conclusion

Vision & light-based methods can be used in WAAM process to control seam geometry in real-time. A concern to produce the corner details in a product must be taken care in process of designing the part and generation of layers giving attention to such details with respect to WAAM, so that the arrangement of sensory system will not hinder the path of welding torch. There is no general sensory device available or image processing algorithm available for WAAM process. With the ongoing research, it will be good to develop process specific devices for the seam tracking and monitoring of real time seam geometry along with image processing module so that process relevant advancement can be made.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Finishing of Additively Manufactured Components by Burnishing – an Overview†

Ashikul Islam [1],*

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: ashikul.islam@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Fabrication of products and parts with special characteristics is continuously increasing with smart manufacturing. It seeks for flexible systems and customizable products, which recognizes additive manufacturing (AM) as a key element. But there are some limitations in terms of product quality and reliability while incorporating AM in the main production chain. One of them is the post processing of manufactured parts. To overcome this limitation, it is necessary to choose post processing operations wisely. Burnishing is a severe plastic deformation process which has the potential to replace expensive finishing post processes. Even though burnishing is applied for conventional materials, knowledge of its effectiveness on additively manufactured materials is still limited. This review aims to fill this gap by presenting experiments on roller and ball burnishing on additively manufactured GP1 stainless steel and cold spray 17-4PH stainless steel, ultrasonic burnishing on additively manufactured 316L stainless steel and AlSi10Mg. While in almost every experiment it has been noticed that burnishing process leads the way to reduce surface roughness and increase surface hardness which develops to product stability and makes it appropriate for critical applications. In some cases, it also minimizes cost and time with simulation models. Furthermore, the experimental results conclude that burnishing process can replace a series of post processes after additive manufacturing.

Keywords: Smart Manufacturing; Industry 4.0; Additive Manufacturing; Burnishing; Surface Roughness.

1. Introduction

Manufacturers are always attempting to find a way to balance product personalization, process flexibility and market competitiveness through digital transformation process, which is part of the Industry 4.0 framework. Manufacturing processes in the industrial sector are evolving. Previously, things were made to customer specifications, which was known as Craft Production (CP) and it was done in small quantities at a premium cost. Later, mass manufacturing was developed to suit the wide range of client requirements by making low-cost goods of equivalent quality. As a result, the mass customization production (MCP) paradigm arose in order to expand the range of products required by clients. It entailed the introduction of automation, information and computer technology which resulted in a diverse range of products through faster and computerized processes, flexibility, increased production, and cost savings.

Additive manufacturing (AM) is emerging as one of the pillars of the 4th Industrial revolution, promoting proactive flexibility strategies. In contrast to conventional manufacturing, which typically involves material removal operations in order to attain a desired shape additive manufacturing is described as the process of depositing and connecting material to produce 3D objects. Additive manufacturing technologies were originally created to make parts for use in the internal product development process (rapid prototyping), but they have now been extensively improved to satisfy the needs of industrial production. In truth, such technology is well suited to take the task of producing individualized items at a low cost. But in order to effectively enable the manufacture of a wide range of individualized items, AM machines must be integrated into a manufacturing system that includes other processes.

If conventional subtractive manufacturing (SM) is still the favored method for mass production of low-complexity goods, additive manufacturing technologies can guarantee a cost reduction when high-complexity items are required. As a result, a comparison based just on production level is insufficient to fully portray the cost-effectiveness between AM and SM.

One of the key benefits of AM processes is the ability to create a final product in a single step, whereas CM procedures involve many stages and processes, meaning the transfer of semi-finished products from one machine to another

(Qaud, 2018). However, the reliability of the AM products can suffer from poor surface quality, porosity, anisotropy, lack of precision and accuracy, etc., consequently requiring additional post-processing and heat treatments (Abdulhameed et al., 2019). In fact, the aforementioned concerns must be addressed when producing components for essential applications (such as aerospace and biomedical) that require great fatigue resistance and harsh working conditions.

The advantages of finishing techniques range from increased fatigue life to increased corrosion resistance and strength. In this regard, burnishing process can successfully replace other surface finishing processes like honing, grinding and superfinishing and recent developments concern the possibility to machine complex-shaped parts.

Burnishing is a chip less severe plastic deformation (SPD) method for changing surface properties. It improves product performance by smoothing roughness by reducing asperities and reducing micro cracks and voids caused by prior manufacturing processes. The burnishing procedure allows the product to obtain a higher surface quality while also significantly improving its serviceability (Sanguedolce et al., 2021). So, this review compares how some of the different burnishing processes on additively manufactured parts to provide product personalization and open new scenarios to companies, allowing other technologies to be adopted, thereby expanding the optimization area.

2. Methods

Unlike traditional manufacturing, additive manufacturing (AM) enables for the fabrication of near-net shape products in a single step, reducing intermediate component relocation stages from one machine to another and lowering costs while making complex parts significantly. On the other hand, AM may produce low-reliability components that are not safe, particularly in essential applications involving harsh working conditions such as aircraft, marine, and biomedical applications. In reality, poor surface integrity, surface quality, lack of precision, and deleterious residual stresses can all affect AM products. In addition, AM component performance is influenced by various architectures compared to conventionally manufactured components, which are linked to differing cooling rates and undesirable phases. Post-processing operations are frequently required for the reasons stated above. Within surface and subsurface modification processes which can be employed, burnishing and machine hammer peening aim to modify surface quality and near surface structure by severe plastic deformation (SPD). In particular, burnishing enables product functionalization through improvement of surface roughness, introduction of beneficial compressive residual stresses, strain hardening and grain refinement. The search was conducted by specific keywords- post processing, surface roughness, additive manufacturing. Different research papers were found on Elsevier, Springer, and Google Scholar. The search strategy was defined with the main objective to find out different methods and experiments of burnishing on additively manufactured materials. But as it is an emerging topic on additively manufactured materials, minimal number of experiments were found to be compared with their familiarity of materials.

3. Results

(Sanguedolce et al., 2021) carried out an experiment on Stainless Steel GP1 which was obtained by laser powder bed fusion (L-PBF) process. The sample was thermally tested for reduction of porosity and also to minimize residual stress. Then to remove un-melted powder residues and for better surface finishing it was machined. After that a commercial roller-burnishing tool with a spring-based forced regulation system was used to perform burnishing process using a biodegradable oil which is under minimum quantity of lubrication (MQL) conditions. Using the software SFTC DEFORM, a numerical 3D model of the roller burnishing process was created to provide a complete understanding and optimization of the real system, which was the subject of the experimental campaign. The main goal was to see how different working conditions and parameters like tool characteristic dimension, burnishing force, feed rate and number of passes affected the final product quality which could be measured in terms of grain size, hardness, residual stresses, roughness, and thickness of the affected layer, among other things. In reality, as printed specimens had a surface roughness (Ra) of roughly 11 μm, which reduced to 0.45 μm after turning and, in the best case scenario, 0.17 μm after burnishing (Sanguedolce et al., 2021). As demonstrated in Table 1, the burnishing process resulted in a consistent change in surface hardness.

Table 1. Surface hardness values for tests on as printed (AP) as turned (AT) and as burnished best (BR) and worst (WR) (Sanguedolce et al., 2021).

Specimen	AP	AT	BR	WR
HIT [GPa]	1.9	2.3	5.0	3.4

Also compressive residual stresses have been found on the burnished surface. Results obtained from one of the tested samples is shown in Figure 1
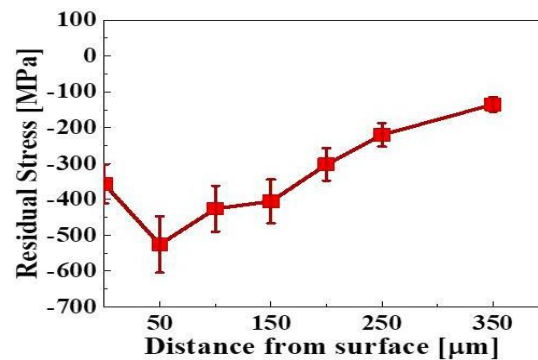
Figure 1. Residual stresses of burnished sample (Sanguedolce et al., 2021).

Similarly in (Rotella et al., 2020) the as-printed samples mean surface roughness Ra was around 11 μm, however rotating significantly improved the surface quality to around 0.45 μm. The burnished surface roughness, on the other hand, was significantly reduced. Because irregularities are severely reduced by pressing the roller on the workpiece, increasing the burnishing force resulted in a decrease in surface roughness (Figure 2). When a result, as the burnishing force increases, a larger section of the material is exposed to the plastic flow. Also, because AM products have a higher porosity content than cast goods, the increased plowing allows the pores to be filled more efficiently, resulting in improved roughness.
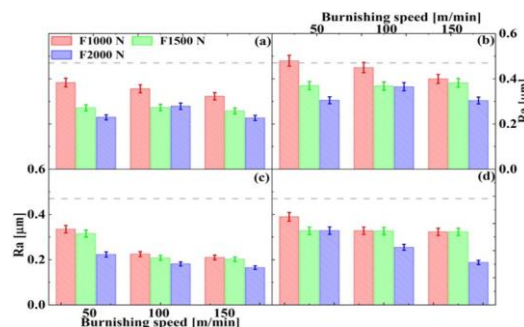
Figure 2. Mean surface roughness measured at different process parameters. (Rotella et al., 2020)

Additionally, the burnishing speed influences surface roughness by lowering the overall mean roughness. The results show that raising the burnishing forces increases the surface and subsurface hardness by revealing a deeper deformed layer and larger localized cold-worked zones. Even if to a lesser extent than burnishing pressures, feed rate has an impact on total surface hardness. In fact, by increasing the contact length from 0.05 mm/rev to 0.1 mm/rev, a little change in surface hardness is justified. Similarly, burnishing speed has a minor impact on hardness changes as compared to burnishing forces. Ultrasonic vibration-assisted burnishing can be also significant in improving surface roughness (Teramachi & Yan, 2019). In this process an ultrasonic vibration spindle is used which manufactured by SEEG Co., LTD., Japan which is attached to a 4-axis simultaneous control stage L4S-300 made by Sodick Co., Ltd., Japan. An alternating current from an ultrasonic oscillator was applied to the piezoelectric element to generate ultrasonic vibration. With a laser displacement gauge the amplitude of the vibration can be measured. In this experiment an additively manufactured AlSi10Mg workpiece was used which was fabricated with EOSINT M280 3D printing machine made by EOS Gmbh and ceramic ball of silicon nitride was used. (Teramachi & Yan, 2019) asserted Applying a reduced lateral pass width in only the last steps of burnishing for AM metals is desirable, the surface roughness was improved by 98 percent in both directions. SEM photos of untreated and treated surfaces shows the surface without treatment contains uneven patches and many voids, making the surface highly rough. The surfaces, however, have been significantly smoothed down after burnishing and at the same time, the holes are filled, as they have shrunk or disappeared. (Salmi et al., 2017) also experimented ultrasonic burnishing on 316L stainless steel which showed improvement of surface quality and hardness values. But it was noticed that the process was much slower compared to machining. (Sova et al.,

2017) showed Ball burnishing, roller burnishing, and other high-load superfinishing techniques that involve extensive plastic deformation of the near-surface layer may cause fissures in the cold spray coating surface. Figure 3 shows the microstructures of coatings after turning and ball burnishing. The ball burnishing technique caused significant distortion of the coating subsurface, as shown by SEM pictures. In both parallel and perpendicular cross sections, the deformation of the particles is more evident in comparison to the rotated samples. The inclined borders between cohered particles become nearly parallel to the coated surface, confirming the material's great shear deformation resistance. At the same time, there were no indication of the coating material's fragility failing.
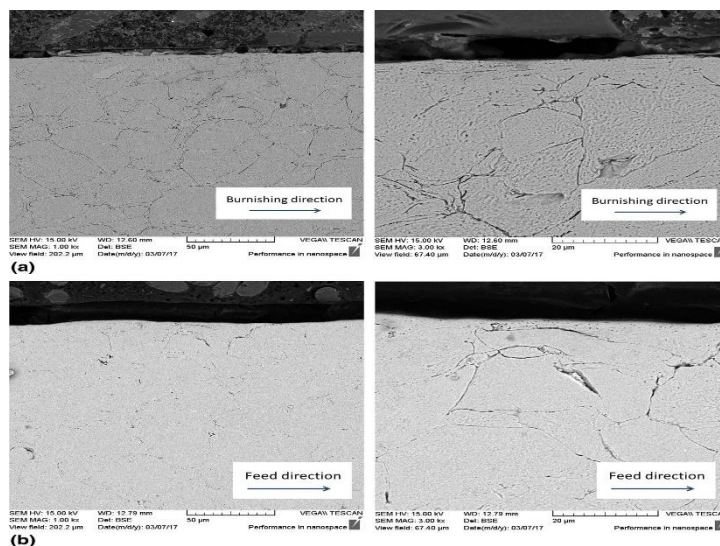
Figure 3. SEM images of the coating cross section after turning and ball burnuishing (a) parallel (b) perpendicular

4. Discussion

The performed review study shows that manufacturing of a product by additive manufacturing process reducing costs, time and scrap generated but machining to remove the external rough layer which is generated by AM process can be reduced by different burnishing processes. Superior surface quality with a considerable improvement of its performance under service can be achieved by this post processing of workpiece. In one of the experiments, presence of a numerical simulation model helped to predict the final outcome of the product considering the main factors affecting the performance. Thus, it helps to reduce the experimental results needed and cuts down costs and time. And it is flexible to work with the industry 4.0 requirements. The low reliability issues related to AM components still need to be faced to safely fully introduce these techniques into application fields involving severe working environments. In fact, defects originating from manufacturing processes represent a risk of catastrophic failure in operating phase. Hence, the growing effort in introducing and optimizing post-processing operations in order to overcome these issues and trying to retain the advantages of AM. SPD processes represent one of the available solutions, in terms of strength, fatigue life and corrosion resistance improvement of components. Burnishing is one of the representatives of this category of secondary processes, distinguishing itself for low costs and easiness of implementation. It has been previously tested for fatigue life improvement of additively manufactured steels revealing promising results. For future research focusing on optimal burnishing parameters considering technical parameters and productivity issues to drive this technology in the real industrial applications. Also, the effect of noise factors and trade-off over response variables can be studied further. Ball burnishing processes change the coating microstructure in the near-surface zone. In particular, a continuous layer with deformed and fragmented particle boundaries are formed. Further studies should focus on analysis of grain size and orientation on the affected layer.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis_kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Mechanical properties of carbon fiber reinforced polymer fabricated by fused deposition modeling[†]

Aftab Ahmad [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
[*] Correspondence: aftab.ahmad@s2018.tu-chemnitz.de
[†] Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Fused deposition modeling (FDM) is considered as the most popular and fast-growing additive manufacturing technology with the advantage of low operation temperature, low cost, ease of material change, and minimum waste. Fused deposition modeling is used to fabricate thermoplastic parts but due to low mechanical properties of the pure thermoplastic material, it cannot be used as load bearing part in actual application. Therefore, there is a need to reinforce the thermoplastic material with fibers such as carbon fiber to increase the mechanical properties of the part made by FDM. Carbon fibers provide high strength and high stiffness even at higher temperature which makes them an excellent option to use as reinforcement in engineering applications. This review study is mainly focused on the mechanical properties of carbon fiber reinforced thermoplastic fabricated by fused FDM. Short carbon fibers are blended with pure plastic to form fiber filled filament and then extruded for homogenous distribution of fibers. The fiber filled filament is used as feed material for FDM. The mechanical properties seem to increase with the addition of short carbon fiber but then decrease with higher fiber content due to the increase of porosity. The parts fabricated with continuous carbon fiber shows significant increase in flexural and tensile properties as compared to short carbon fibers and pure thermoplastic material. The toughness of the material decreases with carbon fiber addition, the toughness of the pure thermoplastic material was higher as compared to the carbon fiber reinforced one.

Keywords: Carbon fiber; Mechanical properties; Fused deposition modeling; Additive manufacturing.

1. Introduction

Additive Manufacturing (AM), which is also known as 3D printing, is one of the most promising fabrication technologies to produce elements with complex geometries from prototypes to final products. As compared to the traditional manufacturing methods, additive manufacturing has an advantage due to the possibility of obtaining complex shapes with the flexibility of easy modification without generating much waste and low energy consumption. Nowadays, AM is implemented in many industries such as automotive, space industry, fashion, electronics, aerospace, and many more. FDM among many other AM techniques has gained the most significant attention because of its availability, relatively higher part quality, and low cost of material used (Podsiadły et al., 2021). In FDM process, the material is added layer by layer, the material passes into the nozzle of small diameter with tension for continuous material supply to the printer. The liquefier head melts the material and passes it to the extrusion nozzle. The material is printed layer by layer from bottom to the top on the heated bed. The nozzle has 3-dimensional movement, and the build platform moves up or downwards according to the requirement (Gavali et al., 2020). It is possible to use any kind of thermoplastic polymer in FDM technology but most frequently acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), Polyamide 6 (PA6), and polyethylene terephthalate glycol-modified (PETG) are used. Despite their numerous advantages over traditional manufacturing, FDM printed samples often warp, and have deteriorated mechanical properties. To overcome this problem and increase in the mechanical properties, fibers or fillers can be added to the plastic material forming a composite. In a composite material, the fibers are used to support the load and the thermoplastic matrix material binds with the fibers transferring load to the fiber and protecting the fibers from the environment (Magri et al., 2021).

There are many different types of reinforcements available but the most expansive and mostly used in engineering application is carbon fiber. The unique properties of carbon fibers make it ideal for applications from automobile, aerospace, to sport goods. Incredibly light and rigid parts are produced by combining carbon fibers with resins to form composites. Carbon fiber offers highest specific strength and highest specific modulus as compared to other reinforcing

fibers. Even at higher temperature, the modulus and strength is better than other fibers (Chand, 2000). In this review, the mechanical properties of carbon fiber reinforced polymer (CFRP) fabricated through FDM technology will be discussed.

2. Methods

The methodology used to find out about the mechanical properties of carbon fiber reinforced polymer fabricated by FDM published on internet and database consisted of systematic review. The keywords used for literature search were fused deposition modeling, carbon fiber, additive manufacturing, and mechanical properties. These keywords were searched as a single and in a sentence as well with different arrangements. The databases used for the search were Google Scholar, Web of Science and Scopus. The keywords were typed in each database for the purpose to get the relevant documents associated with the topic. The search was modified with year of publication and the research papers onward 2000 were considered. For literature selection, skimming through the article method was used.

3. Results

A study done by Ning et al., 2015 in which different content of powdered carbon fibers (3 wt%, 5 wt%, 7.5 wt%, 10 wt%, 15 wt%) with average length of 150 μm and average diameter of 7.2 μm was added to the virgin ABS polymer material. The pallets of ABS and the carbon fiber powder were firstly mixed in a blender and then extruded with the help of plastic extruder to form fiber filled filaments. The filaments were put into the plastic extruder for second extrusion to get homogenous distribution of carbon fibers. The tensile test and flexural test results are shown in Fig. 1.

(a) **(b)**
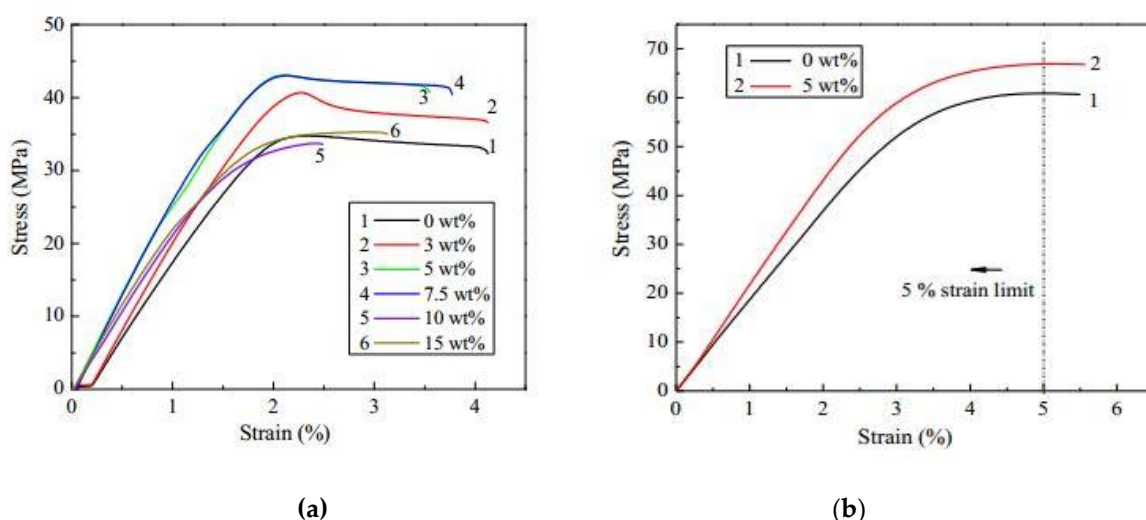
Figure 9. (a) Typical tensile stress-strain curve for specimen with different carbon fiber content ; (b) Typical flexural stress-strain curves with and without carbon fiber (Ning et al., 2015).

Increase in tensile strength is reported with the addition of carbon fiber, the maximum strength is achieved with 5 %wt and 7.5 %wt of carbon fiber. The decline in tensile strength is noted from 7.5 %wt to 10 %wt and again increase in the tensile strength from 10 %wt to 15 %wt. In comparison with the pure plastic specimen, the flexural stress, flexural modulus, and flexural toughness of CFRP with 5 %wt of carbon fiber content were increased by 18.82 %, 16.82 %, and 21.86 %. It can be seen that at almost every given strain, flexural stress of the specimen with 5 %wt of carbon fiber was larger than that of the pure plastic specimen. The results showed that there has been increase in almost every flexural property except for the flexural yield strength.
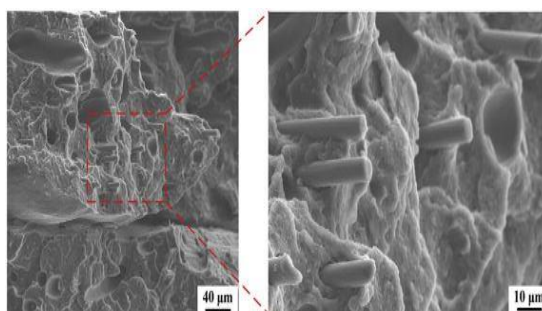
Figure 10. Carbon fiber pull-out in the fractured interface of CFRP composites (Ning et al., 2015).

Micrographs taken by using scanning electron microscopy (SEM) revelaed that the fibers ruptured which indicates an effective transfer of load from the thermoplastic matrix to the carbon fiber and resulted in good properties as compared to the pure plastic part. An important parameter that can affect the mechanical properties is porosity. The porosity decrease has been seen with the increase in carbon fiber content from 0 %wt to 3 %wt but then increased with the addition of filler content and reached to maximum value with 10 %wt. This high porosity can be one of the reason for low mechanical properties with 10 %wt addition of carbon fibers (Ning et al., 2015). The porosity of the samples can be reduced using vibration assisted fused depositon (Keleş et al., 2018).

In another study by Gavali et al.,2020 in which different content of carbon fiber (12 %wt, 15 %wt, 20 %wt) were added to pure PLA and the mechanical properties are shown in Fig. 3 below.

(**a**)   (**b**)
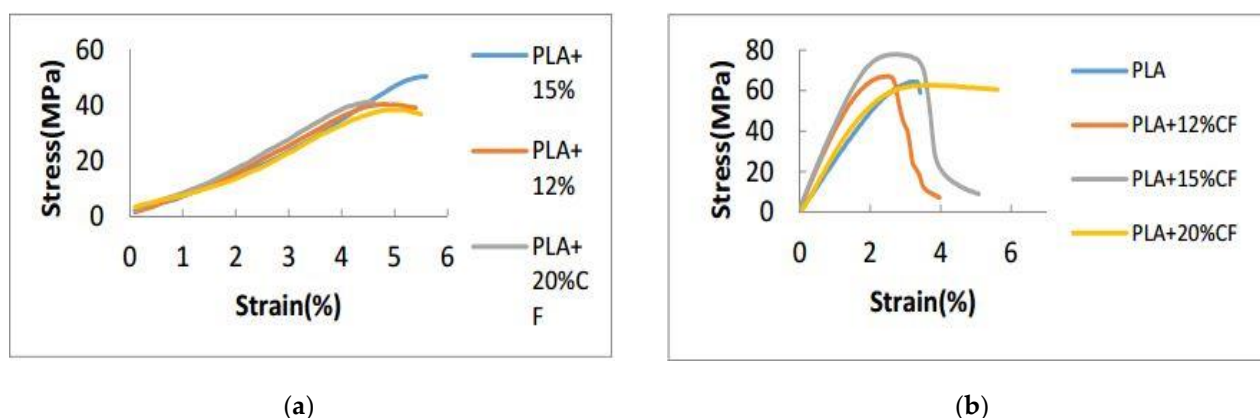
Figure 11. (**a**) Typical tensile stress-strain curves for specimens with different fiber content (**b**) Typical flexural stress-strain curve for specimen with different carbon fiber content (Gavali et al., 2020).

The results revealed that with the addition of carbon fiber, both the flexural and tensile properties of the sample increases. The maximum amount of increase in the tensile and flexural strength is seen when the fiber content is 15 %wt. The hardness test indicated that with the addition of carbon fiber content, the hardness increased, where the maximum hardness was observed for the samples having 20 %wt carbon fiber. The lowest hardness was shown by the pure PLA samples without any reinforcement. With the addtion of carbon fiber to pure polymer, the flexural strength and tesile strength increases but it may decrease the toughness and ductility of the material. The increase in the mechanical properties is due to the presence of carbon fibers (Gavali et al., 2020).

In another experiment, PLA is reinforced with continuous carbon fiber (CCF), 20 %wt short carbon fiber (SCF), PLA-SCF printed with CCF (SCF-CCF), and the mechanical properties are shown in Fig. 4.
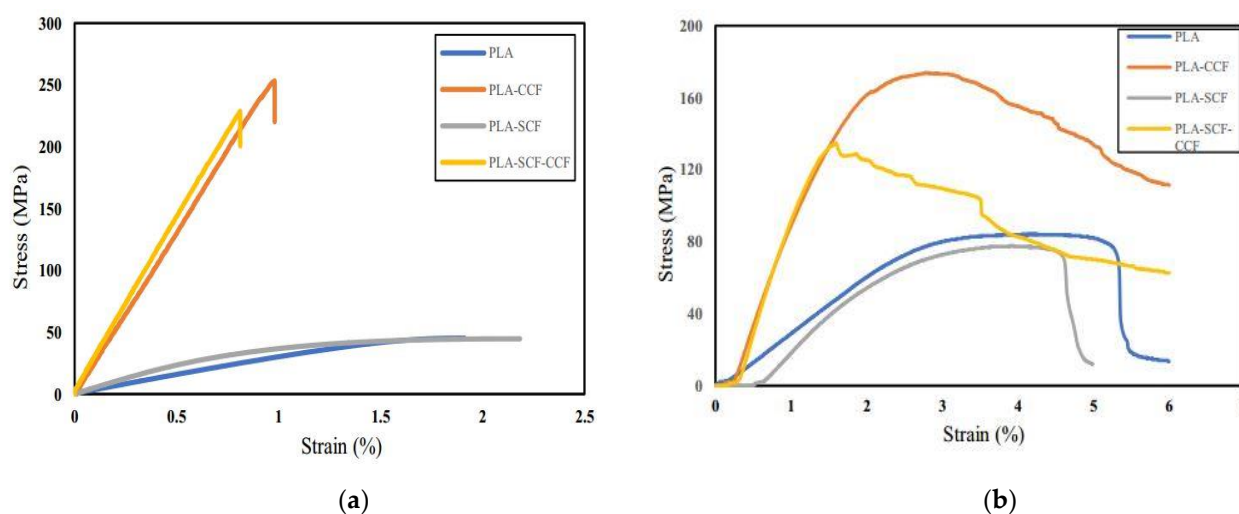
Figure 12. (**a**) Typical stress-strain curve of continuous and short CFRP (**b**) Typical flexural stress-strain curve of continuous and short CFRP (Maqsood & Rimašauskas, 2021).

The results showed a significant increase in the tensile and flexural properties with the addition of continuous carbon fiber (CCF), as compared to the short carbon fiber (SCF) and pure PLA. The tensile stress and flexural stress values for SCF are less because with the increase in the addition of fiber content the porosity increases and the mechanical properties decrease. Moreover, with the introduction of fiber, the ductility of the samples decreases as compared to pure PLA. The microscopic analysis showed the presence of air void content in samples fabricated with continuous carbon fibers. The ruptured continuous carbon fibers after tensile testing showed that the effective load transfer occurred from the matrix to the fibers gaining more strength. The micrographs of the fractured samples after flexural samples showed that pure PLA and short carbon fiber reinforced samples presented a clear fractured region as compared to continuous carbon fibers reinforced samples where the fibers are still held within the matrix, suggesting that continuous carbon fiber reinforced structures can be used during loading (Maqsood & Rimašauskas, 2021).

4. Discussion

The current review study was done to find out the mechanical properties of carbon fiber reinforced thermoplastics fabricated through fused deposition modeling. The review highlights that with the addition of short carbon fibers, the flexural strength and flexural modulus of the composite were increased as compared to the pure polymer, but there was a drop in the mechanical properties seen with the increase in carbon fiber content above a certain value. The porosity was reported to be the cause of decrease in the mechanical properties with increase in the carbon fiber content. The hardness was found to increase with the addition of short carbon fibers and was found maximum with the highest amount of short carbon fiber addition, whereas the pure plastic material showed the lowest hardness. As compared to short fibers and pure polymer material, there has been seen a significant increase in the mechanical properties of samples created with continuous carbon fibers. With the addition of carbon fiber, the mechanical properties increased but the toughness of the material decreased, and the pure plastic material showed the highest toughness. The increase in strength is due to the good bonding between the fiber and the matrix.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Fabrication of Bioactive Porous PLA Scaffold by Fused Filament Fabrication method[†]

Zannatul Tazri [1,*]

[1]   Technische Universität Chemnitz; Chemnitz; Germany
[*]   Correspondence: zannatul.tazri@s2020.tu-chemnitz.de
[†]   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Scaffold that co-ordinate the harmed bone tissue needs a suitable porosity and pore-interconnection alongside biocompatibility and good mechanical properties. PLA (Polylactic acid) can be great material for this purpose due to its better compressive and biomedical properties. Among an expansive number of Additive Manufacturing (AM) process, FFF (Fused Filament Fabrication) has got the foremost ubiquity for being cost-efficient and straightforward. In this review article, the impact of preparing parameters within the creation of 3D porous PLA scaffold by FFF was attempted to be found. Furthermore, there was an undertaking to discover and explicate the correlation of these parameters with the morphological and mechanical behavior of the printed scaffold. Bioactive porous PLA scaffold is surely going to be another era of bone-grafting materials.

Keywords: Tissue Engineering; 3D printing; Bioprinting; PLA scaffold; Fused Filament Fabrication.

1. Introduction

Human skeleton may undergo trauma, infection or disease that requires regeneration or rebuilding of bones. The necessity of bone healing process had made it the second most transplanted tissue after blood (Turnbull et al., 2018). As a result, development of porous 3D scaffold for bone grafting or regeneration has become a key area in Bone Tissue Engineering. The scaffold creates a microenvironment where the damaged site gets support for restoration.

To provide suitable *in vitro* and *in vivo* bioactive environment for bone mimicking and proliferation of the newly generated tissue, various polymeric materials and bioactive ceramics have been used. PLA is perhaps the most generally utilized materials in the biomedical area on account of its processability, mechanical properties and biocompatibility. Among the various strategies that are feasible to handle this biomaterial, AM has acquired consideration as of late, as it gives the chance of tuning the plan of the constructions. This adaptability in the design stage permits the customization of the parts to optimize their utilization in the tissue engineering field. In the recent years, the utilization of PLA for the production of bone scaffolds has been particularly significant, since various investigations have demonstrated the capability of this biomaterial for bone regeneration leaving no further cytotoxic effects on the body (Wurm et al., 2017).

Among various AM technology, FFF become popular for its relatively lower cost and simple process completion. In this article, the effect of process parameters on the manufacturing of 3D printed porous PLA scaffold is reviewed. Furthermore, shedding a light on the morphological and mechanical properties such as porosity, compressive behavior, degradation of the fabricated scaffold was done. The porosity controls the passage of nutrients and proliferation of the newborn tissue while the degradation makes the scaffold more bio-compatible.

2. Methods

The rapidly growing success of Additive Manufacturing (AM) has made it a vast field of research, leaving 1,460,000 results while searching in Google Scholar with the keyword "Additive Manufacturing". Choosing a topic from this huge pool was a strenuous task. While surfing over the 968,00 results of the key word "Application of Additive Manufacturing" in Google Scholar for a long time, the paper named "High strength porous PLA gyroid scaffolds manufactured via fused deposition modeling for tissue-engineering applications" got the attention of the author. At the very moment, the key word changed to "PLA scaffold manufacturing".

Total 7 papers were used to write this review article. Choosing these articles was a challenging task. Papers were chosen from four databases i.e., ScienceDirect, ResearchGate, SpringerLink, and Google Scholar. Time frame was selected from 2010 till date. Thus, the search result narrowed down to 17000 articles. After that, the keyword 'PLA scaffold

manufacturing by fused filament fabrication' reduced the result size to 8,000+ papers. From these papers, randomly 68 papers were selected those possessed good number of citations. From these 68 literatures, 7 papers were selected for this review article using Microsoft Excel meta-search process those are more concerned with the process parameter investigation of PLA scaffold fabrication by FFF. Finally, after extraction of these papers, all are thoroughly read and key points were noted to write this article that'll mirror the following sections. The main focus of this article is to explore the effect of process parameter on the fabrication of PLA scaffold through FFF method and to look into the properties of the manufactured scaffold.

3. Results

PLA scaffold needs to be designed at first in CAD (Computer Aided Design) software with desired pore size and geometry, then it is printed through FFF machine (Baptista et al., 2020), (Alizadeh-Osgouei, Li, Vahid, Ataee, & Wen, 2021), (Singh et al., 2019). After that, topographical and mechanical property investigation was done. **Table 1** shows the processing parameter of the papers used in this study. However, additional laser cutting of the scaffold can be done to investigate the open porosity properties that may enhance interaction of the scaffold with *in vivo* environment (Rodrigues, Benning, Ferreira, Dixon, & Dalgarno, 2016), (Malinauskas et al., 2014).

Table 1. Processing Parameters of PLA scaffold fabrication (FFF)

Authors	Dense PLA $\varrho(g/cm^3)$	Melting Temperature of PLA, T_m (^{0}C)	Process Temperature (^{0}C)	Printing Speed (mm/s)
Rodrigues, Benning, Ferreira, Dixon, & Dalgarno, 2016	1.24	173	210	30
Alizadeh-Osgouei, Li, Vahid, Ataee, & Wen, 2021	1.24	Not specified	195	100
Baptista et al., 2020	1.24	145-160	200,220	30,45
Singh et al., 2019	1.24	150	210	30
Malinauskas et al., 2014	1.24	Not specified	220	30

FFF requires an optimized combination of processing temperature and printing speed to achieve a constant flow rate of filament that produce uniform pore distribution and well-defined geometry along with minimal fabrication time (Rodrigues, Benning, Ferreira, Dixon, & Dalgarno, 2016). Nozzle clogging, one of the most prominent drawbacks of FFF can be eliminated by keeping the processing temperature above the polymer melting temperature. It's been found that ~220°C printing temperature produces a quasi-Newtonian flow to facilitate the printing of the scaffold (Baptista et al., 2020), (Rodrigues, Benning, Ferreira, Dixon, & Dalgarno, 2016). Pore size plays a vital role in the local regeneration of tissue as it depends on the interaction between the cell and *in vivo* environment. Study shows that the increment of pore size results in more deviation of printed PLA with the CAD design (Baptista et al., 2020). Besides, mechanical properties are also essentially needed for the skeleton structure. Combination of higher printing temperature with slow extrusion speed and lower layer thickness produces maximum yield strength and compressive modulus (Baptista et al., 2020). In case of thick layer scaffold production, thinner multi-layer printing scheme instead of one single layer scheme exhibits better mechanical properties (Baptista et al., 2020). While fabricating gyroid PLA scaffold, increased printing accuracy is obtained with the increase of unit cell size and strut size. But this leads to a negative trend in the compressive properties (Alizadeh-Osgouei, Li, Vahid, Ataee, & Wen, 2021).

In the question of morphology, beside other parameter, infill percentage of PLA of this 3D printing process influence a lot to the porosity of the scaffold. It's found that 60% infill percentage has the maximum open porosity that enhances the regeneration of the damaged cell (Singh et al., 2019). However, surface roughness can be modified by acetone bath immersion which also enriches the hydrophilic property (Malinauskas et al., 2014).

The fabricated PLA scaffold needs to be immersed in PBS (Phosphate Buffered Saline)/ SBF (Simulated Body Fluid) solution for a long time to look into the *in vitro* degradation (Rodrigues, Benning, Ferreira, Dixon, & Dalgarno, 2016), (Singh et al., 2019). To increase the hydrophilic property of PLA surface, air plasma treatment can be done before the immersion. The decreasing slope of PH after ~4 weeks of immersion indicates the polymer degradation in both cases. To make sure this phenomenon, (Rodrigues, Benning, Ferreira, Dixon, & Dalgarno, 2016) carried out the molecular weight testing with chromatographic RI detector.

As the skeleton system has to support the body, compressive test analysis is a must for the fabricated 3D scaffold. Porous PLA scaffold shows a three-phase stress-strain nature (**Figure 1**). At first, the initial elastic region, then almost constant stress plateau but increasing strain, and a substantial increase in stress till the end.
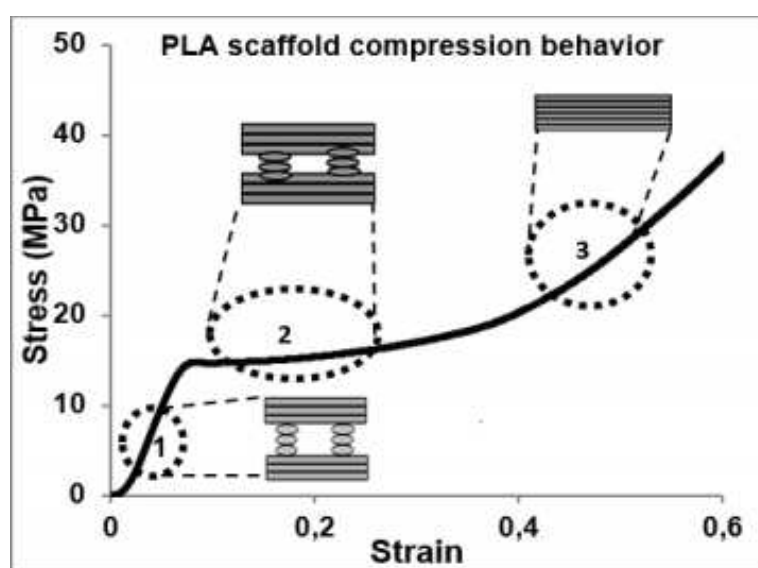
Figure 1. Stress-strain curve of fabricated porous PLA scaffold (Rodrigues et al., 2016).

It shows a trivial change in molecular weight and glass transition temperature after laser cutting, but an increased porosity for better nutrition transformation that results in better regeneration process of bone tissue (Rodrigues, Benning, Ferreira, Dixon, & Dalgarno, 2016). Laser cut did not cause any significant degradation issues.

4. Discussion

In 3D porous scaffold fabrication for bone tissue regeneration, PLA is more promising than acrylic-based polymers and PCL (Polycaprolactone) (Baptista et al., 2020). Fabrication of PLA scaffold by FFF has become popular due to its simplicity and cost-efficiency. In porous PLA fabrication process by FFF, the temperature and extruding speed plays a vital role to control topological and compressive property. So, optimizing these two parameters for desired property of the printed scaffold is the initial requirement. Temperature controls the viscosity of the melted PLA filament. At higher temperature, the melted filament shows low viscosity and can flow through the nozzle without clogging. At lower temperature, the PLA filament changes behavior from Newtonian from power-law as material flows through nozzle. In this condition the scaffold can still be printed with higher nozzle pressure but this may lead to deflection of the whole structure. While printing the scaffold at higher extruding speed, the fabricated scaffold may show deviation from the CAD design due to reduced time for settling down of PLA filament. On the other hand, extreme lower printing speed may lead to nozzle clogging. Therefore, an optimized printing speed to be set for better compliance of the structure with minimal fabrication time.

Open porosity of the printed scaffold enhances the nutrition transmission to facilitate fast regeneration of the damaged tissue. Hence, infill pattern, infill percentage, layer thickness along with other parameters should be optimized to attain better porosity and pore interconnection. With the higher infill percentage of PLA filament, the compressive properties may increase, but this may cause lower porosity. Besides, nozzle clogging can happen in this case as more

material must be extruded through the nozzle. So, infill percentage and pattern should be optimized according to the specific application of the scaffold. One of the downsides of FFF measure is that created 3D porous scaffold are frequently portrayed by shut edges. At the hour of scaffold implantation, this closed edge can influence cell-biomaterial collaboration by diminishing supplements and by products stream and influencing vascularization, which is fundamental for tissue development. Laser cutting can help get rid of these closed edges and ensure better porosity. As the fabricated PLA scaffold is mostly used for damaged bone healing process, the mechanical property should be preserved till needed to support the skeleton and supposed to be degraded afterwards spontaneously. The linear region of the compressive analysis graph of PLA scaffold indicates the initial resistance of pore walls to the compressive load. As soon as the pores collapse by elastic buckling, the graphs tend to be flattened. At last, the scaffold gets fully dense just before being fully collapsed. This phenomenon specifies the mechanical suitability of porous PLA scaffold for bone tissue regeneration process. As the higher porosity of scaffold lessens the mechanical property, compromise should be done between these two while setting the design parameters. The porous PLA scaffold can be the next generation bone-grafting materials. However, the hydrophilic properties of PLA can be modified that is required for better cell adhesion to get more biocompatibility while being used inside human body.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Digitalization of Industrial Production (Industry 4.0)

Review article

3D Printing Farms using Cloud Computing[†]

Shwet Kadam [1,*]

[1]   Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: shwet.kadam@s2020.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Industry 4.0 technologies can effectively cater to today's dynamic market. New technologies have come to light and advancements in additive manufacturing is one of the most recent examples. The aim of this paper is to present current researches and developments of the integration of cloud computing and 3D printing. As 3D Printing has become the Industry standard for prototyping and additive manufacturing, it has given rise to 3D printing farms. Cloud computing on the other hand provides a networked platform to share manufacturing capabilities and resources. The paper briefly describes the collaborative 3D cloud printing service architecture and mentions its potential markets and services along with the current challenges and opportunities.

Keywords: Industry 4.0; Additive manufacturing; Prototyping; 3D printing farms; Cloud Computing.

1. Introduction

From the first industrial revolution until the fourth industrial revolution, there has been a constant digitalization movement which has changed our lives as well as the whole production processes around us. The concept of Industry 4.0 was proposed to facilitate flexible production processes and interpret large volume of real-time data. Industry 4.0 is still in its genesis as it integrates a large number of technological concepts. Industrial Internet of Things (IIoT), robotics, cyber-physical systems simulation, big data, augmented reality, 3D printing, cloud computing and cyber-security are namely the nine pillars of Industry 4.0 (Yang & Gu, 2020). This paper is majorly based on the study of expansion of 3D printing using cloud-based approach.

3D Printing technology enables construction of various complex structures and geometries using different materials. Until now, it is considered to be the best way to increase flexibility in manufacturing and reduce overall manufacturing costs (Yang & Gu, 2020). 3D printing has changed the traditional method of manufacturing through its speed, accuracy, short product development cycles and high quality of product.

Apart from 3D Printing, cloud computing is also an important part of the Industry 4.0 paradigm as it can provide cheap and flexible computing power through parallel and distributed computing methods. It acts like a hub (platform) for exchange of information and also acts like a special service. Cloud computing is widely applied in various industries such as finance, medical, education, transportation and so on (Le, Huidong, Guohui, & Yuan, 2014). A survey report states that 88% of the companies participated stated that cloud yields positive outcomes and often allows access to new markets and customers (Yang & Gu, 2020). In this paper, a 3D Printing cloud is reviewed. 3D printing cloud platforms are the integration of computing and IoT with the 3D printing technology in order to provide customers with flexible, dynamic and diversified online services (Wenyan, 2021). This technology can be used to effectively match printing resources with printing data by simulation of a supply and demand matching process, and provide a supply and demand matching plan for the cloud manufacturing platform. (Wenyan, 2021).

This paper will briefly review large scale 3D Printing facility, which is also known as 3D Printing Farms. These state-of-the-art print farms are operated by effectively intertwining 3D Printing and cloud computing technology. This paper reviews the 3D Print Farm which was developed at the Department of Automotive and machine tools of the Warsaw University of Technology (hereinafter referred to as SiMR PW) (Skawinski & Siemiński, 2017). This paper also compares the print farm opened at SiMR PW with the state-of-the-art technology of 3D Printing farms and discusses questions like 'How will this technology be made available to customers' and 'How will it differ from Traditional 3D Printing Services'.

2. Methods

A systematic literature review from various fields has been conducted in a transparent and orderly manner to organize and blend the research findings from multiple fields. The initial part of this review consists of analysis of other research and review papers with an aim to build a firm foundation of the existing work and to aid in theory building. For this study, the search chain was divided into three parts. The first part was assigned to Industry 4.0 with all its synonymous names like digital manufacturing, cloud-based manufacturing, Industrial Internet of Things (IIoT) and so on. The reason behind this is that Industry 4.0 is a vast term and it covers topics like 3D printing and Cloud computing technology, which forms the 2nd and the 3rd part of the review. The order of the research is shown in the figure 1. The database retrieved for this study was Google Scholar, IEEE Explore, Springer International Publishing, IRJET, Journal of Manufacturing and Materials Processing.

Research Objective

- To conduct a systematic review of literature on 3D Printing Farms based on Cloud Computing.
- Evaluation and Compilation of the existing research on Industry 4.0 and 3D Printing Farms.
- To compare different research papers and exhibit the development done in the field.

Inclusive Criteria

- Electronic search of the above mentioned databases.
- Keyword search
- Covered time period: 2010 till present

Exclusion criteria

- Magazine articles and white papers.
- Articles present in non-English languages.

Validation of the Search Results

- To ensure high cohesion with the paper topic.
- To ensure high relatability.
- Independent analysis of the articles.

Figure 1. Protocol for literature review.

Finally, nine papers were selected for review. In order to limit the scope of the work, most of the reviewed literature is concerned with Fused Deposition Modeling (FDM) technology. The chosen approach for the literature search coincided well with the topic of the paper, as the focus was to explore and identify the cloud computing based approach in 3D printing.

3. Results

Small businesses and start-ups are aided by the implementation of Industry 4.0 to function with limited resources. It effectively enhances process control and automated or semi-automated decision making with reduction in downtime (Pawar & Nikumbh, 2021). One of the applications which are reviewed in this paper is the cloud computing based 3D printing approach. In simple words, a collection of 3D printers controlled by a central network is defined as a 3D printing farm. (Loy & Novak, 2021). The minimum number of 3D printers to be classified as a printing farm is as low as 3 to 5 printers and theoretically can be scaled up to infinity. Skawinski, P., & Siemiński, P. (2017) in their paper demonstrates a basic 3D Printing farm which is used for didactic and research purposes. Since it is mainly used by students for educational purposes, the printing technology has been limited to FDM/FFF for safety reasons. This farm consists of 15 FDM/FFF 3D printers with open and non-protected filament storage. The print material used are PLA, ABS and PETG. These machines are integrated and controlled from one computer (without the use of a memory card or an USB cable). They are programmed using different 3D CAM softwares like Slic3r, CURA, KISSlicer and operated in a separate and secured computer network to monitor the progress of the print.

In order to commercialize this concept of 3D printing farm for small- and large-scale industries, 3D printing farms can be ameliorated through the induction of Industry 4.0 and cloud computing approach. This is well explained by (Guo & Qiu, 2018) in their paper. As shown in figure 2, a cloud manufacturing platform is used for the development of a future smart 3D printing network and enable a new service-oriented 3D printing architecture to achieve mass customization (Guo & Qiu, 2018).
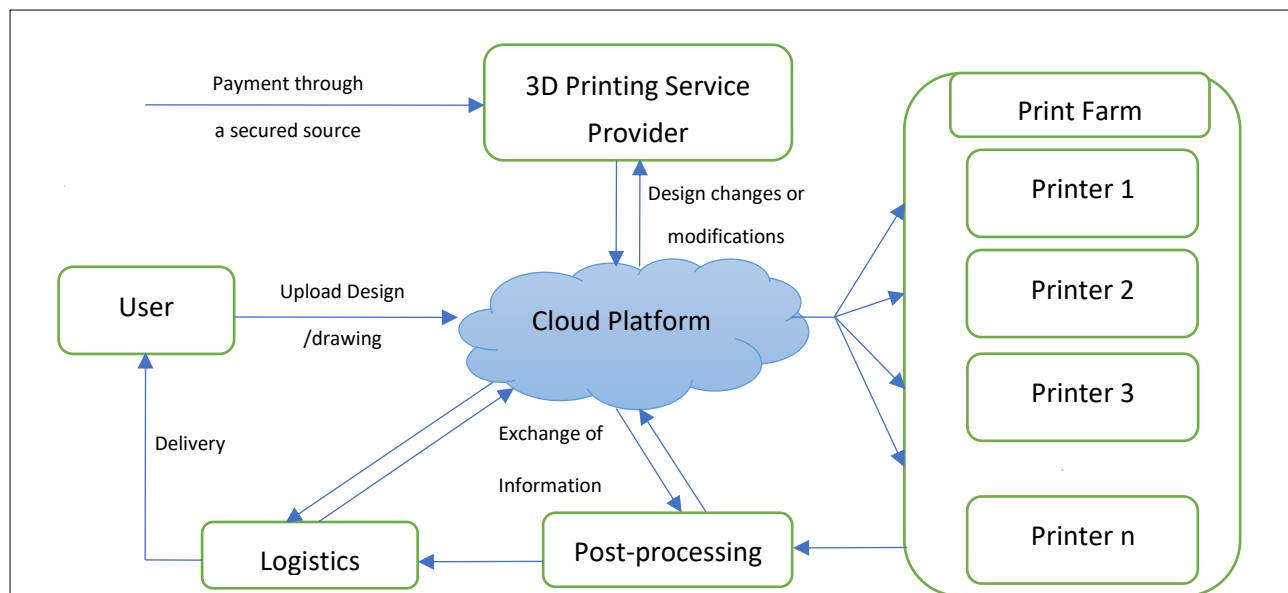
Figure 2. Collaborative 3D cloud printing service architecture.

The user can upload the drawings or models on the website and select the print material. This data is stored on the cloud. The model is screened and a 3D printer from the printing farm is selected based on the requirements of the part to be printed. Once the model is printed, it is post processed and delivered to the customer through logistic service. With further developments in 3D printing combined with cloud manufacturing, personalized customization can be increased with reduction in the cost of manufacturing. The status quo of the 3D printer can be automatically perceived through different kinds of IoT equipment. Complex events can be executed by using Complex Events Processing (CEP) engines.
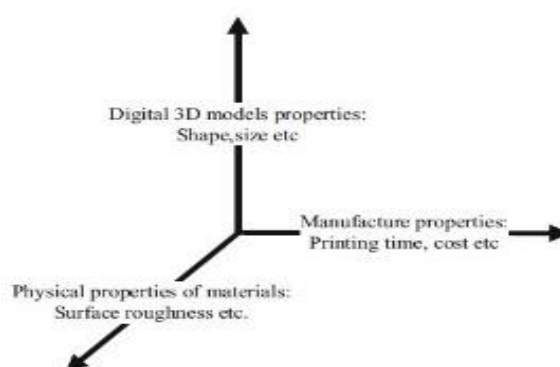
Figure 3. 3D Printing Product mode in Cloud Platform.

The above-mentioned service mechanism is adopted by many businesses and start-ups in the Global market. 3D Hubs, Shapeways and Quickparts are some of the successful Cloud based 3D printing service platforms. The comparison between these service platforms is briefly discussed in the discussion section.

A three-dimensional model of a product is designed in the cloud platform as shown in the figure 3 in order to validate their design and requirements on material properties and manufacturing characteristics before the actual product is printed (Guo & Qiu, 2018). This is mainly to complete the service preparation phase including virtualization of various service tasks. The key point of 3D printing service optimized configuration is to effectively match the supply and demand capabilities in the form of services (Guo & Qiu, 2018).

4. Discussion

With this concept, 3D printing has reached its maturity and has been accepted throughout the manufacturing and economic sector. But along with the opportunities, there are challenges as well. The table 1 shown below includes the social implications and challenges of 3D printing (Gwangwava, Ude, Ogunmuyiwa, & Addo-Tenkorang, 2018) (Ghomi, Rahmani, & Qader, 2019).

Table 1. Opportunities and Challenges in Cloud based 3D Printing

Opportunities	Challenges
• Reduction in manufacturing cost and time	• Reduction in labor jobs due to increased automation
• Growth in consumer access to products and services	• Security problem hampering the cloud manufacturing market since its inception.
• Greater market inclusion by approaching industrial as well as household customers	• Unwillingness to adopt Cloud Manufacturing technique by existing businesses.
• Greater opportunities for job creation and entrepreneurship	• Easy access to 3-D printed weapons
• Reduction in workplace accidents	• Need to update technical skills

Despite of being challenged at every stage, Cloud computer-based 3D printing, which is an important part of Industry 4.0, is a recent concept emerging in the industry. It is getting more reliable, affordable and network connected with time. Shapeways and 3D Hubs are two different examples of service platforms. Shapeways is a combination of 3D Printing and Cloud Platform. The user can upload his designs on the website and select appropriate material. The platform will select a suitable 3D printing service provider and deliver the printed part through logistics. Shapeways has created a network of users and designers from all over the world (Guo & Qiu, 2018). Quickparts has a similar service mechanism to Shapeways. Unlike Shapeways and Quickparts, 3D Hubs has a different service architecture. 3D Hubs has built a shared online platform through which it can connect local 3D printing service providers and customers (Guo & Qiu, 2018). On 3D Hubs platform, the user needs to upload the model and then the system will display the 3D Printer and its owner information in the vicinity. Once the order is placed, the user receives the printed product once it is ready.

In the current digital economy, Cloud Computer based 3D Printing is slowly transforming the ways of doing business (Gwangwava, Ude, Ogunmuyiwa, & Addo-Tenkorang, 2018). In near future, it is possible for the production managers and industrial engineers to create new marketing channels for capabilities and resource sharing in order to improve service quality and reduce time to market (Ghomi, Rahmani, & Qader, 2019). Based on the current application trends, this paper gives a brief introduction about 3D printing farms and cloud manufacturing platforms. It also summarizes the functioning of these platforms and its service potential with opportunities, challenges and future scope for research purpose. Due to on-going developments, the 3D printing industry is shifting from mere rapid prototyping to production ready technology.

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Review article

A Review of Acoustic & Vibration based Real-time Monitoring Predictive Maintenance†

Balasubramanian Vaidyanathan [1,*]

[1] Technical University of Chemnitz, Chemnitz, Germany
* Correspondence: balasubramanian.vaidyanathan@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Maintenance of a machine remains one of the most expensive expenditure of a production company's balance sheets. It is not only cost intensive, but at the same time work intensive, if the root cause is not known. In order to predict an early maintenance problem of a machine, a real-time monitoring system of all the critical components of the machine is necessary. This paper re-views acoustic and vibration based real-time monitoring system which helps in predictive maintenance. Apart from the hard-ware that is required to achieve this, software based on Industry 4.0 components are discussed comprising data processing, stor-age and communication. In conclusion, for a successful real-time monitoring system to predict any future failure, a combination of sensors, seam-less communication and deep data analysis working in tandem is of utmost importance. Sensors that can be placed in existing machines and automation achieved using new Industry 4.0 enabled machineries.

Keywords: Predictive maintenance, Acoustic and vibration, real-time, industry 4.0, Condition based maintenance.

1. Introduction

Maintenance of a physical system is one the biggest financial burden that a company must bear in order to keep the production running at full pace. Maintenance has evolved between industrial revolutions from corrective mainte-nance, which are expensive and work intensive, to preventive maintenance, which focuses on acting before failure oc-curs. In present, with the help of extensive data management approach, preventive maintenance has evolved to Condi-tion based Maintenance (CBM). The data from the condition monitoring system is used to take decisions which are called Predictive Maintenance (PdM). PdM is used to predict the future condition of machines with help of various forms of data analysis using Artificial intelligence, Deep learning algorithms or failure analysis and to take definitive actions before a catastrophic failure. Industry 4.0 helps PdM to be more efficient and accurate by adding values such as real-time condition monitoring systems, flexible evaluation and analysis, targeted notifications to experts using its ex-tensive data management (Kiangala & Wang, 2018). Visual inspection remains one of the widely used methods to iden-tify machine problems. With the help of sensors and signal processing systems, the identification of problems can be automated (Hashemian & Bean, 2011). Lee et al., (2018) helps in differentiating the strategies used for maintenance in order to explain how PdM can be helpful in predicting future failures.

Table 1. Five different strategies of maintenance as per Lee et al., 2018.

Reactive Maintenance (RM)	Common method – Fixing after the machine breaks
Reliability Centered Maintenance (RCM)	Expensive – Analyses all possible failure mode in order to customize maintenance strategy. All spare parts to be kept as back up.
Preventive Maintenance (PM)	Time based – Scheduled maintenance
Condition Based Maintenance (CBM)	Predictive maintenance – requires enormous data
eMaintenance	Web based online maintenance for fault detection

Table 1 describes the different types of maintenance strategies and their comparison. Most of the industries are trying to move to condition-based maintenance in order to reduce breakdowns and increase profits. Whenever an equipment begins to fail, it displays different types of failure precursors which can be detected using eyes, touch or ears. Integrating several sensors to automatically sense these failure precursors are the basis to establish predictive maintenance accurately. SKF bearing limited is one of the pioneers in vibration and acoustic based monitoring system at industry level. Use of advanced accelerometer sensors with high amount of experimental data, they were able to create machine learning algorithms for the sensor to detect and alert maintenance activities (Hashemian & Bean, 2011). PdM or CBM is of utmost importance to this review article. Vibrational analysis of machine has been in maintenance plans from the 3rd industrial revolution but only in limited industries. Horizontal deployment of this technology requires very high amount of data to be stored, analyzed and transmitted. The data fusion and data transmission that is involved in order to identify problems and how the following can be implemented in an existing machine can be realized using Industry 4.0 components. This review paper will be focusing on acoustic and vibration data obtained from different sensors to plan an effective Predictive maintenance of a machine. This paper will discuss how sensor technologies are used in synchronization with Industry 4.0 components such as cloud, big data, artificial intelligence, advanced sensor technologies and mobile platforms for real time data are discussed in situ with predictive maintenance.

2. Methods

This review article made use of research paper databases such as SpringerLink, IEEE Explore and Google scholar. The words Industry 4.0 AND Maintenance AND Vibration were used together to find a whopping 4672 available content with varied form from articles to book chapters. Only 'Articles and conference papers' were of concern here and this filter helped sort out 2089 papers out of the lot. Still the number was too high and only the first 3 pages of the result were considered into the skimming and scanning for relevant papers. The first 3 pages of the results were visually scanned for words such as Industry 4.0, data management, maintenance, vibrational analysis, acoustic analysis, intelligent preventive maintenance, using these words the abstract of these papers were scanned and cross referencing helped find multi array of papers within papers in order to successfully complete this review. Conventional preventive maintenance documents were neglected as they do not have anything to support Industry 4.0 incorporation. After reading the abstract of 4 to 5 papers, cross reference papers were scanned for words such as condition-based monitoring/maintenance, artificial intelligence-based maintenance, predictive maintenance, remote location maintenance, sensor-based maintenance + smart factory. The major contribution to this article was through cross reference and one such patent was identified in order to use this technology in the present existing systems. ESpacenet was used for searching patents with search terms – 'Acoustic and Vibration sensing' AND 'Monitoring'. The search results were scanned for appropriate content related to maintenance of a machine. The inspiration to write this review based on a Patent was from a previous experience in a textile company that was using a condition-based monitoring system to reduce maintenance costs and alert any irregular vibrations in any rotary machines.

3. Findings

An International Standard for acceptable limit of vibration that a motor should not exceed during operation is given in Table 2.

Table 2. Vibration severity creteria based on ISO 2372.

RMS Overall Velocity Level in 1000 Hz Bandwidth		Vibration Severity Criteria			
mm/s	In/s	Class I	Class II	Class III	Class IV
0.28	0.01	Good	Good	Good	Good
0.45	0.02	Good	Good	Good	Good
0.71	0.03	Good	Good	Good	Good
1.12	0.04	Satisfactory	Good	Good	Good
1.8	0.07	Satisfactory	Satisfactory	Good	Good
2.8	0.11	Unsatisfactory	Satisfactory	Satisfactory	Good
4.5	0.18	Unsatisfactory	Unsatisfactory	Satisfactory	Satisfactory
7.1	0.28	Unacceptable	Unsatisfactory	Unsatisfactory	Satisfactory
11.2	0.44	Unacceptable	Unacceptable	Unsatisfactory	Unsatisfactory
18	0.71	Unacceptable	Unacceptable	Unacceptable	Unsatisfactory
28	1.10	Unacceptable	Unacceptable	Unacceptable	Unacceptable
45	1.77	Unacceptable	Unacceptable	Unacceptable	Unacceptable

Classes of a motor are defined using its output power; this forms the basis for vibrational analysis of any motors in the industry and this can be used for data obtained from any types of sensor, such as probes, accelerometer and so on. These values are key for implementing automated vibration sensing and alerting technology.

Class I: small-sized machines (from 0 to 15 kW), Class II: medium-sized machines (from 15 to 75 kW), Class III: large-sized machines (powered > 75 kW) mounted on "Rigid Support" structures and foundations, Class IV: large-sized machines (powered > 75 kW) mounted on "Flexible Support" structures. RMS – Root Mean Squared value of vibration.

3.1. Hardware for Predictive Maintenance

There are different types of sensors for different machineries such as vibration, temperature, acoustic, voltage, force, torque, stress etc. To have a real-time monitoring system, it is necessary to embed each and every component of a machine that is prone to breakdowns with sensors that are capable of giving data of critical parameters such as vibration, displacement, temperature, humidity and much more, depending on the machine (Lee et al., 2018). Other than the hardware required, a strong software support to store, transmit and analyze data from the hardware is essential. Starting with the hardware, (Lee et al., 2018) explains how to identify critical components in manufacturing machines using average downtime graph to install the appropriate sensors. As per his data, acoustic and vibration analysis are highly preferred for rotary machines such as motors, pumps and gears. Hashemian & Bean, (2011) approach predictive maintenance by integrated systems, employing three categories of sensors using data fusion for cross referring faults in a machine. Figure 1 shows the three categories of data sources which are, process sensors – which are already embedded into the system for process parameters handling, test sensors – which are placed onto a machine for recovering vital data points and finally, test signals – the signals which are injected into the system to test them, such as insulation resistance test or LCR.
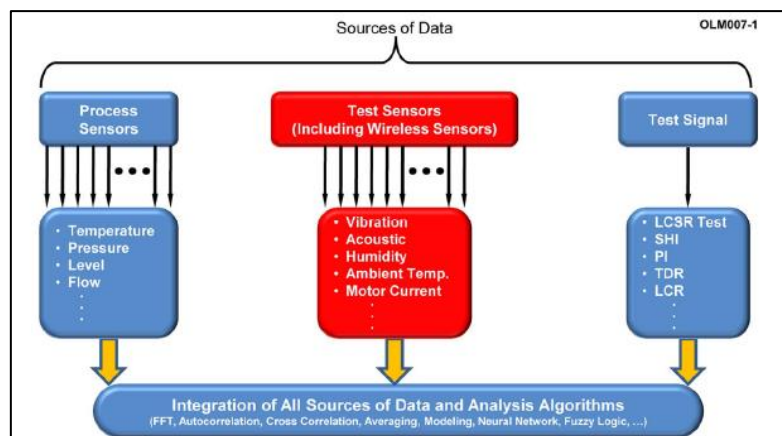
Figure 1. Hashemian & Bean, (2011)'s approach of integrated system employing three categories of data sources.

In order to extract vibrational and acoustical data from an equipment –the example for test sensors, inventors Bhinge et al, (2016) came up with a patent to magnetically attach a sensor assembly onto an existing rotary equipment. This device is transferable machine to machine and consists of an acoustic and vibration sensing apparatus which not only detects vibrations of a machine but also transmits the data to a cloud server. Differences in a system stability can easily be identified through its vibration and acoustic emissions and the difference in vibration and the sounds of its components can be used to determine which part of the system is misbehaving. The claims are, the apparatus acquires acoustic and vibrational data with timestamps, the acquired data can be processed and sent out as single data package via wireless communication or wired transfer to a data monitoring cloud server. This device has a tri-axial accelerometer and displacement sensor in order to acquire tri-axial vibration data. Other than the sensors, multiple electronic systems are required to store and relay information extracted to a software system, such as Programmable Logic Controllers (PLC), Supervisory Control and Data Acquisition (SCADA) and Human Machine Interface (HMI) which are already part of most machineries currently (Kiangala & Wang, 2018). To implement real-time monitoring in an existing system, the maintenance budget needs to be expanded in order to place sufficient hardware.

3.2. Integration of Industry 4.0 Components for real-time monitoring

After the data acquisition step comes the most critical step called data transmission and processing. Data processing involves filtering, conversion and analysing according to the required parameters of a machine. Conventional methods of filtering and conversion of data are part of the digital signal processing (Jardine et al., 2006). Use of Artificial Intelligence, Machine Learning, Deep Learning and advanced algorithms is required to automate data processing with high accuracy. Jardine et al., (2006) explains data processing of vibration data into three analytical types – time domain, frequency domain and time frequency domain which helps in taking appropriate autonomous decisions.   At Porsche, sound based predictive maintenance was used to analyse different mechanical sounds. Sound profiles from different machines were captured using a microphone at various operations such as running, stand by, offline and failure. The algorithm was trained to analyse different sound profiles using deep learning in order to evaluate machine health and suggest changes or maintenance steps. This method has superior mobility and the hardware is not necessarily required seperately on all machines (der Mauer et al., 2019). Although the hardware is of typical industrial use in the above case, the data obtained from the hardware is analysed using deep learning, an advanced Industry 4.0 technology.

On the other hand, Lee et al., (2007) introduces Computerized Maintenance Management System (CMMS) architecture which is a wireless sensor-based monitoring system. The advantages of this system over a typical PLC based sensor are its free range of mobility of sensors within the ranges of transmission of radio frequency and distributed computing of sensors. Wireless Sensor Network (WSN) is decentralised, which means if one sensor stops working, other sensor and the entire system does not get affected in performance. This is the basis of Internet of Things (IoT) where every single entity is capable of sending and receiveing data in a deceentralised manner. Machine to machine communication is key in a smart factory for seamless data transmission and decision making. Various types of advanced communication are part of Industry 4.0 such as Open Platform Communications Unified Architecture (OPC UA), Simple Mail Transfer Protocol (SMTP), Message Queing Telemetry Transport (MQTT), Hypertext Transfer Protocol (HTTP) and WSN. These form the backbone of data transmission to and from the central hub for real-time monitoring system.

4. Discussion

For a real-time monitoring system, which can help in predictive maintenance, needs extreme financial and technical support. As described above, existing systems have sensors that can extract few data points but are not efficiently stored, transmitted and analyzed. Further data points are required in order to effectively predict machine problems, such as acoustic and vibration emissions. Existing machines can utilize patent technology such as the one claimed in Bhinge et al, (2016) for vibration emissions or for only acoustic emission an industrial type microphone used in der Mauer et al., (2019). Post data acquisition, for efficient data storage, transmission and analysis, CMMS by Lee et al., (2007) might prove to be an ideal solution. In simple terms, a hardware should be supported with strong communication and analysis software methods such as deep learning (der Mauer et al., 2019) or wireless sensor network (WSN) by Lee et al., (2007). The other way to deal with this problem is by shifting to a newer version of the entire rotary equipment, just like how IE 2 and IE 3 rated motors were replaced by IE 4 motors systematically for improved energy efficiency. Dol & Bhinge, (2018) introduces a new type of smart and intelligent motors that can perform its own condition monitoring 24x7. All these hardware and software changes discussed above should have phase wise implementation onto existing machineries and procurement of new machineries must be done bearing in mind its capability and adaptability of communicating with future technologies. The future of real-time monitoring system depends on how effective data can be communicated and analyzed using these new Industry 4.0 technologies. With the new industrial revolution around the corner, Predictive maintenance will reach its pinnacle with absolute effectiveness. Thus, the author likes to conclude that, a combination of sensors, seamless communication and deep data analysis is the key for a future real-time monitoring predictive maintenance.

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Machine learning approaches on digitalization of Life Cycle Assessment in Industry 4.0: A review†

Razieh Haghighi Poshtiri [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: razieh.haghighi-poshtiri@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Machine Learning (ML) has played a very important role in integrating industrial data in recent years. In Industry 4.0, which is divided into many parts, digitalization is one of the most important steps to achieve the final concept of Industry 4.0. In this paper, an in-depth review of Industry 4.0, Life Cycle Assessment (LCA), digitalization and integration of all this data in collaboration with ML algorithms. The new ML algorithms and methods and their relationship to the LCA concept are briefly described. In the following, the reasons for the problems related to the study of the traditional life cycle are mentioned and the latest LCA method - Ubiquitous-LCA (U-LCA) is introduced. The questions attempt to answer during this study include finding the types of problems that can solve by machine learning in factories, the methods of machine learning used to solve the digitalization problems, and finding the benefits and limitations of using machine learning. The purpose of this study is to get familiarized with the latest methods for digitalization and integration of data within ML algorithms.

Keywords: Industry 4.0; Digitalization; life cycle assessment (LCA); Machine Learning (ML).

1. Introduction

Industry 4.0 attempts digitalization manufacturing and remains capable to make a revolution through the industry (Armengaud et al., 2017) also several novel concepts appeared as a consequence of advances in the Information Communication and technology (ICT) field (Raihanian Mashhadi & Behdad, 2018). Hence the information and data collection and its accuracy (Arm et al., 2018) are the backbones of the implementation of adjustments that must be achieved at the company level and between different departments and throughout the LCA (Armengaud et al., 2017). it particularly examined the effects of digitizing the automotive industry to improve the supply chain and new features (Armengaud et al., 2017). Smart manufacturing, cyber manufacturing, computer-integrated and cloud manufacturing, and cloud remanufacturing (Arm et al., 2018) are paradigms that require interconnectivity. Manufacturing modules and services are interactive through cyber-physical systems (CPS) (Raihanian Mashhadi & Behdad, 2018). The goal of Industry 4.0 is to change fundamentally current industrial production processes (Angelopoulos et al., 2020) and simultaneously deliver production samples to social communications and services driven by CPS. This transfer usually has immediate effects on the customer and the factory, through appropriate decision-making promoted by advanced data management techniques (Raihanian Mashhadi & Behdad, 2018) (Lee & Lim, 2021).

LCA is a method for systematically examining the effects of interactions between the environment and human activities. In addition, LCA is the evaluation of the environmental and social impacts of a product over its entire life cycle, from the extraction of raw material to end-of-life and waste management (Raihanian Mashhadi & Behdad, 2018) (Diez-Olivan, Del Ser, Galar, & Sierra, 2019). On the one hand, the LCA examines issues globally and at high levels of homogeneity and uncertainty (Raihanian Mashhadi & Behdad, 2018), which segregated systems that offer a high degree of diversity and heterogeneity to influence the results of the LCA. On the other hand, due to the high volume and variety of data obtained, it does not have the appropriate technology to integrate the system and analytics to prognosticate (Raihanian Mashhadi & Behdad, 2018). An important challenge for LCA is the reaction time to a critical factor change. The challenge is for the algorithm to be able to ideally analyze the effect of the change agent in "real-time" and adapt the product and digital supply chain throughout. The ultimate benefit, in this case, is the reduction of product launch time and Total Cost of Ownership (TCO), while also guaranteeing a high degree of product customization (Armengaud et al., 2017).

Machine learning (ML) is one of the most significant aspects of the development of modern technology, which represents the methods of artificial intelligence aimed at educational systems during the practical solution of several practical tasks (Prudius, Karpunin, & Vlasov, 2019). Implementing ML algorithms requires a large amount of

information to be capable of tracking decision-making, self-configurable ,and preventive decision (Bortolini, Ferrari, Gamberi, Pilati, & Faccio, 2017). For this reason, the implementation of new ideas such as CPS has created new structures of data (Angelopoulos et al., 2020). The ability of ML, based on the timely processing of data, protects the cybersecurity of the Internet of Things (IoT), which has interconnected production environments, to accurately identify and reduce threats (Angelopoulos et al., 2020). ML algorithms can be categorized to: supervised learning, unsupervised learning (Dogan & Birant, 2021), and semi-unsurprised learning, reinforcement learning (Xie et al., 2019), and deep learning (Angelopoulos et al., 2020).

2. Methods

Only published literature, academic, scientific research, and review articles in journals within the five years 2017 until 2021 - Due to the up-to-date concept and the fast-growing technology and scientific studies in order by the research topic- considered on the research topic. The literatures were collected through reliable databases. i.e: Elsevier, Springer, EBSCO, Google scholar, and ScienceDirect.

Synonym keywords used for researching for the topic were Industry 4.0, life cycle Assessment, machine learning, digitalization process, neural network, product life cycle, and deep learning. The stopping criteria for the research were getting similar articles using synonym keywords.

Software called Citavi was used to identify and sort the relevant articles. In addition, the criteria for including access literature, article history, abstracts related to the research topic, research methods, and methods used, were categorized by OneNote and Excel databases. Following this, reference analysis was done by the same software was performed to identify other relevant literature.

As the name of the article proposes, this research was based on a study of the literature to identify the newest methods used in the implementation of digitalized LCA through Machine Learning. The latest methods were studied and a summary of methods and used technologies collected.

3. Results

The main concern of industry 4.0 is the prominent role of human beings in its processes. For the research, they used a human-based learning machine, which puts humans at the highest stage of the process, the best way to avoid possible errors in important points of prediction (Angelopoulos et al., 2020). The integration of different parts and different data in Industry 4.0 led to the definition of AS40 assembly process management. An assembly control system (ACS) uses this data stored in each defined station, which can use standard methods for automatic data management and classification. AS40 collects a lot of data and must be converted into meaningful information. ACS is used to automatically configure data. It can also implement real-time optimization models and ML algorithms automatically (Bortolini et al., 2017).

To address the LCA reaction time challenge, an integrated approach is proposed that not only meets production but also addresses internal needs. Consideration of cost information in the early stages of development in decision-making algorithms is arbitrary. This method helps to optimize the total cost of ownership (TCO). Limitations hinder the ability of the current LCA to comprehensively assess the environmental impact of smart manufacturing in the industry 4.0 environment. In an extremely interconnected network of production modules, it is impossible to define a robust functional unit without neglecting the relevant processes (Lee & Lim, 2021). Instead of defining the physical boundaries and linear scaling of results used in the conventional LCA, the Ubiquitous-LCA (U-LCA) attempts a novel concept of the wide interrelationship created by the ever-expanding Internet. Cyberspace enables machines to tag, monitor, and track any input or output, and evaluate impacts individually and in real-time (Raihanian Mashhadi & Behdad, 2018).

As mentioned before, ML algorithms were divided into 5 categories.   Supervised learning was divided into two methods: classification (classification forecasting, such as law, medium, high) and regression (sequential forecasting, such as car price during the time). In classification, the most algorithms used were the following respectively, Neural Network (NN), Support Vector Machines (SVM), Decision Tree (DT), K-Nearest Neighborhood (KNN), Naive Bayas (NB). ACC and F-measure were frequently applied to measure performance in this method. At the regression method, the more common algorithms used in the reviewed articles were the following sequentially, Support Vector Regression (SVR), NN, and Random Forest (RF), respectively, and R2 is used to measure performance. In this article, unsupervised was divided into 5 methods: clustering, associate role mining, anomaly detection, density estimation, and representation learning. Most of the unsupervised algorithms used in the reviewed articles were K-means, Hierarchical Clustering, DBSCAN, and Self-Organization Map (SOM) (Dogan & Birant, 2021). Hence unsupervised algorithms capable of evaluating disordered and uncategorized data, unsupervised frequently used in industries. In the industry, clustering

should be used before classification (Xie et al., 2019). For Reinforce method, learning algorithms are reinforcement learning (RL), Deep Reinforcement Learning (DRL) and RL-Based Game Theory (Xie et al., 2019).

To solve the complexity of ML, the use of Software Define Networking (SDN) is suggested by (Xie et al., 2019) .This new system helps to improve the ML in four sections: first, the development of computational tools used in the ML, second, accuracy in collecting and controlling global data, third, data analysis, network optimization, and automated network services, and finally, programmable SDN on real networks implementation .ML tries to examine and achieve the desired results in 5 stages in SDN topics such as traffic classification, routing optimization, QoS / QoE forecasting, resource management, and security (Xie et al., 2019). Prudius et al. defined key methods on ML, clustering for unsupervised learning, classification for supervised learning and regression as most accurate data analysis method. Logistic regression of input parameters is the most common ML algorithm, its popularity is due to the large input parameter that can divide the output data into two or more different classes. Figure 1 clearly shows the linear function that the inputs are divided into different classes (Prudius et al., 2019).
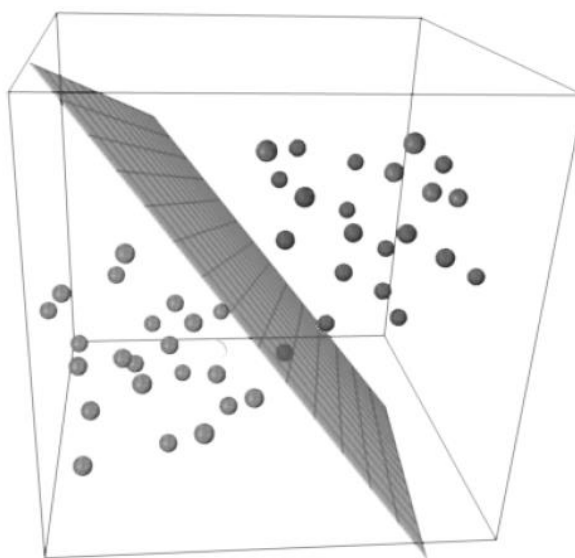
Figure 1. Visual representation of logistic regression discrimination (Prudius et al., 2019)

4. Discussion

This article considers new methods for performing the digitalization Industry 4.0. Through a precise explanation of ML algorithms, A regular process for each algorithm declare. This study discovers the limitation of LCA, then tries to suggest the unique structural-industry development which considers the benefits of using all Ml methods on digitalization for replacement with conventional LCA. New articles in the lifecycle, introduce a new study of data integration among influential factors of the digitalization process. Therefore, this article mentioned the AS and U-LCA as practical methods and can customize for each situation. Therefore, the data optimization method (ACS-Assembly Control System) or network optimization method (SDN-Software Define Networking) for the Supervised Learning (Classification), Unsupervised Learning (Clustering), or Reinforcement learning, based on network characteristics, type Data and the degree of digitalization could implement. The use of these methods will not only help to integrate different parts of the company but also lead to supply chain integration. Reviewing and categorizing data is crucial in today's competitive industry in decision-making and prognosticating. So, find newest industry requirements through Industry 4.0 and adjust fast learning approach to solve the feature problems and disorganization between industries levels can be consider as new approach.

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Review article

Interdependence of industry 4.0, circular economy, and sustainable development†

Badal Khandelwal [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: badal.khandelwal@s2020.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Due to population growth, heavy industries such as automobile components and casting manufacturing sectors, use more natural resources, and our planet cannot keep up with these trends, this led to think about the advancement in manufacturing capabilities linking sustainable production, circular economy and smart factory (Industry 4.0). A potential solution for better utilization of resources would be to implement advanced manufacturing processes by integrating human, products, machines and other resources with cyber physical systems. This paper discusses about the relation between industry 4.0, sustainability development and circular economy and the methodology that can be used to find the relation among these 3 important terms.

1. Introduction

Resource efficient strategies (i.e., circular economy) can be implemented for better use of natural resources. In circular economy, the resources stay in the closed loop and undergoes one of the resource utilisations practices, stated as 9R (Recycle, Reuse, Refurbish, Refuse, Rethink, Repair, Remanufacture, Repurpose and Reduce (Et al., 2021; Uçar et al., 2020). To meet the needs of present and future generations, it is important to deal with overconsumption of natural resources and environmental change (global warmimg, greenhouse emission gas etcetera) (Et al., 2021; Velenturf & Purnell, 2021). Resources are best conserved by minimizing waste and focusing on prevention whenever possible. However, if the waste is unavoidable, it must be appropriately managed for environmental and human health protection (Et al., 2021).

Sustainability development has a positive relation with circular economy (Bag et al., 2021). The pillars of sustainability development (environmental, social, economic and technological) interact with each other and require a well-balanced long-term relationship (Velenturf & Purnell, 2021). By embracing circular economy practices, it is easy to achieve the 17 sustainable development goals (SDGs) adopted during the 2015 UN General Assembly (Et al., 2021; Velenturf & Purnell, 2021).

Smart factory (Industry 4.0) has a positive relation with circular economy and sustainability development (Bag et al., 2021). In smart factory: human, products, machines and other resources integrate with each other in a more efficient way through artificial intelligence information systems, which includes the use of industry 4.0 technologies such as Internet of Things (IoT), cloud computing, digital twins, IT based management, cyber security, real time data processing etcetera (Resman et al., 2020; Simoes et al., 2020). With these technologies, efficient communication among machines, computers and sensors takes place. The data generated from these wireless networks can be easily analysed to improve any flaws during production (Manavalan & Jayakrishna, 2019). Smart factories must be implemented in order to increase productivity, flexibility, reduce costs, and save time and materials (Et al., 2021; Simoes et al., 2020).

Therefore, the factories needed to be built in a well-planned manner. While planning the methodology, one should always consider that the smart factory must be self- aware (identification, location, status, and time), modular (building the new systems by using different individual subsystems) and interoperable (that enables the subsystems to exchange information with each other) (Resman et al., 2020).

2. Methods

The study was started with the terms like- sustainability development, circular economy, industry 4.0, smart factory and finally linking these terms in pairs. A total of 7 literatures were identified and all the reviewed literature were

obtained from google scholar databases from 2018 to 2021. Collected literature was overviewed briefly, which involves exploratory research approach, based on real world occurring events, questionnaire-based survey was used to gather the primary data for hypothesis testing. When papers were found to have similar findings, selection was based on higher number of citations. Papers were thus finalized after this process.

3. Results

The lasim smart factory (LASFA) architecture model can be implemented which determines the interconnection of technologies and where the data needs to be gathered for the smooth operation of digital twins and the factory itself. It is important that technology such as digital twins and digital agents be used for visualization. The digital twin transmits new production plans and feedback to the real world with the assistance of various digital agents, as each local produc-ion process has its own digital agent with its own database. Section 3.1.1 discusses the approach to find the realationship between Industry 4.0, circular economy and sustainability development, whereas section 3.1.2 discusses the case study, which focuses on the importance of digital technologies to increase the circular economy practices.

3.1. Relationship between Industry 4.0, circular economy, sustainability development

3.1.1 Exploratory research approach (EFA) based on questionnaire based survey

It was observed that manufacturing companies have shown more interest for the survey conducted in adopting industry 4.0, sustainable manufacturing and responses were received by the management person, having wide experi-ence in the particular field (Bag et al., 2021). Secondly, the much popular Harman's single factor test was used to check the common method bias (CMB). From the SPSS output, it was found that nine factors emerged and first factor ac-counted for 14.15 percent of variance (see table 1) which is much below the maximum limit of 50 percent, which means that the data is free from CMB and the Kaiser-Meyer-Olkin Test (KMO) value was observed 0.87, which is more than the recommended minimum value of 0.60 (Bag et al., 2021). The 9 key resources that emerged from the EFA analysis are listed (see table 1). PLS-SEM (structural equation modelling) technique was used, in which any latent variable can be measured through many indicators, in this step, the path coefficients and their corresponding "p" values were exam-ined as a way of assessing the links (Bag et al., 2021). Hypotheses were tested utilizing WarpPLS software. The results of hypotheses testing are illustrated (see table 2). As values found were appropriate as per the requirements, hence there is a positive relationship between I4.0 adoption, sustainable production and circular economy (Bag et al., 2021).

Table 1. List of 9 key resources based on EFA analysis

Group	Resources	Cumulative percentage
1	productions systems	14.153
2	human resources	26.582
3	project management	37.312
4	management leadership	45.500
5	green logistics	52.818
6	green design	59.216
7	information technology	64.973
8	big data analytics	70.605
9	collaborative relationships	73.761

Table 2. Path coefficient and p values for hypotheses testing

Sr. No.	hypotheses	path coefficients	p value
H-1	production systems have a positive relationship with I4.0 adoption	0.21	0.05
H-2	human resources have a positive relationship with I4.0 adoption	0.11	0.03
H-3	project management have a positive relationship with I4.0 adoption	0.15	0.05
H-4	management leadership have a positive relationship with I4.0 adoption	0.12	0.05
H-5	green logistics have a positive relationship with I4.0 adoption	0.10	0.05
H-6	green designs have a positive relationship with I4.0 adoption	0.41	<0.001
H-7	information technologies have a positive relationship with I4.0 adoption	0.10	0.04
H-8	big data analytics have appositive relationship with I4.0 adoption	0.44	<0.001
H-9	collaborative relationships have a positive relationship with I4.0 adoption	0.27	<0.001
H-10	I4.0 adoption has a positive relationship with sustainable manufacturing	0.22	<0.001
H-11	sustainable manufacturing has a positive relationship with circular economic capabilities	0.08	0.05

3.1.2 *Case study based on business model canvas (BMC) for circular economy*

Three different case studies were conducted to find the importance of digital technologies for implemantation of circular economy (see table 3) (Uçar et al., 2020). It was observed that, in order to increase the product's life and to optimize the product's energy consumption, it is important to monitor the location, condition and availability etcetera of the product, which is only possible by data collection, data exchange, data storage and analysis, hence cyber physical system is needed to achieve this all (Uçar et al., 2020).

Table 3. Relation between circular BMC and digital technology

Cases	Functionalities (cases)	Digital technology
Alpha	monitoring product location, condition, availability	IoT
	optimizing energy consumption	IoT and big data analytics
	monitoring product	IoT
	creating intelligent product	IoT
Philips	monitoring product	IoT
	optimizing remanufacturing, energy consumption	IoT and big data analytics
	virtual communication	IoT and cloud
	creating intelligent product	IoT
Zen-robotics	optimizing recycling	artificial intelligence

4. Discussion

This paper summarises three important concepts which includes Industry 4.0; 9R advanced manufacturing principles and the third is sustainable development. Cyber-physical systems (CPS) and the Internet of Things (IoT) introduced in the industrial environment led to the current fourth industrial revolution. In addition to green manufacturing processes, cyber physical systems can help achieve flexible production, rapid product switching, and rapid response times. With the LASFA model, the data can be remotely accessed by mobile phone, tablet or computer, allowing the user to switch product specifications during production. Hence, Industry 4.0 adoption, sustainable production and circular economy capabilities have a positive relation with each other and they are truly dependent on each other.

As it claims for cleaner production, implementing I4.0 helps in overcoming CE challenges such as value proposition (products and services), market (target segments and distribution channels), infrastructure (supply chain architecture, manufacturing technologies, etcetera) and financials (cost structure and revenue models). Therefore, a successful sustainable production is needed to be carried out. Values for the company's stakeholders and customers can be achieved by using new and innovative CE business models. Business models which use "cradle-to-cradle" concepts can better tackle resource scarcity, since the product will take a second life at the end of its lifecycle.

Small and medium sized firms are the backbone of any country's economic development, since they consume larger portions of resources and generate more waste, hence it is crucial to place focus on them. This is only possible if the competencies of employees are examined by the organization culture or top management or the green human resource teams. In order to move the production forward, employees need to be motivated and trained on green production related tasks. Our knowledge and power, combined with our collaboration, can help us move towards a circular economy.

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Review article

A Review on Technologies implemented in Industry 4.0 for the increased productivity, flexibility and communication†

Dinesh Kumar Ravi [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: dinesh.ravi@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: The implementation of Industry 4.0 in the manufacturing Industry has increased productivity, quick response to the customers as well as cost effective. The digitization of Industry 4.0 has revolutionized the entire manufacturing style and now everything is driven by the internet. The Industrial Internet of Things (IIoT) has digitized production and operations and uses big data and analytics to achieve advanced level of optimization and efficiency. This paper provides information about various new technologies or methods implemented and the reason for implementation with some explanation of its working and how technologies serve for the increased productivity, flexibility and improved communication.

1. Introduction

Industry 4.0 plays a major role in the manufacturing sector which increases manufacturing flexibility to meet production demands. The aspiration of Industry 4.0 is to promote virtualization, decentralization and network building to change conventional production environment. The traditional or conventional production system has high productivity but the flexibility of the production is very less which does not respond to the changing environment. The implementation of Cyber Physical System (CPS), Artificial Intelligence, cloud operations have revolutionized the manufacturing environment and now the manufacturing sector becomes more responsive to the changing environment and production demands. The technologies like Autonomous Mobile Robots (AMR), Smart Scheduling, Cloud sharing, autonomous computing has created the great impact in Industry 4.0 and made the flexibility even higher. In Industry 4.0, the automatic detection of errors, and storing the reason for errors in a database and using it for future has made the Industry 4.0 a huge success. The System-on-Chip (SoC) enables the automatic detection of errors which saves the stoppage time. In the methods section, the detailed explanation of how the paper was chosen are explained. In the technologies and results section, the technologies implemented in industry 4.0 are discussed and are compared with the previous technologies used with some experimental analysis to justify its usage in the industry along with analysis result. In the discussion part, the limitations of technologies are discussed along with future opportunities and the aspects to be considered in future are also mentioned with reasons.

2. Methods

The research papers discussed in this review article were obtained from the legit and renowned publications and journals such as Science direct, Research gate and Elsevier using google patent search engine. The search strategy was based on the research papers and journals published in last five years which discussed about the technologies implemented in Industry 4.0 for improving production flexibility, efficiency and worker's integrity. The key words used to find sources were "Increased flexibility and productivity in industry 4.0" and "improved communication in Industry 4.0". Totally 1430 articles were found based on these keywords. From these 1430 articles 50 articles were listed based on the technologies used in Industry 4.0 for increased productivity, flexibility and communication and then 7 articles were selected based on its wide usage in the manufacturing industry.

3. Results

3.1. Smart Scheduling

In the manufacturing industry, unexpected failures and disturbances are quite common, but this affects production planning which leads to the rescheduling of the process. To avoid such unexpected problems Rossit, et al. (2019) states that industry 4.0 has employed the technology known as smart scheduling which uses advanced investigation procedures to avoid rescheduling. There are several stages in the process of smart scheduling. In the initial stage, the typical or unpredictable problem is solved which produces the initial schedule. Then the limitations are stated to find a solution to the tolerance scheduling program. In the second stage, production begins according to the formerly planned schedule, till any trouble is identified. Then the disruption is examined to check whether it requires a rescheduling or not. The commonly used Manufacturing Scheduling System (MSS) scheduler which requires manual scheduler to compute the deviations and check for the reschedule can be replaced by the same problem which can handled with smart scheduling which incorporates the same functionalities as an MSS, but it will do the same up to sending an alarm and compute the deviation. Smart Scheduling then recalls the tolerances obtained solving the Tolerance Scheduling Problem. These tolerances determine whether rescheduling is needed or not. So, with the help of smart scheduling, proper process planning can be done even in case of unexpected and disruptive events using an efficient screening procedure known as tolerance scheduling.

3.2. Cloud platforms

Cloud platforms has provided flexible and economical way to distribute resources. If a company has good sharing sources, it can improve production efficiency and reduce equipment downtime. Cloud platforms, which is the basic component of cyber-physical system is used for storing and sharing data and information. Cloud platforms is divided into three components, Cloud storage, Cloud computing, and cloud sharing. Yen, et al.(2014) explained that Cloud storage which is online speed, reliable with the files or recover function, information centre keeps their data in the diverse servers. The second one is cloud computing, in which users can access all data and information online using normal in-built browsers which does not need any multifaceted software for the access. Cloud sharing is the final element which is the most important through which information about planning and machine status can be shared among peers. As far as the sharing technology is considered, cloud sharing seems to be an effective way for sharing information. For instance, if any information about the data and machine status is needed, conventional way of extracting data and sharing it among peers takes ages to complete the process. But if CPS is used, it accelerates the data collection and sharing process through automated production management system. Through the cloud sharing, the production efficiency can be improved and the reasons of machine failures can also be identified.

3.3. Intelligent Gateway using System-on-chip (SoC)

Astarloa, et al. (2016) explains that, for the easier and flexible manufacturing process, an intelligent gateway implemented on System-on-chip (SoC) was presented in the Industrial Internet of Things (IIoT) which allows data collection, exchange, and analysis efficiently. Some problems in implementing CPS involves the advanced level security for data and information due to the online threats and hacks. So, the users and devices should be authenticated before the sharing of resources. This can be solved by addressing the problems with layered cyber security approach but this becomes even more worse when a greater number of devices gets connected. This issue can be resolved by implementing SoC which enables efficient communication. SoC overcomes the challenge through dual core processor with different memory resources to support multiple users and high-speed networking links. The software and hardware processing are partitioned in order to face CPS challenges. Through SoC, it is possible to predict problems or failures in the machine and act accordingly. To get to know about the machine behavior, predictive analytics is carried out by big data analytics software. For the progressive changes, user friendly technology and solutions, SoC has been designed, which along with software frameworks like python can offer the high level of productivity. But the system must also be provided with high level of cyber security at the software and networking levels to overcome online threats and cyber-attacks.

3.4. Autonomous Mobile Robots

Fragapane, et al.(2020) explained that the conventional material handling system is replaced by Autonomous Mobile Robots (AMR) to attain greater flexibility in the production lines. The reason AMR is introduced in the production industry is to replace traditional material handling systems for flexibility improvement. The experiment comparing

production lines and AMR is done to assess the impact of flexibility. The parameters are as follows. As represents the availability, M is the number of phases, and ΔFL is the flexibility.
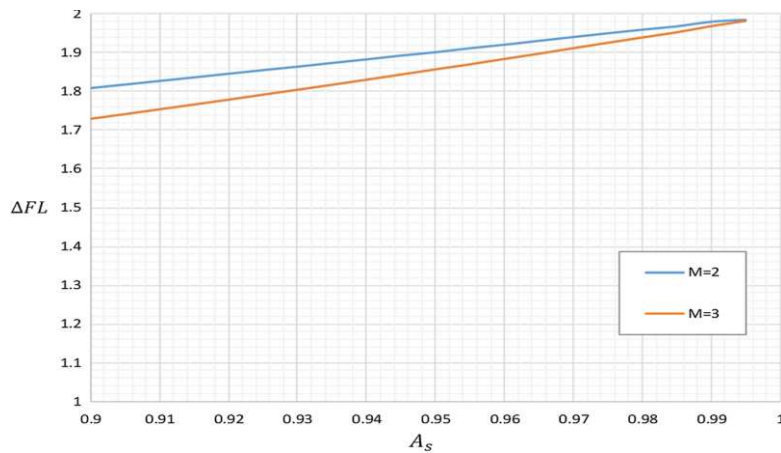
Figure 1. Additional flexibility of production network Fragapane, et al. (2020)

From fig 1. it is certain that use of AMR increases 1.7 to 2 times flexibility compared to production lines. Both throughput and flexibility increase through AMR system which allows interconnection among all the machines of the production system.

3.5. Adaptive Automation Assembly System

In order to achieve flexible assembly systems and to reduce task phases the adaptive automation assembly system are implemented. In Manual Assembly Systems (MAS) the activities take place in several phases. The process of MAS will be flexible but has lower productivity. Bortolini, et al. (2021) explained that in an automated assembly system, high productivity can be achieved but less flexible. To achieve both productivity and flexibility, Adaptive Automation Assembly System (A3S) in Self Adaptive Smart Assembly System (SASAS) has been introduced. The experimental analysis was carried out between MAS and SASAS (manual and automatic configuration) to assess the cycle time reduction and productivity. Configuration #1 represents MAS, Configuration #2.1 represents SASAS prototype with manual reconfiguration and configuration #2.2 represents SASAS prototype with automatic reconfiguration.

Table 1. cycle time(s/pc) Bortolini, et al. (2021)

	Average cycle time	Gap towards configuration 1
Configuration #1	93.6	-
Configuration #2.1	69.9	-25.3%
Configuration #2.2	57.5	-38.6%

Table 2. average productivity Bortolini, et al. (2021)

	Average productivity	Gap towards configuration 1
Configuration #1	38.5	-
Configuration #2.1	51.5	+33.9%
Configuration #2.2	62.6	+62.8%

From table 1. and table 2. it is certain that SASAS with automatic reconfiguration reduces cycle time by 38.6% and increases productivity by 62.8%.

3.6. Digital Twin

A digital twin is digital replica of a physical system. Novák, et al. (2020) explains the technology implemented for production planning is the smart production planning using digital twin. It enables energy efficient process with auto recovery facility. Digital twin requires the following input about the machine and the process to store and use it during the time of machine failure to save time and cost. It requires component state and position, the position of a robot arm,

sensors, Human-Machine interfaces, quantities, and locations. Planning Domain Definition Language (PDDL) is the software, the way the inputs are fed into digital twin. The process planning is carried out between Enterprise Resource Planning (ERP) and digital twin in industry 4.0 testbed to check the process planning time using XML based standard (XES) and ProM. Based on these analyses it is found that production planning took 8 seconds in ERP but using digital twin it took less than 1 second which results in providing enough performance and reliability.

3.7. Autonomous Computing

Autonomic computing supports in autonomy and flexibility of production process. Sanchez, et al. (2020) states that Autonomic Computing in Industry 4.0 assures self-decision making and flexibility of the production process. This is made possible by internet services which use Internet of Everything (IoE) to increase the autonomic properties of the production process. "Everything Mining" generates data which is extracted from different areas and provided to the machine which helps to improve the autonomy of the production process. This information creates knowledge bases that is used for making decisions. Compared with previous works done on manufacturing process coordination, autonomic computing proves to be effective as it satisfies four agendas which is required for coordination. First are the actors (data, people, things and services) attain their vertical and horizontal integrations by coordinating their interactions. Second is the sending and receiving information during coordination process. Third is the coordination which is managed by the autonomic cycles of data analytical tasks and the last one is interoperability of the workers. In other researches, one among these four agendas will not be satisfied which leads to the failure of the tasks. But autonomous computing successfully satisfies four agendas which is why this is preferred in the industry.

4. Discussion

In this review article, the technologies implemented in Industry 4.0 to increase the manufacturing flexibility, productivity and integrity were discussed. Even there are other areas where these technologies can be successfully implemented like the use of artificial intelligence in further development in the production system. For example, the usage of AMR to figure out possible solutions in increasing flexibility and production. AMR can also be used in decentralizing flow of the material due to its firm on-board computational power. But there are some disadvantages like high investment and lack of product mix flexibility which has to be considered before investing in AMR even though it has many advantages. The limitations of smart scheduling procedures involve requirement of readily available data for the new components for decision making as well as it must be protected from cyber-attacks and any online hazards. The future of smart scheduling is based on the examination carried out in different real-world cases for further improvement. In A3S design approaches, prototypes and numerical analysis to the benchmark towards the traditional assembly system is missing and anticipated and then it is applied to the Self Adaptive Smart Assembly System (SASAS) which results in the assembly cycle time. The inclusion of economic and environmental dimensions would further improve the process as it reduces the energy consumption and economically serve for the company. Autonomic Computing improves the communication and exchange of data using IoE which in future can be applied to simulated environment to verify the functionalities of the solution and in other case it can also be applied to autonomic processes for collaboration and cooperation in Industry 4.0. The digital twin which is used for efficient production planning can also be used to industrial simulation system in future for the precise validation of energy and cost. In future cloud computing can used with augmented reality tools to deliver training and guidance to cloud technical staff working from home but the company should be vigilant about the cyber-attacks and online data stealing. Overall, the technologies implemented has their own pros and cons which depends on the working environment and production demands. Each and every technology discussed in this article improves productivity, flexibility and communication yet there are some pros and cons. The usage of these technologies depends on the situation. Even though these technologies increase productivity, the energy consumption for the process is high. Rather concentrating more on the technical side, the life cycle assessment of every process should also be considered to make the process eco-friendlier and more economical. Industry 4.0 is still under research and anticipated to provide the best in the manufacturing industry in upcoming years.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Digitalization in Agricultural Production[†]

Gurban Hashimli [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: gurban.hashimli@s2020.tu-chemnitz.de

Abstract: Modern technology has revolutionized every field of life, and agriculture is no exception to it. The research examines the numerous uses of digital technology in industrial production and considers the changing industrial paradigm. Content analysis may be used to discover collaborative applications and technological trends for digital tools and advanced industrial technologies. Digital technology and its applications have become a critical component of industrial processes. This study investigates the role and applications of Digital Manufacturing, particularly in the field of agriculture. Compared to human labor and old technology, digitalization has increased productivity, efficiency, and wastage of resources. Prospects look bright.

Keywords: digital production; industry 4.0; smart manufacturing.

1. Introduction

Digitalization is applying digital technologies that can help industries make better decisions and increase production by providing them with tools and information. Digital industrial revolution has replaced old methods of production mainly due to their inefficiency and higher costs. Industry 4.0 refers to the fourth industrial revolution, which will usher in efficient, networked, and even customized manufacturing, as well as a new organizational level that will oversee goods whole supply chain management and its complete production process as well. Due to sudden increases in data storage and new computer capabilities and modern technology tools like artificial intelligence, robot technology, and cyborgs have unleashed revolutionary developments that have altered the character and substance of production. Emerging digital technologies have significantly influenced production processes, techniques, concepts, and even companies in recent years (Silva, 2020). The modern technological developments aim to strengthen industry to tackle many worldwide difficulties. It is built on digital and virtual technologies and is powered by data exchange in real-time and flexible production that enables customized output. The researchers believe that advancement in technology is the main reason that have revolutionized every elements of the value chains of the production systems. Computer Integrated Manufacturing (CIM) originated in the 1980s, evolved into Digital manufacturing technology when CIM costs were low enough to allow large-scale use of computers for the machine, planning, and programming control. CIM acted as a bridge between manufacturing, systemic science and other associated manufacturing challenges (Silva, 2019), (Silva, 2020).

2. Methodology

A careful examination of the literature underlines the study strategy. Based on prior work and contributions, it presents a comprehensive picture and refers to future research. Bardin's content analysis lens is used to analyze the selected articles in order to gather recognized themes. The study was reviewed on a case-by-case basis. Text coding, word frequency, and word relationships are used to get the findings. The Science Direct and Research Gate databases were used to investigate the topic of digitalized/smart production. Because they are commonly used as synonyms in academic and professional works, we chose the search words "digital production" and "smart production." Various research papers and publications have been examined to understand the impact of digital technology on industrial manufacturing processes in this regard. By analyzing the content of academic and research publications, consultative studies, many roles of digital technology have been identified.

3. Results

3.1. Higher productivity

The use of digital technologies and tools for the collection, storage and analysis of information to boost food production from paddock to consumer is a global initiative that focuses primarily on supporting sustainable farming and food safety through using information and communication to improve decision making by using internet technology devices. Yield mapping and a GPS navigation system are also components of the exact choice. Data analytics and app development can also give information to the consumer so that they are aware of what they are purchasing. Digitalized agriculture is also known as smart agriculture and e-agricultural, and it was first mentioned in 2017. The automation of farm machinery reduces the labor cost, and digital logistics services offer the potential to the food supply chain. It is estimated that by 2030 it would be a trillion-dollar industry (Horvat, 2020).

3.2. On-Farm efficiency

Digitalization has enabled high production with greater efficiency and better profit ratios. Automated machinery has replaced human labor. It can generate 56% more food for the world's 9 billion people by 2050. Agriculture provides food for more than 60% of the world's population. It can help address climate change, food waste and improve the efficiency and sustainability of agriculture. It also reduces transportation verification costs, the inputs for yield and data searches, and increases efficiency across the agriculture value chain. In the United States, guiding systems have resulted in a 9% rise in peanut fields and a 13% improvement in output due to soil mapping. It also enhances the capital between farms through platforms such as Hello Tractor and WeFarmUp, among others. Search cost between buyers and sellers has reduced because of E-commerce, and it makes the use of agriculture more productive and efficient. Adoption of these new digitalization methods are very costly, and their long-term benefits are rare, so there is a need for collaboration to combat these issues (Parke, 2021).

3.3. Digital Farming

Digital agriculture is reliant on technology and plays a critical role in the interpretation of trustworthy data. Digi farming is accomplished by the use of linked networks and IoT, which stands for the internet of things; these things include sensors, drones, robots, and cameras that are used to provide services. There is a requirement for these tools to be linked to the dashboard for analysis and data relating to the field. This system setup necessitates extensive knowledge and expense, and SaaS, also known as software as a service, is a cost-effective way to transition a farm to digital farming.

3.4. Infrastructure for Digitalization

Improving natural resource efficiency is critical for future sustainable food production. Increasing input efficiency does not ensure the conservation of two resources. According to searches, the agriculture industry is the least likely to use digital technology. And digital technologies operate within 3G and 4G coverage in some countries, making network connectivity for poor farmers prohibitively expensive. In 2007, only 1% of farmers used the internet, but by 2015, that figure had risen to 40%. Digital agriculture is also affected by the importance of agriculture and farm size in a country. Farmers must learn new skills in order to reap the benefits of digital agriculture. Literacy is sometimes required in the digital economy, as is literacy in English or another widely spoken language. There is still work to be done to guarantee that farmers can profit from it (Bacco, 2019).

3.5. Improving Economy

FAO says that the food demand would climb to 70%, as the population increases there is a desperate need to enhance production of food. Many additional challenges, including climate change, water shortages, food safety and other problems, are destroying the farmlands totally, and this will present a significant obstacle to the achievement of food. These challenges may be addressed without damaging the natural by using technology or digitizing agriculture on the key theme of "agricultural sustainability." The development and the support for the farmers was shown to be favorable. The main goal is to boost food production and security while also introducing new technology. The United States of America, China, and India have lately joined this alliance to develop agricultural techniques (Klerkx, 2019).

3.6. Robotics

Robots play a vital part in crop field automation and regularly contribute to crucial tasks; they can be employed for various reasons such as seed harvesting and the application of pesticides and cut labor costs. Although the speed of

farming to automation is love, it happens. Some vital tasks performed by robots are to monitor and forecast a minimal environmental impact because specific artificial intelligence projects are underdeveloped and will be relevant shortly. Drones can be utilized for security and safety in the field, given their ability to stream a video live. Time is gone when only military drones are deployed. A single drone company can watch the hundreds of hectares broad field, and the actual application is precise agriculture by professional drones (Klerkx, 2020).

4. Discussion

In a review of the digital manufacturing literature, two significant concerns were discovered. First, there is minimal agreement on the definition and uniqueness of the phrase "digital production." Several definitions of digital production overlap with the central idea of enhancing manufacturing via the integration of technology. Digital manufacturing is frequently confused with 'digital plant.' The lack of precise concepts for digital production is crucial as it reduces researchers' communication effectiveness and makes the planning, design and implementation of digital producing initiatives more difficult for managers. Secondly, Industry 4.0 on digital production and the influence of technological progress on its use are not transparent. Various research papers and publications have been examined to understand the impact of digital technology on the agriculture industry (Silva, 2019), (Silva, 2020).

5. Conclusion

The agriculture industry's digitization has dramatically enhanced productivity while simultaneously addressing all shortage problems. Sensors are an example of technology. The use of an irrigation system and drones has assured that the fields are healthy and disease-free. Modified crops also allow farmers to cultivate foods under dry conditions, where present methods are insufficient to provide the body's nutritional needs. The world's food system has been challenged in providing food to an ever-increasing population. Its rapid rise is also pioneering a new set of technology and providing new and improved approaches for small-scale farmers. The potential latent in agriculture's digitization is being put to good use in developing nations putting these digital initiatives in place and seeing benefits.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Quality assurance in the manufacturing process using object detection with deep learning methods[†]

Wang Yu Cheng [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
[*] Correspondence: yu-cheng.wang@s2019.tu-chemnitz.de
[†] Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: With the advances in new-generation information technologies, especially artificial intelligence algorithms, industry 4.0 is becoming the focus of global manufacturing upgrading. The challenges in quality assurance of the manufacturing process are resulted from the increase of complexity of the manufacturing process. Object detection with the deep learning method is a solution to deal with these problems. It is based on the concepts of convolutional neural networks and data processing in deep learning. In this report, a study is performed to discuss the structure of CNN and compared the applications to understand the procedure of implementing quality assurance in the manufacturing process using deep learning methods.

Keywords: Industry 4.0; Quality assurance; Deep learning; Object detection; Smart factory.

1. Introduction

Nowadays, Industry 4.0 is an important field in manufacturing. There are so many concepts such as the Internet of Things, Digital Twin, Smart factory regarding industry 4.0. These methods make the manufacturing process more flexible and smarter. The most important objective of Industry 4.0 is the realization of intermittent manufacturing at mass production's productivity and specific cost (Illés et al., 2017). It increases the complexity of the manufacturing especially in the quality assurance of the workpieces. To achieve quality control, they build an object detection system with deep learning theory (Saca et al., 2020). They proposed a Convolutional neural network model to recognize the gears with different colors and shapes. In the real-time detection system, they established a tiny part defect detection method and compared the results with other object detection models such as YOLO, Faster-RCNN, FPN model (Yang et al., 2019). There is a traditional image processing method, Compensated edge images to extract features, and implemented a three-layer neural network to achieve object recognition (Kim et al., 2012). In another application, quality assurance via a deep learning detection system is also an important process in metal powder bed fusion (Kunkel et al., 2019). A prototype of a Smart factory to understand the function of the deep learning method in the manufacturing process (Ozdemir et al., 2019). This report discusses object detection technologies and understands the role of deep learning in industry 4.0.

2. Methods

The industry 4.0 field contains much information. Using a search on google scholar contains the term "quality assurance", "object detection", and "manufacturing process". There will be many applications using the object detection method. Some applications use the traditional method like template matching, edge detection to achieve object detection. Considering the technologies of industry 4.0, the current research will use the deep learning method. I focused on using the CNN model to implement object detection. Finally, I found the four different applications using the deep learning method and three papers about the theory of convolutional neural networks and the idea of industry 4.0 related to quality assurance.

3. Results

Convolutional Neural Network is a class of deep neural networks, and it is usually used to analyze the image data (Albawi et al., 2016). In Neural Network, It contains three main layers, input layer, hidden layer to implement feature extraction, and output layer to get the results. Because the input feature of the image is in the pixel type, and each pixel

contains 3 elements like the RGB value. The size of features of an image is too huge. Therefore, there is a convolutional layer in the hidden layer of the Convolutional Neural Network. This convolutional layer not only reduces the size of the image but also remains the feature of the position by using Kernels. The kernel is a filter to get convolved feature maps by sliding along the input image. deep learning, we could control the size of the kernel and strides to get the different feature map. In the feature extraction layer, we use the Activation function, Rectified linear unit (ReLU), and max-pooling layer to determine the output of the neural network. The main concept of object detection with deep learning is the structure of the neural network model.

There will be different datasets according to different applications. The dataset of the Automatic product identification system is 800 images which contain four different colors and two different shapes. The total database is divided into two sets, 80% of the images are training data and 20% of images are testing data for the model (Saca et al., 2020). Image processing before training is important to get better results. It resizes the images and applies the filtering by the color band for each one of the colors sought. After finishing the preparation of the dataset, we use the loss function to evaluate the score of the model. In Fig. 1, we could see the training loss is decreasing and training accuracy is increasing with more epochs.

(a) Training loss   (b) Training accuracy
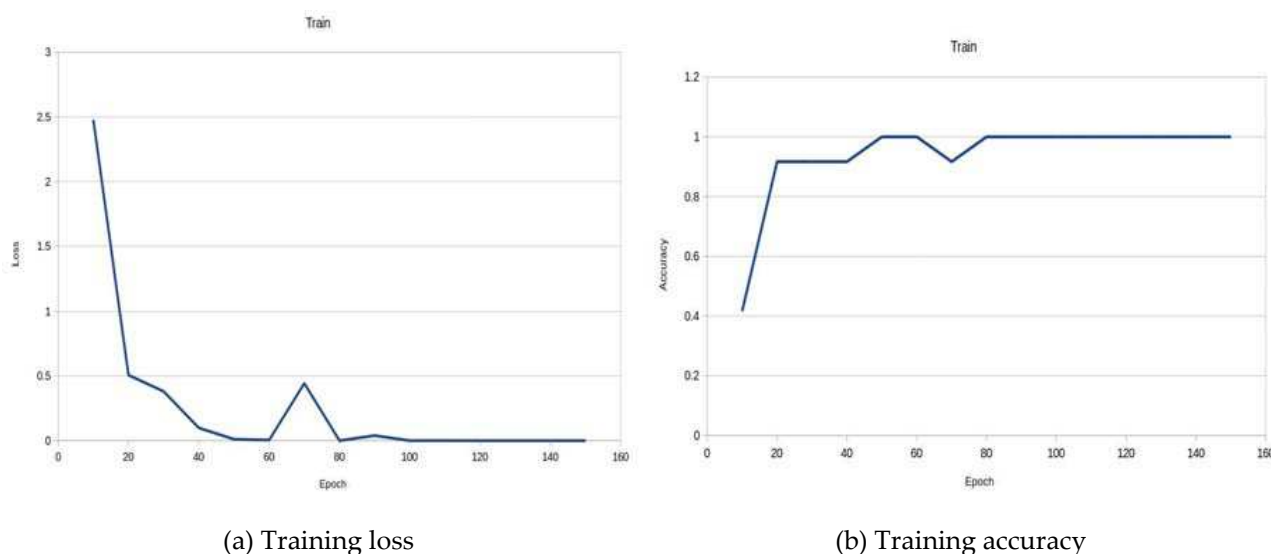
Figure 1. Training results for the proposed CNN architecture (Saca et al., 2020)

In another application, they collect a darning needle dataset with 3000 images including 2140 training and 860 testing images. The training and testing images contained 6306 and 2000 0.8 cm darning needle labels. The samples are in Fig 2. Data augmentation, a kind of image pre-processing, is a common technique that can improve the robustness of an algorithm. They operate on the image data with rotation angles of 0°, 22.5°,45°, 67.5°, 90°. It expands the size of the dataset to five times. Data augmentation methods can create variations of images that are more flexible to get higher accuracy under different surrounding conditions. They include translation, cutting, horizontal flipping, etc.

(a)   (b)   (c)   (d)   (e)
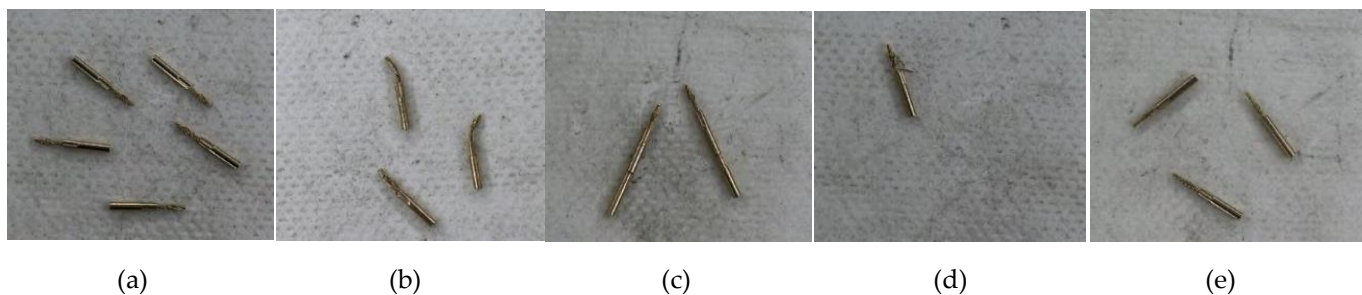
Figure 2. Example of autonomous collection of experimental data in the paper [3]. (a) Normal (b) Defect 1: Crooked shapes (c) Defect 2: Length size errors (d) Defect 3: Wringing errors (e) Defect 4: Endpoint size errors

In the cell manufacturing system, there are different image processing methods. It uses Compensated edges to do feature extraction. The Compensated edges method combines the two parts. One is local adaptive binarization, the other is the difference of Gaussian filter in Fig.3 . It will reduce the complexity of the neural network model to achieve object recognition (Kim et al. 2012).
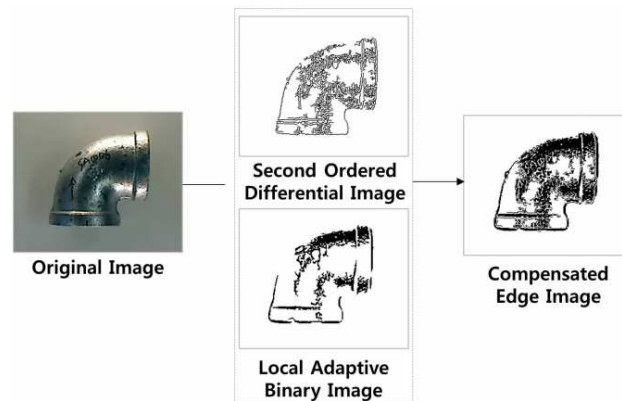
Figure 3. Compensated edge images.

The quality assurance in metal powder bed fusion via deep-learning-based image classification used two additional convolutional stages in the neural network. The filter size for all convolutional stages was set to 11×11 pixels with a max-pooling and stride of 2×2 pixels and padding set to "same". From overall 18581 centered, randomly rotated, and shuffled images 1,000 were withdrawn for testing so that 17,581 images remain for training. The training comprised 10,000 training epochs with a training batch size of 10 images per epoch and a learning rate set to 0.0002. Finally, the result was the 99.7 percent test accuracy (Kunkel et al., 2019).

4. Discussion

From all the papers we discussed in this review, it is seen that using object detection with deep learning is influenced by many factors, the real situation, the number of images, the structure of models. The convolutional neural network is used in tobject detection (Albawi et al., 2017). There are already some useful CNN models for object detection, YOLO, FAST-RCNN, etc. The automatic product identification system tried to detect different colors and shapes of gears (Sara et al., 2020). Real-time tiny part defect detection system focused on the tiny part defect, crooked shapes, length size errors, wringing errors, endpoint size errors. Data augmentation is a solution to expand the size of the dataset to improve accuracy (Yang et al., 2019). If we have more understanding in the field of manufacturing, it will get better results possibly. After completing the algorithm of object detection, the next step is how to combine the system with the existing manufacturing process. We could understand that the traditional image processing methods are also important to implement feature extraction (Kim et al., 2012). To reach the vision of Industry 4.0, object detection with a deep learning method is an important part of Smart Factory. The model of Smart Factory shows the deep learning techniques can be used in many areas as well as providing effective solutions in the field of quality control automation studies (Ozdemir et al., 2019). The effective quality assurance method is a core of smart factory.

Nowadays the flexibility and specific cost of manufacturing have a relevant role in the competitiveness of the companies. This aim increases the manufacturing complexity which results in new challenges in the quality assurance of the manufacturing process (Illés et al., 2017). The new technique, Deep learning, is a kind of effective solution to implement object detection. However, it is hard to implement the existing model to get the best result directly. We still need to understand not only the concept of neural networks to adjust the model but also the knowledge of manufacturing to decide the input label and final target. In these applications, they ignore the cost of training a new model. The time of collecting useful images, labeling the images, and training a new model is higher than traditional object detection methods. Besides, the deep learning method is a kind of black-box method, it contains uncertainty and increases the difficulty of adjusting the model. Object detection with a deep learning method is a solution to overcome different manufacturing applications. Although it should adjust the structure of the model and implement the image processing of the dataset, it is a flexible and best solution to achieve quality assurance with high accuracy in the manufacturing process. It can

work in variable surrounding conditions and in real-time, and it also contains more possibilities in the field of Industry 4.0.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

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Review article

Application of Deep Learning Algorithms in Industry 4.0[†]

Seyed Ali Hoseini [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
[*] Correspondence: sehos@hrz.tu-chemnitz.de

Abstract: Industry 4.0 refers to the world's fourth industrial revolution, which has accelerated global development. One of Industry 4.0's key goals is to increase asset uptime to boost productivity and lower production and maintenance costs. Emerging technologies like artificial intelligence (AI), the industrial Internet of things (IIoT), and cyber-physical systems (CPS) have sped up the development of data-driven applications, including production planning, predictive maintenance, and inventory management. To minimize failure or high costs, an accurate estimate of future demand or future demand is essential. Deep learning is a type of prevailing machine learning algorithm widely used in big data analytics. This review paper will focus on the application of deep learning under industry 4.0 during the recent years between 2016 to 2021.

Keywords: Deep learning; Machine learning; Industry 4.0.

1. Introduction

Industry 4.0 refers to the fourth industrial revolution, which is transforming industries all over the world. Digitization and Intelligentization are two essential components of Industry 4.0 that have significantly impacted the industry. New technologies such as AI, IIoT, and CPS have expedited the industry's development in this environment. AI is a branch of cognitive science that focuses on image processing, natural language processing, and robotics, among other things. It has emerged as one of the most important technologies in Business 4.0, attracting significant interest from both industry and academics (Rauch, Linder, & Dallasega, 2020).

"Autoland Saxony" is one of Germany's leading auto locations today, with five production sites operated by Volkswagen, Porsche, and BMW, as well as around 780 branch suppliers, equipment, and service providers. The automobile industry, which employs approximately 95,000 people in Saxony, has the biggest turnover. It accounts for more than a quarter of industrial turnover and more than a third of international sales. For more than a century, motor cars produced in "Autoland Saxony" have provided people with mobility. It was here that innovations like the first mass-produced left-hand drive vehicle and front-wheel drive found international success. Saxony is responsible for around one-eighth of all automobiles produced in Germany. Assets are crucial to the industry's operations.

Asset failure results in significant revenue and productivity losses. Unsurprisingly, asset lifetime management has become a crucial concern in modern industry, given the huge business impact of unexpected failure. In the framework of Industry 4.0, big data has dominated. Industrial big data analytics is a major problem for the sector since it can provide significant insights for decision-making. These characteristics make typical data processing techniques difficult to use to process industrial big data. The big data gathered from the industry provides various information on the assets' processes and events. These details may be pertinent to the asset's lifespan. With the growth of data analytics, it is now possible to gain insights that will help to manage the maintenance better (Chen, et al., 2020). Artificial intelligence, the industrial Internet of things, and cyber-physical systems have all contributed to developing data-driven applications such as predictive maintenance. Maintenance is a top responsibility for an automotive fleet management company. It can avoid catastrophic failure and subsequent loss by using an accurate maintenance model. Deep learning is a popular machine learning algorithm that has become increasingly popular in large data analytics

This research answered the following research questions concerning the targets of the study:

- Question 1: Under Industry 4.0, which categories have been classed as deep learning applications?
- Question 2: Which major contexts are mentioned for deep learning applications in industry 4.0?

2. Method

This research used the Systematic Literature Review (SLR) method as a research study evaluation approach to categorize deep learning applications under industry 4.0. The keywords used in finding the studies were including:

Deep learning, Application of deep Learning, industry 4.0, Big data in industry 4.0, Digitalization using deep learning, deep learning in the automobile industry, Artificial intelligence in the industry

The selection of an assessment chart and criteria for research surveys showed in Figure 1. Chapters from books, incomplete studies, and non-peer-reviewed surveys are among the items that have been left out. The principles that are deemed to be included were:

- The researches published from 2016 to 2021
- The studies with more than 15 citations

The following researches were excluded:

- Researches not available in Web of Science (ISI-indexed)
- Researches not written in English

Finally, nine research articles were approved to examine and answer the analytical questions outlined before.
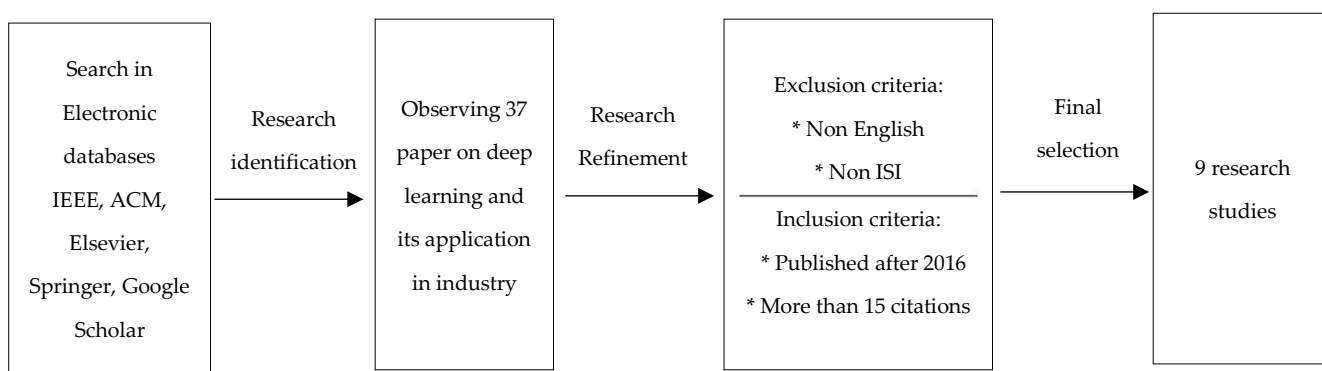
Figure 1. The selection criteria, as well as the chart for evaluating study outcomes.

3. Overview of Deep learning and algorithms

Deep learning is a subset of machine learning that can automatically learn hidden patterns inside data by stacking numerous nonlinear processing layers. According to the literature, the difference between deep learning and conventional machine learning in terms of modeling path was evaluated and illustrated in Figure 2below. It can be shown that both deep learning and traditional machine learning require data pre-processing, with the key difference being how features are processed. Feature engineering, such as feature extraction and feature selection, is required in traditional machine learning methodologies. Domain knowledge is crucial in these procedures. On the other hand, deep learning can automatically learn hidden patterns, making the modeling process more efficient and effective. However, there is a disadvantage to it. The feature abstraction process in deep learning is a black box since it cannot be understood or articulated. Several key deep learning algorithms are introduced in this part and the industry's deep learning applications.
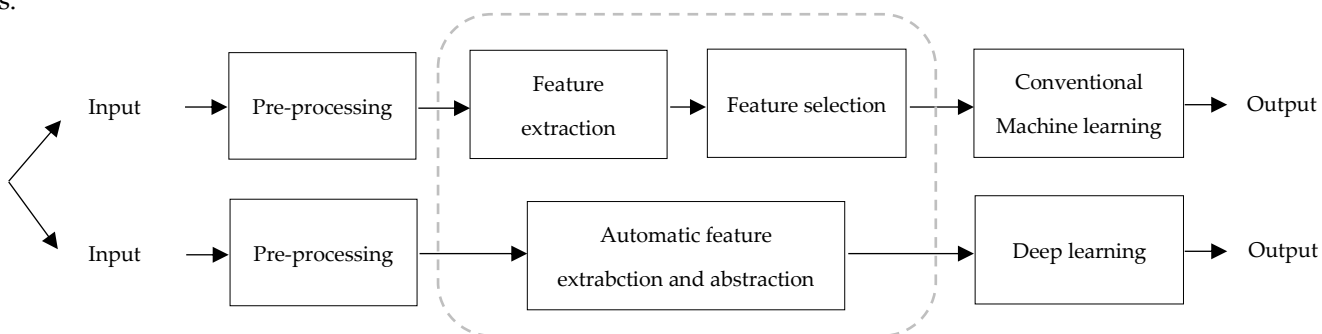
Figure 2. The contrast of conventional machine learning vs. deep learning modeling.

3.1. Deep Learning Algorithms

3.1.1. Fully Connected Neural Network (FCNN)

The most basic type of neural network is the fully connected neural network. It's also known as a Multi-Layer Perceptron (MLP) or a feedforward neural network. MLP was proposed by Rumelhart, E. Hinton, & Ronald J. (1986). The input layer, hidden layer, and output layer are the three layers in the most basic MLP. The input layer is responsible for processing the data, whereas the output layer is responsible for obtaining the result. The abstract features that are important to the output are obtained using the hidden layer. The failure of the learning process is caused by the gradient explosion and disappearance in the back-propagation phase. As a result, training an MLP with several hidden layers at that time is difficult. A deeper neural network is now possible due to advancements in modern methods such as Rectified Linear Unit (ReLU), dropout, and optimizer. A deeper FCNN can model the nonlinearity of the input data more effectively.

An FCNN has multiple layers, each with a variable number of neurons. A computational unit is each neuron. The neurons in the previous layer's output (x_1, x_2, ..., x_n) are fed into the neuron. The input will then be multiplied by the weights (w_{j1}, w_{j2}, ..., w_{jn}), and the products will be added together with a bias (b_j). The following is the equation:

$$S_j = \sum_{i=1}^{n} W_{jn} * x_n + b_j \tag{1}$$

S_j will then be routed to the activation function f(). The neuron's output is represented by y_j from f(). The weight (w_{jn}) and bias (b_j) of each neuron are the most important factors to consider when training the neural network. The back-propagation (BP) algorithm will be used to determine the weight and bias. To generate a rough weight and bias, an FCNN is initially trained feedforward. The final output will be compared to the actual value. In order to fine-tune the weight and bias, the model will be trained from the output layer to the input layer if the error is high. The BP algorithm is typically executed numerous times to fine-tune the weight and bias, resulting in a long training time (Goodfellow, Bengio, & Courville, 2016).

3.1.2. Convolutional Neural Network (CNN)

CNNs are neural networks that can handle data with a grid-like layout, such as images. A two-dimensional matrix can be thought of as an image. CNN has a lengthy history of being probed for speech recognition and document reading, dating back to the 1990s. CNN has reached the mainstream in computer vision since ImageNet (a deep CNN structure) was established in 2012. It excels at processing a large number of photos with over a thousand different categories.

3.1.3. Recurrent Neural Network (RNN)

In deep learning, RNN is a popular method for dealing with sequential data. RNN has been widely employed in the fields of speech recognition and text mining since its inception. Unlike FCNN, which processes each instance independently and updates the weights and bias, RNN has a state unit that can store the information from previous elements. To put it another way, the weights in an RNN are shared by multiple instances of the neurons (Goodfellow, Bengio, & Courville, 2016).

3.1.4. Autoencoder

For unsupervised learning, an autoencoder is a deep learning structure. The autoencoder's input and output are identical. The encoder and decoder are the two halves of an autoencoder. The encoder and decoder usually share the same hidden layer, which is the neural network's middle layer. The encoder, which seeks to compress the input, is made up of the input layer and the first part of the hidden layer. The number of neurons in the layers of the encoder must be reduced layer-by-layer in order to compress the input to a more dense and complicated representation. Code is the term for a dense and complex representation. The decoder, on the other hand, must be set symmetrically to the encoder in order to construct the input data from the code. As a result, an autoencoder has a sand clock structure, with the code as the output of the bottleneck (i.e. middle layer) (Goodfellow, Bengio, & Courville, 2016).

3.2. The Applications of Deep Learning in Industry

The amount of data available in the sector has expanded dramatically as a result of the rapid adoption of the Internet of Things. Deep learning, as a collection of popular machine learning algorithms, has gotten a lot of interest recently because of its capacity to handle big industrial data. Deep learning is a sort of machine learning that is commonly used to recognize objects in photos, transcribe speech into text, and choose data from databases (Wang, Ma, Zhang, Gao, & Wu, 2018).

CNN's main focus in the industry is fault defect detection. CNN is well-known for its visual data processing abilities. It's becoming more and more common in the industry. (FERGUSON, 2019) presented a standardized CNN format based on predictive model markup language to detect casting errors using X-ray pictures (PMML). To begin, the pre-trained Image Net models are transformed to PMML format in order to optimize their distribution and deployment. The categorization results are then obtained by fine-tuning these models. Because of its low interpretability, deep learning is considered a black box (FERGUSON, 2019).

In the industry, CNN is used for tool wear monitoring, design optimization for additive manufacturing, and human action recognition, among other things. (WILLIAMS, G, MEISEL, N. A, SIMPSON, T. W, & MCCOMB, C. , 2019)study the effects of design repository standardization on CNN's ability to analyze additive manufacturing geometric data. In human-robot collaboration, identifying human action is a critical task. To address the difficulties of low accuracy and robustness of human motions recognition as well as a lack of data volume, (XIONG, Q, ZHANG, J, WANG, P., LIU, D, & GAO, R. X., 2020) developed an integrated method based on optical flow and CNN-based transfer learning. The optical flow pictures, which contain information about human motion, are employed as the input to a two-stream CNN in order to forecast human motion in this study. The feature extraction capabilities of the pre-trained CNN are then transferred into industrial settings using transfer learning.

Autoencoder has also piqued the interest of researchers in recent years. For machine defect prediction, (SUN, C, et al., 2018) presented a deep transfer learning network approach based on autoencoder. Weight transfer, hidden feature transfer, and weight update are three transfer strategies used to train a sparse autoencoder in this study. When the historical failure data is restricted, the transferred sparse autoencoder can achieve a similar performance to the supervised learning strategy, according to the experimental results.

4. Discussion

Deep learning can bypass complex feature engineering and be trained in an end-to-end learning method by stacking raw data and data labels. More data, such as photos and vibration signals, is becoming available as the Internet of Things grows. Label accuracy is important for deep learning. Because past maintenance data is gathered from the real world, data with incorrect labels is considered a minority. Second, in order to conduct reliability analysis, the failure time of automobiles in historical maintenance data is assumed to follow a particular distribution. Deep learning can be a useful method for dealing with enormous amounts of data in the industrial sector. A number of deep learning algorithms were shown. Deep learning has become the industry standard in industrial big data analytics due to its capacity to analyze numerous sorts of data.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

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Review article

Blockchain in the age of Industry 4.0: Current applications and challenges regarding the industry 4.0[†]

Samuel Cardoso [1,*]

[1]   Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: samuelrscardoso@gmail.com

Abstract: The industry 4.0 concept became necessary due to the new reality of transformations provided by the advent of the internet being applied throughout the production process. The usage itself generates lots of data which brought more concern in the last five years. This review uses articles to analyze the usage of one of the possible ways to manage the industry 4.0 database, especially in the supply chain area: blockchain technology. The objective is to point out how Blockchain is being used in industry 4.0 and its challenges. The review is conducted based on internet-based data management and processes throughout industry 4.0.

Keywords: Blockchain; industry 4.0; smart contracts, industry data.

1. Introduction

The concept of Industry 4.0, due to its broad scope, has gained more notoriety and applicability around the world in recent years. The reason for this is that many technologies are under the umbrella of the fourth industrial revolution. Among them are the Internet of Things, high degree of automation, artificial intelligence, additive manufacturing, greater complexity in the production process, connectivity throughout the product's life, integration between processes and sectors, and this whole range of technology producing, using, and transferring lots of data. (Esmaeilian et al., 2020)

When it comes to data, it refers to all types of information related to the projects, processes, products, services, supply chain, customers, and relationships between all the links contained in the product life's chain. Regarding industry 4.0, how all the data is managed, either using or keeping it safely, determines how much a company can apply the industry 4.0 concept. All those analyses and connections generate data bringing more quality, cost reduction, waste reduction, complexity, efficiency, and personalized products.

Nowadays, a significant part of the industry's dataset is not being used properly due to some factors, such as difficulty to filter the data, lack of knowledge about different ways to take advantage of the database, lack of security, and insufficient storage capacity. Recently, after 2015, a new technology, known as Blockchain, is being discussed and, in some cases, applied in industry 4.0 technologies.

The Blockchain itself was created in 2008, but until 2015 was hidden behind Bitcoin. Bitcoin is a currency developed in 2008 after the world economic crisis. The currency was projected to bring more decentralization, eliminate intermediaries' financial institutions, and bring more security to monetary transactions. All those advantages took place because of the technology that is the basis of Bitcoin, which is the Blockchain. (Mushtaq & Haq, 2019)

Blockchain works as a register shared on a network between its members on a peer-to-peer basis; no intermediaries are needed, which helps to save time and cost in the first place. Not only that but Blockchain also has some features that drawn attention regarding its usage into the industry. Some of the intrinsic Blockchain characteristics are immutability, in other words, has sophisticated cryptography that does not allow changes on it after registering a piece of information. It is transparent. Each computer that is part of the network has a copy of the register. It is distributed, not being necessary a particular location for it. It has no links between the peers, which means the algorithms are self-executable. Besides that, Blockchain has a mechanism known as a proof of work (PoW) that makes all the transactions inside the network easy to be verified by other members. Moreover, the transaction also has a timestamp giving to it the exact moment it was done. (Esmaeilian et al., 2020)

All these attributes make Blockchain an exciting technology to be linked to industry 4.0. Either for saving time or making supply chain registers, for starting a 3D printing process or any other machine process autonomously, or even for increasing security. Both technologies are relatively new and have a path to be constructed from now on. Industry

4.0 may bring more notoriety to Blockchain and, as an immediate consequence, more development regarding its attributes. On the other hand, Blockchain may improve transactions, registers, specific autonomous actions, and database security for Industry 4.0.

This brief review focuses on possible combinations between these two technologies, pointing applications, benefits, and challenges. Also, pointing out how industries are using the technology already, how it can be used, in which areas it can be beneficial enhancing versatility, and the challenges faced by the industries that already decided to take the risk of using new technology.

2. Methods

The research was conducted based on internet-based topics and their connection to industry 4.0. In order to realize the selection of papers, previous research was done aiming to select the main points discussed during the last decade related to industry data management, data transfer, information transfer, information security, and information flow throughout the product life cycle.

The first step of the research revealed essential points that are being studied recently, such as security issues with managing the industry's data, data transfer, and data usage. Based on those results, a second research step was conducted aiming at new technologies used to address the issues related to the previous analyses. Among many technologies that are being used, one appeared to be relevant in the last three to five years: Blockchain technology. The relevance noticed while researching made the topic of Blockchain and its current usage the center point of this review. An additional filter used to pick the blockchain topic is that since 2015 many industries 4.0 areas have been developing. However, the database area, such as data usage, data security, and data storage, is struggling to achieve a new level of development, and Blockchain can be a way to a new patamar.

3. Blockchain usage analysis in Industry 4.0

As mentioned before, Blockchain as a technology can bring more efficiency for some areas that belong to Industry 4.0, such as supply chain, product life cycle, and more security for all the generated databases. The most effective way Blockchain may impact manufacturing is through smart contracts acting in the database area. Smart contracts are autonomous agents that work in real-time within a decentralized business network. Some protocols such as Etherium, for example, allow writing contracts using logical codes, in other words, programming in a public Blockchain, in a way that makes previous arrangements to be done automatically, fulfilling what was determined in the smart contract. It grants permission to execute tasks such as activating a 3D printer, starting an AGV inside the factory plant, or even realizing a simple delivery process using small robots that operate through smart contract conditions. (Kapitonov et al., 2018)

Managing all the links in a product life cycle can be a complex task depending on the product regarding the supply chain area. Creating and distributing goods may span multiples stages, locations, invoices, and payments. The greater the number of assignments to be performed, the greater the time and cost involved, and these factors maintain the chain with less efficiency and decrease industry 4.0 efficiency.

Nowadays, related to the supply chain area, most companies have their supply chain divided in several ways. It happens due to the lack of transparency and all those complexities along with the product life. One example that can be given to illustrate it is a manufacturer ordering some essential components from a supplier to provide a good for end-users. The supplier also orders different elements from other suppliers, supposing that each link works on a just-in-time basis, which requires dynamism in the whole chain. If there is a delay in one link, the entire chain will be delayed.

Additionally, it is difficult to take legal actions against the one who promoted any postponement. Because of its unique attributes, Blockchain, through smart contracts, can transform the whole supply chain by dividing it into two dimensions: The first is the physical supply chain, which is the transportation part. Smart contracts can control transportation via autonomous vehicles for supplying material within short distances. The automated vehicle can deliver goods to customers too. Whether delivering to customers or supporting actions into the factory, both actions are done via smart contracts. This usage promotes more reliability to the process once it is done through a contract written as a code and constantly checked to meet the written conditions all the time. Additionally, legal actions can be taken if one link brings losses to the others during the product cycle.

The second dimension, the data value chain, represents data collected from the machines and sensors present along the entire end-to-end supply chain. All those data can be placed on blockchains to keep the records and add value to the business for future analyses.

Another application of Blockchain in Industry 4.0 is related to traceability. In other words, the ability to verify the product's history and trackability, which are ways to find key performance indicators. Those two factors are very relevant because they describe the product from the inception to the service and disposal phase. Blockchain can help organize securely distinct development strategies, capabilities, and information throughout the product life management. This use would give all the managers and company's stakeholders a better product life view in real-time, without waiting for reports. Besides that, the ability to track the product's life allows more improvements for future products, keeps the organization up-to-date, and manages product intent and customer expectations. The ability to track makes contributions in improving product quality and liability, providing more accuracy. (Mohamed & Al-Jaroodi, 2019)

The third possible application pointed for Blockchain and industry 4.0 in many articles is its capacity to add more safety. Due to its distributed linked actions records, named blocks, connected and secured using encryption codes, there are two keys for enhancing this system's effectiveness. One is a necessary consent among the members that add blocks to the Blockchain, and the other is the links created from one block to the next, making it very difficult to be changed once it is added to the chain. The blocks are usually timestamped, encrypted, and replicated on different sites. All that combined gives the ability to protect data as industry's copyrights, for example, using Blockchain to register a catalog containing original works. Not only that, but in the IoT era, where everything is connected all the time, blockchains can make things happen safely without human intervention for further verifications. An example that describes it is devices connected to a blockchain network contracting services and paying for them autonomously. Current many frauds happen during transactions like that, which are online payments and transfers. Once an intermediate is needed for transactions, hackers often create a virtual mask for websites that fakes the intermediate, and through that, they can redirect the money paid. When using Blockchain, those frauds became much more challenging due to the transparency of the distributed and checked system that does not require an intermediate. (Jovović et al., 2019)

Still dealing with security, many of the safety mechanism used until now is incredibly centralized. This centralization is not well suited for IoT because it has one central point of failure making the system more vulnerable. As Blockchain is a widely spread system, it may bring fewer vulnerabilities. Not only that, but Blockchain also has an improved authentication system either for members' privacy or for checking what happens within the network when any information is required or transferred. As previously pointed out, the decentralization and verification by different members, once a data transfer or access is required, is immediately confirmed by others and documented, granting more integrity.

Many more blockchain applications are being discussed right now related to industry 4.0. However, these briefly described in this review are the ones which have more acceptance at this moment. The approval to use or not Blockchain still in argumentation due to the challenges that come with new technology as it is. In the next session, some of these challenges are discussed.

4. Blockchain Challenges in Industry 4.0

Blockchain seems to have many advantages to be explored and used in the following years. Nowadays, some companies like IBM are investing resources to develop even more the designed attributes that belong to the technology itself. Nevertheless, like every innovation, Blockchain has many blind points related to challenges for companies working on it.

The main problem at this point regards security, and it is known as the 51% effect. Blockchain requires different agents into the network to check the actions registered into the block. If someone takes control over 51% of this verification process, then the person/entity controls the block. Due to this majority attack possibility, hackers or people interested in some specific database can join together, forming checking/mining pools, holding more than 51% of the power. It is possible to modify transactions and interfere with the chain faking data, creating double checks. (Lin & Liao, 2017)

Additionally, there are also attacks during the authentication process, in which one chain node is corrupted, and all the following nodes receive wrong commands. One serious problem with authentication attacks is when it happens to AGV (automated guided vehicle), where the hackers can lead the vehicle in another way from the original route. Private Blockchain could decrease the probability of suffering these kinds of attacks. However, private ones are not always suitable because different agents have different purposes requiring a public blockchain, which is more vulnerable. Besides that, even private networks have loopholes that make cyber-attacks possible. (Gupta et al., 2020)

The second challenge widely discussed is Blockchain scalability. Having all the transactions registered on a ledger brings more security, but on the other hand, it makes it more difficult to store all the data recorded. The significant number of transactions also affects the ability to scale because it results in communication malfunctions among users. (Esmaeilian et al., 2020)

Parallel to those challenges, some others have been improved, but still a problem somehow. It is possible to point the lack of knowledge about Blockchain by most companies. The cost of implementation once is necessary to train

people and replace existing infrastructure. Legal and compliance issues are not well defined as the technology is still being developed—lastly, the challenge in verifying data accuracy, known as the last mile problem. (Lee et al., 2019)

5. Results

Given the research carried out, the information obtained regarding the use of blockchain technology in Industry 4.0 concerning the industry data management and its nuances, can conclude the following:

Some large industries, such as IBM, for example, are getting ahead of the curve in researching more about the use of the technology and are carrying out more robust implementations in specific areas of the industry such as in supply chain logistics.

Some industries develop private blockchain networks and use the function of smart contracts for small-scale internal robotic operations, in which a programmed robot performs tasks as conditions previously described in the smart contract are met.

The vast majority of industries exposed to the possibility of using Blockchain are still very skeptical about the technology due to possible security problems and the early stage of development in which the technology is found.

These were the main results found in the research conducted on the implementation of Blockchain in the industry, considering its use for data management, information, and commands performed throughout the industry's processes. Considering industries already operating in the molds of industry 4.0, having all the processes, machines, and levels connected and operating on an internet-based system.

6. Discussion

From the facts exposed in the review of the papers and articles, some conclusions can be drawn. Either Blockchain or Industry 4.0 are new technologies and have much room for improvement. Industry 4.0 already has some notoriety due to the necessity of a more related industry in the internet era and the urgency for more efficient product life management. On the other hand, Blockchain has its history linked to Bitcoin only, making its application in other areas somehow delayed due to the lack of knowledge.

After drawing more attention in the last five years, Blockchain demonstrated that it could be used behind Bitcoin and other applications. For example, this paper is describing Blockchain usage throughout the industry. In this case, this technology can enhance security using a ledger that registers and checks every transaction by its members. Also, it can improve the supply chain by using smart contracts that establish certain conditions beforehand and execute tasks autonomously since the previous conditions are met. Additionally, Blockchain promotes better performance for traceability and trackability. Finally, but still significant, Blockchain facilitates the management of payments and invoices.

Despite offering many advantages, there are still uncertainties and challenges intrinsic to Blockchain. Such uncertainties are related to security, scalability, lack of knowledge, implementation costs, and data storage. Assessing the positive factors and the challenges brought by Blockchain, at this point in industry 4.0 history, Blockchain is not the first option to be adopted yet. Neither for security nor supply chain. The technology must be more widely known, improves security fails, and especially find a way to deal with the amount of data stored. Then the costs for training and implementation will be justified, and the technology itself will be more reliable to be applied on a large scale.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

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Advances in the field of Cyber-Physical Systems

Review article

Cyber-physical systems architecture for industry 4.0[†]

Md Thariqul Islam [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
[*] Correspondence: md-thariqul.islam@s2020.tu-chemnitz.de
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Abstract: When it comes to Industry 4.0, Cyber-Physical Systems (CPS) are regarded as one of the most essential components, with the state-of-the-art and standard CPS architecture playing a significant part in comprehending the nature of the industrial environment. In particular, traditional CPS designs are not up to date or persuasive in their ability to meet the objectives of smart industries. Currently, CPS is lagging behind in terms of adopting and emphasizing the main interface features that are necessary for Industry 4.0. In this paper, we have examined the designs of 5C, 8C, Anthropocentric Cyber- Physical System (ACPS) and an enhancement to the 3C CPS design in order to improve the performance of CPS-enabled smart manufacturing in Industry 4.0.

Keywords: Cyber-Physical Systems; Industry 4.0; smart factory; Cyber-Physical System architecture.

1. Introduction

Cyber Physical Systems (CPS) is a fast-growing subject that will impact every part of life in the near future. It will revolutionize the way we interact with information and will contribute to the rise of information technology professionals. It is a new and evolving paradigm that consists of a mixture of cyber and physical components. With the use of sensors, actuators, robots, and embedded systems, CPS is the primary linking element that helps to establish strong linkages between the real and virtual worlds, while also transmitting and processing critical and sensitive information. The term CPS originally surfaced in 2006, during an NFS workshop held in Austin, Texas, USA, and has been used since then. Specifically, it was defined as a system composed of collaborative entities, each of which is equipped with calculation capabilities, as well as actors who are in close contact with the physical world and phenomena in which they live, using and providing all together services of data treatment and communication that are made available through the network Sadiku et al. (2017). CPS is a critical technology for Industry 4.0, and it has recently gained a great deal of interest from researchers working on smart manufacturing, Lu et al. (2017). That's why we need a efficient and effective CPS architecture. There are various distinct smart manufacturing architectures described in the literature, including the 5C architecture, the 8C architecture, and the 3C architecture. The purpose of this article is to examine different architectures and recommend the one that is best suited to the requirements of CPS integration in Industry 4.0. To be more specific, this study proposes to expand the 3C CPS design, which is based on the classic 3C design, by integrating the primary interface components, such as connectors and protocols, along with sub-components, such as human, cyber, and physical portions. Furthermore, the adaption of sub-interfacing parts contributes to the improvement of the degree of uniformity of human, cyber, and physical components in Industry 4.0. Furthermore, the embedded system-based electronics sectors will be the primary users of our suggested CPS architecture in the real world.

2. Methods

The research papers discussed in this review article were obtained from renowned publications and journals such as Elsevier, springer, and IEEE publishing. At the first stage, 'Cyber-Physical Systems architecture' and 'Industry 4.0' were chosen as the keyword to search published papers by search engines such as Scopus and Google scholar. The search returned 23 results. At the second stage, these 23 papers were carefully reviewed and unrelated papers were dropped. At the end, 10 papers were left. The search strategy was aimed at finding the research works performed in reputed universities and research institutes which focused on different Cyber-Physical Systems architecture. Citavi 6 software was used for citations adhering to the APA (6th edition) format. This paper is organized into four parts, namely the first part about the introduction, the second part of the method, the third part of the results and discussion of the architecture of CPS technology in industry, and the fourth part is the conclusion.

3. Results

3.1. Traditional architecture

Connectivity, Conversion, Cyber, Cognition, and Configuration are the five stages of the 5C architecture that must be implemented in order to develop the CPS for smart factories. The connection level is concerned with the acquisition of precise and dependable measurements of production machines through the connection of sensors to production equipment. With regard to the conversion of measuring data into information, the conversion level is concerned with the process. The cyber level underlines the fact that by linking more devices, more information may be gathered. When it comes to describing the twin model of every physical thing in cyber space, it makes use of the idea of a time machine. The configuration level finally gives feedback to the physical system, Bagheri et al. (2015). It has been proposed to create a development of this architecture by incorporating 3C facets into the 5C design, which is known as the 8C architecture. Coalition, Customer, and Content are the 3C facets. The coalition facet is concerned with the integration of value chains and production chains amongst various parties involved in the manufacturing process. The customer aspect is concerned with the function that customers play in the manufacturing process. The content aspect is concerned with obtaining, storing, and asking about product traceability info, Meen et al. (2017).
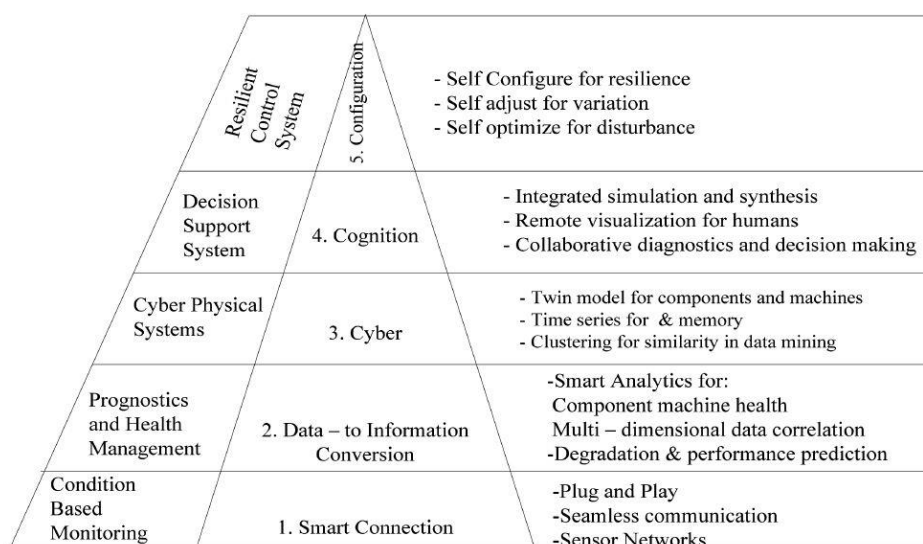
Figure 1. 5C Cyber-Physical System architecture, Bagheri et al. (2015).

The Anthropocentric Cyber-Physical System (ACPS) reference model was developed in order to give the greatest abstraction level for the Anthropocentric Cyber-reference Architecture for Smart Factories. ACPS is a factory automation reference model that combines the physical component (PC), the cyber component (CC), and the human component (HC). The ACPS reference model is based on cutting-edge technical advances in service-oriented architectures, semantic web, and human–machine interaction. The ACPS reference model's unique integrity can't be further broken down into smaller technical resources without losing its usefulness. The ACPS idea prioritizes adaptive and dynamic division of labor among ACPS components because of their continual interactions, Pirvu et al. (2016). The 5C architecture places greater emphasis on vertical integration and less emphasis on horizontal integration, and it has been enhanced by the addition of 3C components (Coalition, Customer, and Content) while the ACPS architecture emphasis more on human, cyber, and physical components. Nevertheless, while developing the smart manufacturing platform for Industry 4.0, they fail to take into account the most important interface components. Consequently, in order to address the issue, this part discusses the robust and long-lasting connections that may be established between heterogeneous components in smart manufacturing sectors. In addition, the idea of important and main interconnecting factors, such as connectors and protocols, is presented in conjunction with the proposed upgraded 3C CPS design.

3.2. Enhanced architecture

The fundamental concern of control engineers is to enhance the performance of unmanned and manual system-based factories, which are hampered by sophisticated and technical procedures, as well as an infeasible strategic plan,

in order to increase productivity. As a result, ACPS is seen as a critical component of the future manufacturing sector, Pirvu et al. (2016). Every individual level of operations was proposed by the authors in the ACPS model for all connected components Physical Component (PC), Cyber Component (CC), and Human Component (HC) on every individual level of operations. Another model takes into account the associated Cyber Component and Physical Component that are operated by people, Thramboulidis et al. (2015). In three main components of proposed 3C CPS architecture for Industry 4.0 there are some additional interfaces to attain a common goal of CPS in manufacturing. In addition, the HC-CC interface, CC-PC, and HC-PC plays an important role in connecting all the components into an integrated system to achieve a common goal.
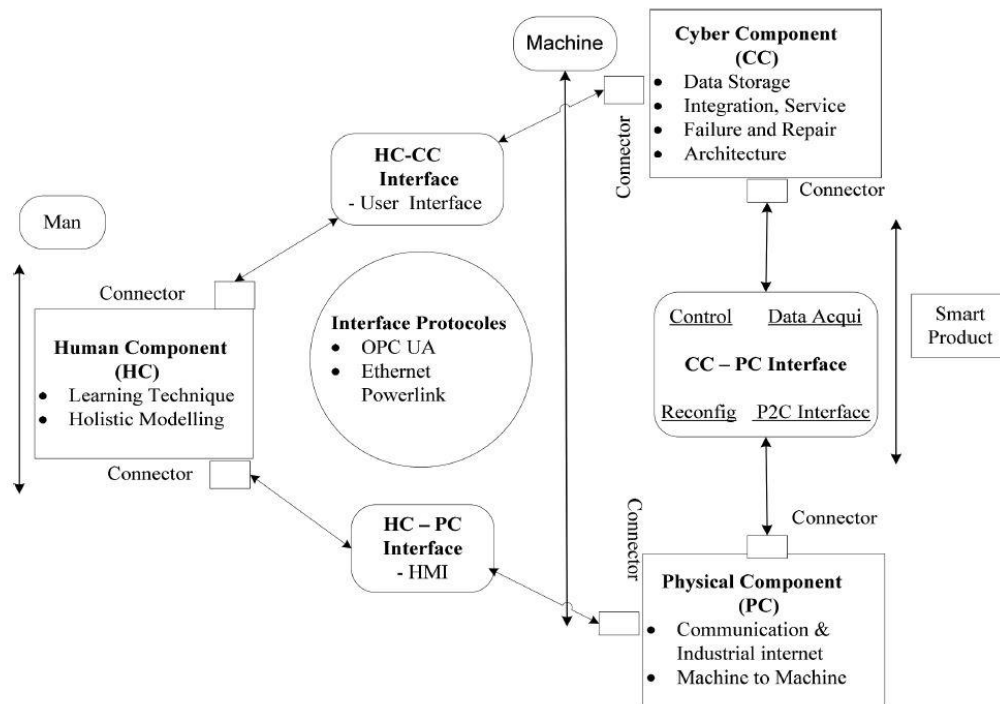
Figure 2. Enhanced Cyber-Physical System architecture, Ahmadi et al. (2019).

Customer expectations for customized goods are rising, and the fast changes in machinery/systems of CPS-based manufacturing in Industry 4.0 necessitate a shorter product life cycle, individualized goods, and rapid adaptation of employees to increasingly inventive modifications in the manufacturing process. The human being is regarded as a necessary component for the newly coined Industry 4.0 to succeed, and this component is referred to as the Human Component (HC), Meen et al. (2017). Cyber is another critical component of CPS for production in Industry 4.0, since it makes extensive use of computers devices as processing tools. While different content focuses on the many Cyber Component (CC) elements including data storage, data management, and services, as well as dynamic reconfiguration, and overall cyber architecture, several articles discuss these topics, Sodhro et al. (2018). Several cyber-physical component designs are applying layered technologies, plant engineering, monitoring and diagnostics of Cyber-Physical Systems, service organization, lifecycle models of Cyber-Physical Systems in inter-organizational value networks, and Advanced Planning Systems (APS), Cheng et al. (2015). Physical Component (PC) is a lower-level hardware component of the CPS for manufacturing that makes use of physical or hardware as a technology component. It is a subset of the CPS for manufacturing that employs physical or hardware as a technology component. Several articles cover PC elements like communication and machine-to-machine (M2M) interaction, Berger et al. (2016).

4. Discussion

The Fourth Industrial Revolution (Industry 4.0) will bring about a rapid shift in both technology and conventional patterns. A challenge in the developing and designing CPS is the large differences in various engineering disciplines involved, such as software and mechanical engineering. CPS require a highly skilled workforce, encouraging multidisciplinary collaborations between academia and industry. When it comes to the design and development of future manufacturing sectors, cyber-physical systems are playing an increasingly essential and astonishing role. CPS represents a

paradigm change that will have a substantial impact on Industry 4.0 and beyond. Our research in this article has looked at the designs of 5C, 8C, Anthropocentric Cyber-Physical System (ACPS) as well as an improvement to the 3C CPS design, all with the goal of enhancing the performance of CPS-enabled smart manufacturing in the context of Industry 4.0. This proposed architecture is now in the theoretical stage, and future work will concentrate on using it in a variety of industrial scenarios in order to demonstrate its effectiveness in directing the digital and smart transformation of a manufacturing enterprise. Standardization is one of the important issues and features of smart manufacturing since it safeguards the quality, reliability, and safety of goods, processes, and services; efficient production; and supports regulation. For this new developing technology to develop, we need to continue working on standardization efforts, Ahmadi et al. (2017). Research on architecture of CPS will continue in the next years, not just for unresolved issues, but also for complicated and intriguing challenges that will continue to challenge academics.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Virtual and Augmented Reality Technologies throughout the entire product Life Cycle

Review article

Virtual and Augmented Reality in Product Life Cycle†

Siddhartha Biswas [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: siddhartha.biswas@s2020.tu-chemnitz.de
†Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Today, industries are facing many challenges and it is very essential to overcome these challenges to outlast in the market. There has been a notable increase in customer expectations, resulting to a rise of complexities in products, as well. Industries must keep evolving with time, keeping in mind that the quality of the product, the time taken to manufacture and finally sending it to the market is not jeopardized. Keeping the development of the product efficient and bringing down the costs are the hurdles, that they need to overcome. This paper is specifically focused on Virtual and Augmented Reality, and how this technology caters and benefits in a product life cycle.

Keywords: Virtual Reality; Augmented Reality; Virtual Prototyping; Product Development; Product Life Cycle.

1. Introduction

Virtual Reality (VR) is an interactive computer simulation, which gives the user a complete immersion in a virtually generated environment(Steinicke, 2016). The user gets to interact with the virtual environment, and "interacting" with the environment is a very vital element in VR applications. When coupled with the right algorithms and tracking systems, the user feel that they are physically present in that environment.

Augmented Reality (AR) is another type of computer-generated environment, and it can be differentiated from virtual reality in a way that the former (i.e., AR) is set in a real world unlike the latter (i.e., VR). The main aim of AR is to make sure that the user gets the information in an unambiguous way.

With the advancement of technology, computer visualization is implemented in various stages of a product life cycle. From design reviews, simulations to service and even training of workers, it plays an important role(Blümel, Straßburger, Sturek, & Kimura, 2004). Usually, these visualization techniques are known as Digital Mock-Up, and it helps the industries to keep up the right direction by providing products at competitive prices and in a shorter time.

This review paper highlights how these technologies successfully manage to improve the product life cycle by not only monitoring the product quality, but also adapting to production rescheduling and several other approaches which are currently being used in today's market.

2. Methods

The field of Virtual and Augmented Reality is quite vast, with an approximately 652,000 articles published when searched on Google Scholar with the keywords, "Virtual and Augmented Reality". Articles and review papers were used to conduct this review, and this review paper was solely based on these studies. This article was written by studying 9 different papers from these research paper databases; ResearchGate, SpringerLink and Google Scholar. Narrowing down to9 papers out of 652,000(approx.) was done by using keywords like "Product Development" and "Product Life Cycle", along-with the terms virtual reality and augmented reality, additionally the time frame from the year 2000 to 2020 was also used for filtering the result. The reason for choosing this time frame was to focus on the updated technological advancements. The entire goal was to look out for an article which addressed the impact of VR and AR in product life cycle, and anything which did not lie in that scope was ruled out. Articles which just talked about the applications of VR and AR, or any other field which was not centered around product life cycle were not considered. It was possible, by skimming through the title, and the abstract of the paper. After finalizing the shortlisted articles, it was thoroughly read and key elements from every paper were separated and the results are laid out in the subsequent section of this paper.

3. Results

Virtual Reality has three basic characteristics: immersion, interaction and imagination(Feng, 2014). A 3-D model is needed which then through a computer program can be made interactive. These 3-D models, when visualized on a VR technology is known as a virtual prototype. Different types of tracking systems are used to enable the position and orientation of the object. There are many imaginable configurations of Visual displays; a single large projection screen (like Powerwall), multiple connected projection screens (like CAVE), stereo-capable monitors with desktop tracking and Head mounted displays (HMD)(Berg & Vance, 2017).

A product life cycle begins with marketing, undergoing several production processes and finally concluding with recycling. The designing phase is considered to be the strenuous step, but with the practice of concurrent engineering it is able to meet the goals- good quality, minimum cost and short time to market(Blümel et al., 2004). Computer-aided Design (CAD) is used for generating an initial design of the product on computer. However, at times it becomes difficult for the workers to work with, because not everyone is familiar with the interface. But with VR, computer visualization has become much easier. In a broader aspect, "virtual reality" is a simple visualization of a 3-D model on a monitor, or even on a fully immersive environment. VR can fulfill all the requirements of each stage of product development—like resolving design related concerns, process concerns to even issues related to logistics. Industrial design becomes more understandable with VR technology. The use of 3D graphics, a multiple interactive sensing technology, and a high-definition display, can generate a 3D realistic virtual environment. The tasks which VR can deal in a product life cycle is listed in Table 1.

Table 1. VR in a Product Life Cycle(Blümel et al., 2004).

Stages of Product Life Cycle	Roles
Marketing	Presentations, Documentations
Conceptual Design	Design Reviews, Concept Validations, Design comparisons
Detailed Design	Part modeling, Assembly modeling
Prototyping	Design optimization, Shape optimization and topology optimization
Testing	Simulations, Feasibility test, Tolerance, Part or system interaction, Motor operations, ergonomics
Process Planning	Fixture design, Job planning, NC programming, Training
Delivery	Logistic planning
Use	Training, Documentation (trouble shooting user's manual)
Recycling	Disassembly simulation and planning

Since, the number of physical prototypes is reduced, VR successfully shortens the product development cycle. Additionally, VR aids the designers to develop a system as a whole, and hence it can address total quality management. Traditional physical mock-ups are expensive and consumes a lot of time. VR- based machine mock-up solves all the drawbacks, thereby improving the entire design-review process. Figure 1 shows a comparison of production cost in a life cycle with and without VR. Identifying any component failures at a preliminary stage is very important. VR-based application for failure modes and effects analysis (FMEA) and criticality analysis (CA), sets up a VR-scene with the 3-D data of the product and contains kinematics object and interaction functions that allows the worker to carry out virtual machine operations like- assembly, equipping the machine with necessary tools and even retooling(Bellalouna, 2019).
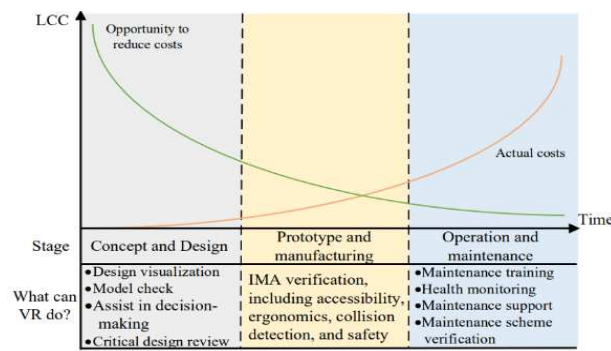
Figure 1. Product Life Cycle cost with and without VR(Guo et al., 2020).

Multi-Agent System (MAS) retrieve and re-use engineering knowledge so as to develop new products. Collaborating MAS on a VR platform will enable research and development team to do the same. MAS enables to localize, extract, capitalize knowledge from previously built projects inside a PLM environment(Mahdjoub, Monticolo, Gomes, & Sagot, 2010). Further this knowledge when used by a VR tool, will help in analyzing the virtual prototype. Having a real-time interaction and sensory-immersion, can help engineers to study the initial steps of a design process. Improving the life cycle product design and integrating it to human factors will make help in staying competitive and ensure innovation from time to time. With a complete sensory immersion, designers get to analyze the product with respect to the user, and hence get a better evaluation. The figure below (Figure 2), shows a collaborative design process, where project knowledge is capitalized by MAS. A parametric CAD model, 3d human model, VR tools and MAS are embedded in a PLM environment.
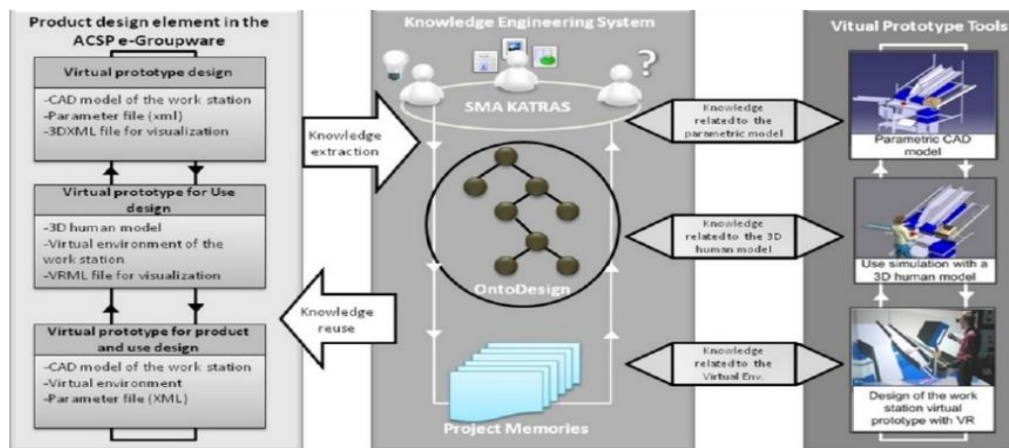
Figure 2. Collaborating MAS on a VR platform in a PLM environment (Mahdjoub et al., 2010).

Augmented Reality focuses on real product and real environment, and augments this reality with information attached to the object that facilitates the design process, manufacturing and maintenance. ARVIKA is the world's largest AR based project which is user-centric and functions in an application-driven manner(Friedrich, 2002). The foundation for all work is AR Base technologies that support high end power applications in designs. AR being a visualization tool are used in manufacturing industries for monitoring quality of the products. Real time reports are given by these AR devices (like Head Mounted Displays), which is the key element for making decisions. An AR system is linked to a Computer Aided Quality software (CAQ), which displays Key Performance Indicators of each workstation and is further transmitted to a mobile device which is located by an Indoor Positioning System(Segovia, Mendoza, Mendoza, & González, 2015). Besides being a dynamic tool, audit times are also reduced significantly. Depending on workstations, different measuring devices are used. There are some basic statistical measures like Process Capability (Cp, Cpk) and Process Performance (Pp, Ppk) which is retrieved from CAQ. However, the Cpk index is the most useful indicator and is used to represent the production behavior. Information can be collected from torque wrenches, digital indicators, seal gaps, which are further transmitted to CAQ. One of the major benefits of adapting the AR technology is, it can be used as an educational tool. User gets a better understanding when using this AR technology. The worker gets a quick access to the database, thus having a guidance when and where needed.

Even in the era of Industry 4.0 where there is a high rate of automation, manpower still holds a vital position. So, along with proper data handling it is important that the data reaches the end user in a well-defined manner. Mass customization requires things to be flexible, and most importantly error free(Mourtzis, Zogopoulos, & Xanthi, 2019). AR when combined with human abilities an efficient way to accomplish such tasks. Assembly instructions are laid out using AR technology, considering all customization options. Workstation schedules are retrieved by the system and instructions are sent through a cloud environment to an operator at the assembly station. It depends on the production schedule, thus making it more flexible. When smart algorithm is applied on a CAD project, it allows breaking down the assembly in tiers of assembly and disassembly. In other words, the parts are moved in all possible direction, and just in case if it can be released it can successfully store that information. Realistic AR instructions are created considering this crucial information and it makes the visualized information much more intuitive. Below is the figure (Figure 3) of an architecture with an increased flexibility in production and ability to production rescheduling.
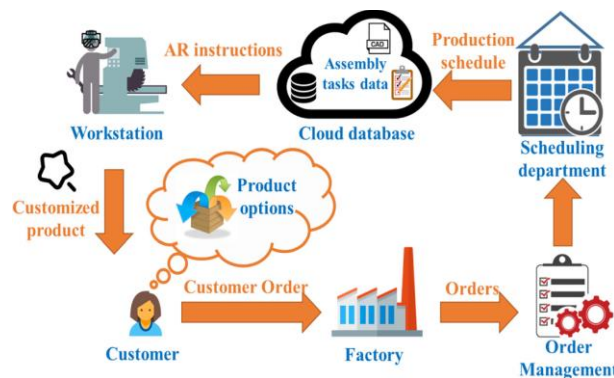
Figure 3. Architecture of the product(Mourtzis et al., 2019).

4. Discussion

As Harry Houdini once said, "What the eyes see and the ears hear, the mind believes", Virtual Reality is all about taking advantage of such human information processing system. There has been a significant growth in the field of Virtual and Augmented Reality, in the last 20 years(Berg & Vance, 2017). The virtual world is simulated by algorithms, and it renders as per our needs. AR and VR technologies provide a lot of flexibility in the entire product life cycle, and in-fact it can be applied in the entire PLC by improving the quality of the product and its service, whilst keeping the product cost low and shortening the time- to-market are the main objective of this technology. Physical mock ups are expensive and time consuming, replacing it with VR based technology can save a lot of money and time. Technicians can use Augmented Reality as a guidance tool, during a maintenance and as a training course, as well. Not only it reduces the working time, but at the same time reduces the chances of any mistakes. Written manuals, even though help to clarify the walk through to a user, but a visual aid gives a much better clarity. What makes this field a class apart is the "sense of presence". However, an integrated CAD data modification in VR and refeeding the CAD systems should be made available. Or else, the Head Mounted Display based VR technology will not be beneficial. For adapting to a VR technology, a lot of changes has to be implemented starting from installation of new systems, hardwares for training of the workers. Undoubtedly, it is a time-consuming process and initial investment is high. But, looking at all the benefits which are covered in this paper, the positive aspects outweigh the negative aspects of VR technology in production. To conclude, we can say that Virtual and Augmented Reality can be used in a product life cycle and it will boost the overall quality of the product at a reasonable cost.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Virtual and augmented reality applications in maintenance and inspection†

Sami Saleh [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: sami.saleh@s2020.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: In the manufacturing industry today, one of the main areas of focus is lowering the production cost and enhancing the efficiency and quality of the products. These motivations led to the rapid development of technologies around the manufacturing world. Two of these technologies, which are the focus of this paper, are virtual and augmented reality (VR and AR) systems which are newly introduced over the whole life cycle of products. Maintenance and inspection are considered to be two of the most important after-sales operations for machines, and are responsible for over 30% of the total costs (Mourtzis, Zogopoulos, & Vlachou, 2017). The focus of this review paper is the systems in which AR and VR technologies are implemented in maintenance and inspection, to minimize the time needed for the execution of the maintenance task, reduce the cost and increase the efficiency of the machine tools by the user. Additionally, we will discuss using fully immersive VR systems, such as the use of virtual scenes with HMD (head-mounted display). This system displays information for fault recognition and procedural steps on the workbench and systems that support collaboration and exchange of experience, to enable the efficient completion of the task.

Keywords: Virtual reality, Augmented reality, Maintenance, Inspection.

1. Introduction

Machines and technologies are getting more complicated and more independent from the technician. Complexity and advancement come with a lot of benefits, but on the downside, maintenance becomes more difficult, and the knowledge required to perform the task becomes greater and harder to obtain. Even though automatic inspection and fault recognition are introduced into such complex technologies, unexpected malfunctions make the need for human inspection and analysis necessary (Goodman & Addison, 2017; Schwald & Laval, 2003).

VR and AR technologies are usually used in the design phase of the product life cycle, especially in virtual prototyping, in addition to sales and marketing applications. In recent years, these technologies have been utilized in assembly tasks, maintenance and inspection, where they are mainly used for easy access of necessary information. They benefit from the rapidly developing and spreading internet of things (IoT) and cloud manufacturing, which provide all needed documents, schematics, procedures, readings, and collaborations between experts worldwide. This can greatly speed up and improve maintenance applications by supporting technicians in cognitive activities which consume almost 50% of the effort and time needed to successfully evaluate, report and fix issues and malfunctions. (Abramovici, Wolf, Adwernat, & Neges, 2017; Neumann & Majoros, 1998).

Using VR and AR comes with some challenges, such as the complex nature of 3D engines and the skills and knowledge required to efficiently use these technologies in the maintenance and inspection departments. Another challenge is the ability to take advantage of the technicians' expertise and include them within the system's databases and functions. Furthermore, using the knowledge of several experts, enhancing communication and maximizing collaborations require a lot of effort. Lastly, choosing the suitable VR or AR system to implement and use in the facility with the suitable degree of immersion of the system.

In this paper, we are going to investigate possible solutions for the aforementioned challenges. One example is using a simplified AR system which employs a simple tracking system, such as a mobile camera, to track real objects, retrieve relevant documents and procedural data, and then project them on an HMD (Webel et al., 2011). Tackling another challenge, we will discuss a concept that proposes having an editable AR system which allows for higher interaction, customizability and a bidirectional data exchange (Lorenz, Knopp, Kim, & Klimant., 2020). Another possibility

is introducing a fully immersive VR system which connects the client with an expert that is provided with a sufficient infeed of data in order to create 3D scenes and help assist the client perform maintenance tasks (Goodman & Addison, 2017). In order to determine which system is the best fit for the given task, a new concept was developed to investigate the degree of interaction between the human , machine, and virtual objects, which allows us to choose a suitable degree of immersion and system to meet the nature of the task given. (Eschen et al., 2018)

2. Methods

The focus of this review paper is discussing new concepts and ideas on how to incorporate VR and AR in maintenance and inspection. A thorough literature search was done to identify useful references on this topic.

The main data bases that were used in the search for published research were Google Scholar, Research Gate and TU-Chemnitz University Library. The main search terms used were: virtual reality, augmented reality, maintenance, inspection, assembly, and a combination of two or more of these keywords. This search yielded a large number of results, so a further criterion was set to choose the most recent articles published in the past decade (2010-2020), in order to obtain the latest updates in this field. After the relevance of each reference was determined by reading the title and abstract of a large number of articles, 18 papers were chosen for further assessment.

The last step involved reading the chosen papers in more detail, and a final selection was made based on proposing an easily applicable system, and systems that tackle one or more of the challenges that were explained above in the introduction. And thus, 8 papers became the focus of this review. These papers were confirmed to be credible sources that were published in recognized journals.

3. Results

Choosing the right system for the right environment is always a challenge, and this also applies to choosing which of the mixed reality systems is best to use and what degree of emersion is necessary. Briefly explaining what is meant with mixed reality system, it is that technologies allowed us to extend our environment, and between the real world and the full virtual environment lie Augmented and Virtual realities with different degrees of integration between the real-world object and virtual objects. That is why it is important for us to investigate and choose the suitable technologies, and to do so one must analyze and understand the nature of the maintenance task that our system is going to assist. To start that, it is suggested that in performing a task an interaction between human, model and object exists, and the degree of interaction between the three entities defines the required mixed reality system to be used. If the interaction is, for the most part, between the object and human, the use of mixed reality system may become an obstacle rather than assistance with the task. However, if the interaction between human and object is close to the need for interaction with models and data, an AR system with medium immersion and a bidirectional data exchange capability is preferred. This system will assist the technician in performing the task by the quick access to the information, data and procedural steps. On the other hand, if there is almost no interaction between the human and object, then a VR system is the best choice which helps us perform monitoring , inspection and analysis tasks. (Eschen et al., 2018).

Of the main uses of AR technologies in maintenance is providing necessary information for technicians which minimize the need for extensive training and takes out human knowledge and experience effect on the completion of the task. This can be done by using an HMD that projects information on a predefined location, which can either be on the real object itself or adjacent area depending on the engagement between the human and object. This data is retrieved from a cloud server. Neumann and Majoros (1998) suggested a system using an ARML language as an AR model which is the center point connecting the documents, CAD models, readings or related procedures with the help of a certain tracking system, that uses object ID , to automatically display related data on an HMD as virtual object in the real world. Their system assists the technician in inspection and maintenance by easy access to the necessary data. (Neumann & Majoros, 1998). One of the disadvantages of this technology is the need for extensive additional knowledge, which a technician dose not possess, to add features and incorporate one's expertise in the system. A similar but simpler system that is proposed by Webel et al. (Webel et al., 2011) capitalizes on using smartphones as the mobile devices which help in tracking objects. These objects are defined using QR codes to retrieve predefined information and project on the HMD. To achieve this, they used an AR engine " unity" to apply AR technology with smartphones using an application (Webel et al., 2011). The use of HMD is important because it provides the opportunity to view virtual objects while still being fully aware of the real world around you (Webel et al., 2011).

As mentioned, the need to further connect a human and a model together, a simple system which enables higher interactivity is needed in a lot of applications. Such simple system is that suggested by Abramovici et al. Their system defines the task to be a sequence of small activities that are accomplished in a specific order. And so, the AR system,

which should be connected to the Cloud or IoT, displays this sequence to a technician or multiple technicians through a smart device. By connecting the system with IoT, it can use the sensor data to automatically register the accomplished task and indicate the next step. If sensors are not applicable, manual input is possible. This is an advantage which allows the use of this system for older facilities. Such system makes sure that the procedure is followed and helps the collaboration between multiple technicians, which maybe be difficult for them to be in direct contact to complete the task in the correct sequence. The sequence should be followed to prevent any cause of harm or injuries. (Abramovici et al., 2017). Still, the content and procedure cannot be edited easily by the technician. This was one of the reasons why a 3D – content Editor is an important tool which allows the technician with minimum knowledge of AR and VR programming to further interact with the AR system in order to make it better and customizable to their need since they own the proper knowledge of their field. The 3D-content Editor system allows them to place the 3D objects and the scenes from a library of 3D objects into a 2D picture of the machine at first, then fine-tunes the position using live video and manipulate its position using 6 degrees of freedom (DOF). The user interface is minimal and provides little functions so that it doesn't require a lot of previous experience and knowledge with CAD systems or AR systems to control it. This system gives the user a way to keep the data updated and easily handled since the state of machines is continuously changing which leads to an increase of efficiency and time reduction (Lorenz et al. 2020) .

Another important application is remote maintenance, which is simply being able to play a big role in performing analysis and fault recognition remotely when unable to physically examine the machine. This is mostly beneficial to improve the aftersales services provided by the manufacturer and reduction of time and cost of providing an expert to examine the machine physically. Instead, it uses an AR or a VR system while collaborating with a technician which is present on the site accomplishes the task with an extensive cut in cost and time required to get the factory back and running in its previous state. This can be done by an AR system which uses a cloud platform that can exchange data and AR scenes between the expert and the client or on-spot technician to perform maintenance. On the expert side, a report is provided by the customer explaining the current status of the machine or equipment with a brief description of the fault or even image and audio data. By using these data and the use of previous saved AR scenes from similar cases, an expert can provide an AR scene that contains the necessary procedure and information to the client that enables the technician without previous knowledge to execute the necessary activities. Figure 1 explains the flow of data, concept, functions and steps needed to implement this system (Mourtzis et al., 2017).
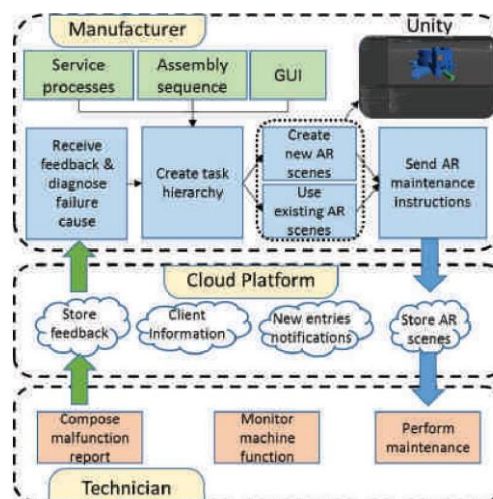
Figure 1. Archeticture model with the necessary information and the flow of data. (Mourtzis et al., 2017, p. 47)

The hardware used in this system is mainly a mobile interaction device, which can be a smartphone or a tablet connected to an HMD used by the client, and a computer that controls, generates and exchanges the AR scene. The computer uses all necessary information such as CAD models, sensor data, reports, and data from the tracking system in use to make the process as effective as possible.

One can also use a higher degree of immersion system which is a full virtual system that the expert can use to further assist and examine the malfunction and correctly diagnose the faults and be able to provide the specific data and procedures required to restore the object to its former state. A 360° camera life feed connected to an analytical system is used to detect malfunctions and changes of state automatically and point it out to the expert. Thus, with a full spherical view of the factory's floor and the information that is provided, the operator can better analyze and inspect

especially that the capability of interaction with the life feed and inserting virtual objects is included. The main hardware used is a 360° degree camera, computer, HMD and an interaction device is sufficient to use the system (Goodman & Addison, 2017). Using a VR system gives the expert more control in collecting the necessary data and a better view of the malfunction itself comparing to an AR system, but it is more complicated and requires more skills and knowledge from the expert's side. Figure 2 shows the main processes implemented within the suggested system, in addition to input and output data, along with the necessary hardware.
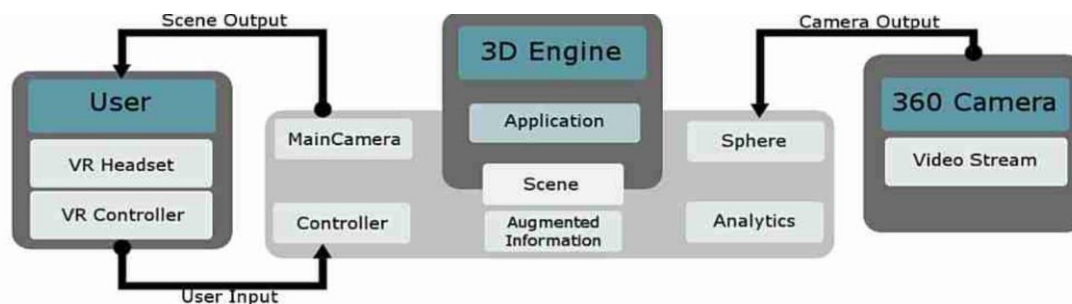
Figure 2. Processes, steps and hardware necessary for the suggested concept. (Goodman & Addison, 2017, p. 3)

4. Discussion

This paper discussed 6 different systems which use AR and VR technologies to assist in the inspection and maintenance tasks. While all systems had significant advantages, they still only tackled mainly one or two of the challenges that we discussed. These challenges include the complexity of the system and the knowledge required to operate it, flexibility, collaboration and taking advantage of the onsite technicians. Some of them focused on the simplicity of the system but didn't support sufficient interaction and data exchange along with limited functionality. Other systems were more complex and needed increased knowledge base that clients don't possess and may not have the time or desire to. Despite the fact that they provided more functions and extended possibilities comparing with the simple systems, they are still not preferred by the technicians. Despite the issues, the use of VR and AR systems would be a major upgrade in the maintenance department. The investment in these technologies reduces the time and cost significantly and is more interesting and inviting than normal data and information search found in manuscripts, catalogs and traditional monitors.

The next step would be to focus on increasing the functionality of the simple AR systems which can allow the editing and creation of scenes in less time, effort and knowledge necessary. And another important point is reducing the dependency on CAD models and sensor data which may not be available for certain machines. For example, we can incorporate the use of 3D scanning technologies and simple software which acts as an application, through which we can insert data and certain parameters to help document and inspect the faults in order to get better and faster assessment and procedural steps to perform the given task at hand.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Use of virtual reality technologies for training in automotive industry†

Keyur Raval [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: keyur.raval@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: This article describes a method for converting traditional training system to virtual training system as well as effectiveness and efficiency study of the virtual training system. The system consists of a virtual reality environment developed with Unity 3D graphics engine, the same one that allows the user to have greater immersion in the teaching-learning process in order to optimize material, infrastructure, time resources, among other benefits. This system allows the user to select the work environment and the level of difficulty during the training process. Effectiveness and efficiency study helped in understanding workers experience of using virtual reality system. The experimental results show the efficiency of the system generated by the man-machine interaction oriented to develop skills in the area of automotive industry.

Keywords: Automotive industry, virtual training system, efficiency and effectiveness.

1. Introduction

Customer oriented production within the automotive industry has resulted in the manufacture of number of different models and different model versions (Michalos et al., 2010) along with a customization process that allows for the addition of variety of optional components and to accomplish this product variation, the assembly worker needs to either identify and memorize a large number of parts and operations for each product variation, which are often changed throughout the day, or spend time consulting instructions or seeking advice from supervisors or manager, with the quality of the final product relying on the ability of the worker to correctly perform the different assembly operations (Michalos et al., 2010). Therefore, training that is flexible and adaptive is essential for learning complex assembly procedures, including the acquisition of the correct metal model and the components and tools of the assembly procedure (Gavish et al., 2011).

Traditional methods for training usually involve a combination of paper based and video-based instruction and/or demonstration of a task by an experienced worker (Berg & Vance, 2017). However, advances in technology have led to a number of investigations into the potential of virtual training to improve and accelerate learning in a realistic and safe environment. The idea of virtual training is defined as training that is undertaken within a Virtual Environment using Virtual Reality and/or Augmented Reality. It is often designed in a way that simulates equivalent real world scenarios, which allows a more intuitive learning environment compared to traditional classroom based training (Mujber et al., 2004), enabling individuals to interact with the training system and from which user can experience failure or success. Using the virtual reality, nearly perfect workplace environment can be created including the sights, sound of assembly area and the actions which can provide guidance and instruction of procedures and the actions for assembly operations. For virtual training to be fully accepted as a valid tool for training, evidence is required of the effectiveness and efficiency of the virtual training program and also its acceptance in the use by the workers or employees (Stork et al., 2012).

In this context, the present article shows the development of a virtual reality application for the recognition and assembly of vehicle components, with the aim of understanding the use of virtual reality in creating effective and efficient assembly training program. The present work shows that virtual reality technology can considerably improve the productivity of teaching and training by allowing workers to apply theoretical knowledge to real industrial problems. It also develops creativity and innovation, problem solving, communication, team working skills.

2. Methods

Virtual reality has many applications. Use of virtual reality in automotive industry covers many areas like product design and development, manufacturing, training, supply chain etc. To address the topic, literature review of vast topic was done. Databases that used for this research were IEEE Xplore, Google Scholar, ResearchGate, and Springer Link and ScienceDirect. Firstly, literature reviews were searched using "virtual reality in automotive industry". After that some specific keywords, like "virtual training system", "use of virtual reality in training" and "application of virtual reality technologies in manufacturing industry", were applied to narrow down the search. For this review, conference papers and articles in journals were taken into account. For selecting the literatures, skimming through the article method used.

3. Findings

To find out the usefulness of virtual reality technologies, multiple studies screened and included in this article. Inclusion of these studies provide better understanding of the topic and its application in the automotive industry. These studies include topics like method for converting traditional method of training to virtual training method and efficiency and effectiveness of virtual training system.

3.1. Machine Virtualization

A multi-layer scheme is proposed by (Hutchison, 2016) for the development of applications in virtual environment in order to provide a greater immersion to users in training tasks in the area of automotive mechanics. In this scheme, layer 1 is responsible for importing 3D models created in CAD software. Layer 2 is determined from the reference system and establishes the hierarchies of each of the parts of the 3D model and Layer 3 is responsible for the interaction between the virtual input devices and the environment where the application is executed. In addition, the evaluation phase of the training performed by the user is implemented in order to evaluate the knowledge and skills acquired with the application developed.

The software 3ds MAX is used to import the 3D model created in CAD software to the Unity3D graphics engine. The hierarchies are established according to the assembly of the machine or modelling equipment, it also depends on the number of elements and the position constraints of each element according to the model. For the orientation and location of the parts of the model, the reference points (Pivot) are determined. At the end of this process, you get a *.fbx file compatible with Unity3D in which the virtual environment application will be developed. While in Layer 3, the configuration of inputs for the interaction of the moving parts that make up the 3D model and the user interface using HTC VIVE and Gear VR devices, is performed by using functions of OnTriggerEnter, OnTriggerStay, OnTriggerExit. For the manipulation of the object (moving part of the model) the GRIP or TRIGGER button is considered, emphasizing the collider of the object. While for the user's movement in the virtual environment, "teleportation" is implemented, which consists of pointing a reference point on the surface for the purpose of transferring a desired point to the user as shows in Fig.1.
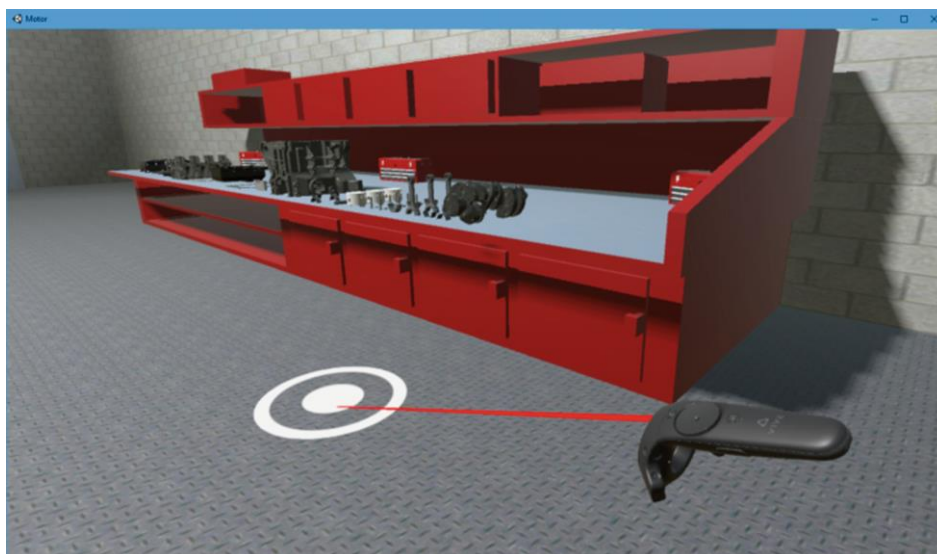

Figure 1. Use of Teleportation (Hutchison, 2016).

In the next process, one sublayer is added. In this, the local position of each of the parts and pieces is recorded in relation to the original 3D model. The objective of doing so is to make comparison between the correct position and the position in which the user locates the object. In case the manipulation of the object is nearby of the correct position, an outline is shown for guiding the user in the assembly process. For gripping the object, the user must configure the same response as stored in the data. For example, the gripping of the object only works if the user tries to grip the object in right way as suggested in the manual (in this case stored data), see Fig.2.

(a)   (b)
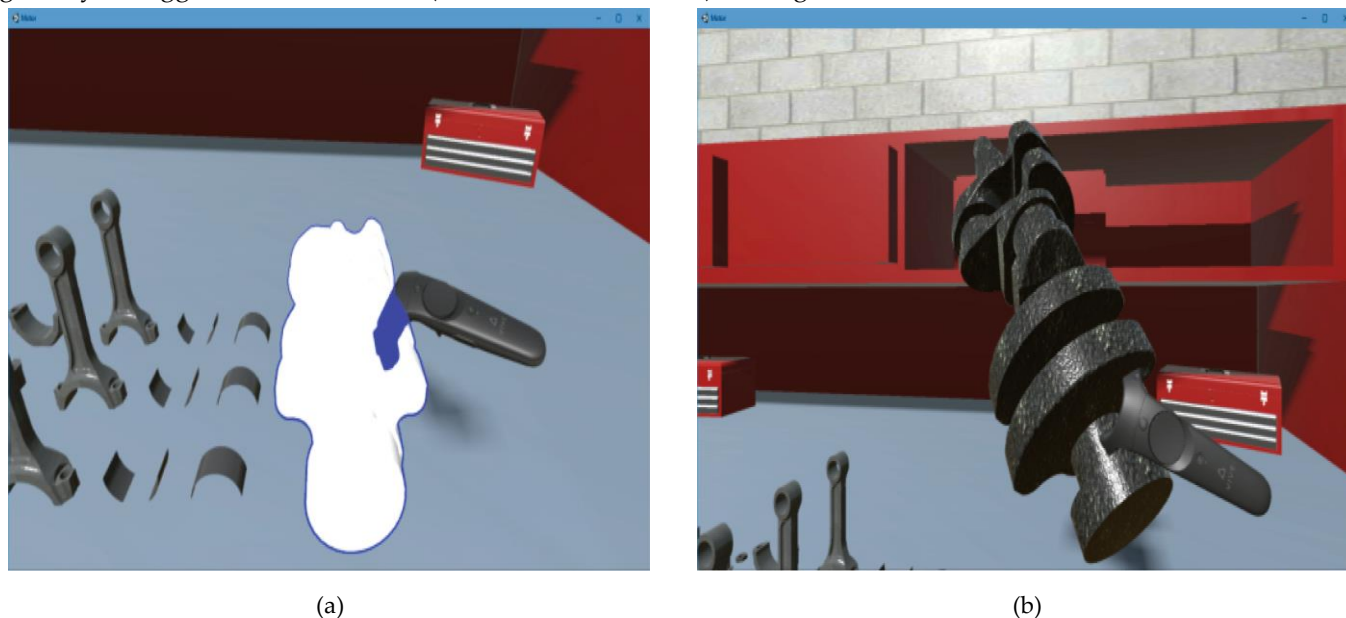
Figure 2. Handling of object. (a) selecting of object; (b) griping of object.(Hutchison, 2016)

After that, sublayers can also be added in order to focus on virtual environment and texturing of each part for more real feeling. Such details include colour, sound, lightning etc. Other sublayers can also be added for the movement of an object, gripping of an object and assembling of parts by the work (Hutchison, 2016).

3.2. Efficiency and effectiveness of virtual training system

In this method (Langley et al., 2016), two separate studies were carried out. Study 1 was an objective study with the aim to investigate the effectiveness of virtual training system. Study 2 was the subjective study with the aim to establish efficiency and acceptance of the system. In study 1, two groups created and both of the groups were given training. In his, one group was given traditional paper-based training while the other group was given virtual training. After one week of training participants of both the groups were asked to perform real world tasks.

Participants were evaluated based on their performance. In the measuring performance following measurements were taken: overall errors, trainer corrected errors, self-corrected errors and task completion time. In study 1, real train-ers, who has no prior experience of assembly work, were taken as participants. In study 2, all participants were given consent form and computer self-efficiency questionnaire as a pre-task. After that, they were given some tasks, which includes login and navigation of the system, performing of assembly training task and performing of disassembly train-ing task. After completion of tasks, they went through post task interview. The aim of the interview was to get the feedback of their experience of using virtual system. In study 2, real trainers and managers were taken as participants. Results obtained from both of the studies indicated that using virtual training system has more advantage over the use of traditional classroom base training system.

4. Discussion

In this paper, two topics related to usefulness of virtual reality technologies in training were covered. As a finding, a virtual training system for automotive mechanics is proposed. This system consists of a virtual reality environment developed with the help of graphic engine in Unity3D, which allows the user to have a greater immersion during the teaching-learning process in order to optimize material resources, infrastructure, time and other benefits. The experi-mental results obtained show the efficiency of the system generated by the human-machine interaction oriented to de-velop skills and abilities in the area of automotive mechanics.

As another finding, efficiency and effectiveness of virtual training system was presented. Results of this study were very encouraging. Results from study 1 showed that the virtual training reduced the overall errors and trainer-corrected errors. Results from study 2 showed that most of the participants liked the virtual training experience compared to the traditional paper-based training system.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Augmented Reality in Manual Assembly†

Jawad Kanso [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: jawad.kanso@s2020.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: The integration between the human and automation to reach the high complexity at reduced time is one of the trends in industrial manufacturing. Augmented reality is a new technique that enhances the adaptation of humans within the highly automated manufacturing industries and reducing the life cycle time. Augmented reality systems can be implemented in different phases of the production life cycle such as the assembly phase. This review paper expresses different augmented reality systems used in real world manual assembly tasks and their application area. It illustrates the affectivity of such systems to increase the collaboration between the worker and the assembly environment, to release the difficulties in the assembly of complex models, and to reduce the assembly phase time. The paper throws light on the influence of augmented reality towards smart manufacturing.

1. Introduction

As the world is going further through the effective use of technology in all life domains, it is axiomatic that industrial applications will be the ideal model of implementing new technologies and techniques. This lead to a high state of flexibility, adjustability, quality, and many other challenges that face industrial manufacturing on its way towards smart manufacturing. Going through smart manufacturing requires the merging of technology and manufacturing in parallel with the utilization of human qualities and capabilities. This result in moving from mass production to customized mass production and reducing the product life cycle time (Büttner, Sand, & Röcker, 2015), and benefiting from the high complexity instead of avoiding it.

Graphical User Interface (GUI), is the most known and used user interface in the last years, because, on the contrary of other user interfaces as Command Life Interfaces (CLI), it provides an immediate visual interaction between the user and the system. This makes it easier for the user to be able to access all commands (Paelke, 2014). On the other side, and since our target is to visualize virtual objects in a real environment, the implementation of traditional GUI is not quite suitable. That is, augmented reality comes in as a better fit user interface for assembly applications.

Augmented reality, even though being one of the new suggested preferred technologies to reach these aims, it is still rarely used in real life industrial applications in compare with sales and advertisement applications. As a historical preview, Thomas P. Caudell and David W. Mizell, were the first to use "augmented reality" as a one combined term when describing the technology used in their invented Heads-Up Display Head Set (HUDset) to differentiate it from full virtual reality (Caudell & Mizell, 1992). Defining augmented reality as augmenting the real world perception through the registration of real and virtual objects in one real environment and in an interactive real time system goes back to Azuma (Azuma, 1997). That is, in assembly applications, augmented reality is the combination of real spatial environment with a computer generated virtual objects to enhance and visualize the instructed steps throughout the assembly process (Wohlgemuth & Triebfürst, 2000).

An augmented reality system is consisted of 4 components: tracking, interaction, visualization, and data management. Moreover, the system can be glass-based (such as optical or video see-through Head-Mounted Display), monitor based (such as tablets or smart phones), or projection-based systems.

In manual assembly tasks, problems in understanding and applying the assembly steps for new or high complex models with the lowest error possible at reduced time, even for the experienced workers, do significantly impact the production life cycle. However, these problems boost the demand on the implementation of augmented reality systems in manual assembly applications. This paper illustrates effective advantages of using augmented reality systems to solve such problems, taking into consideration their impact on the worker's physiological and mental aspect on the long-run time.

2. Methods

Augmented reality technology is considered somehow a new technology, especially in applying it in industrial manufacturing. Hence, my research approach began in identifying the concept of augmented reality and its definition to let my topic seems familiar and clear throughout the paper. For that, I used three databases platforms: Google scholar, Research Gate, and Chemnitz University of Technology Library (TUC Library). After searching for the definition of augmented reality, several papers agreed, after viewing and scanning, on the main definition of augmented reality as a concept by Azuma (1997), and the first to use "augmented reality" as one combined term were Thomas P. Caudell and David W. Mizell (1992).

Knowing that AR is a new technology quickly improving over years, my target papers' publication date was more on papers after 2010. Based on my intended aim to find out the benefits of using augmented reality systems in industrial manufacturing, I went over choosing its influence in the manual assembly application area, since this application area faces problems where augmented reality may solve. I started searching using two terms: Augmented reality, Assembly phase. The results were too broad, and many of them were out of the topic range like applying augmented reality in design phase or in maintenance phase or even in the production life cycle as a whole, even though I found some papers that I used. Then I had to narrow my search to get touch directly with papers related to my topic, and that's why I used the other terms as: Augmented reality, Manual Assembly Applications, Work Instructions. I found out many beneficial papers that supplement my aim in reviewing the invented systems of augmented reality to be implemented compared with other techniques in manual assembly applications. After viewing, scanning, and reading around 25 chosen paper, I then went into the next step by choosing 15 papers. After I identified the main sequence that I will follow in presenting the information throughout this paper, and after choosing papers that differs in the aspect of the proposed studies, I chose 9 papers that will base my review, defining augmented reality technology, presenting augmented reality systems and their performance results in manual assembly applications, and conducting studies on the influence of using such systems on the user's mental and physiological aspects compared to other techniques.

3. Results

Different exemplary augmented reality systems are reviewed: glass-based systems as the modular production system presented by (Paelke, 2014) and the system used by (Tumler et al., 2008) (Head Monuted Display HMD), or the Hololens augmented reality device used by (Drouot et al., 2021); projection-based systems as the augmented reality system presented by (Büttner et al., 2015); and monitor-based system as the MOON project (asseMbly Oriented authOring augmeNted reality) presented by (Serván, Mas, Menéndez, & R'ıos, 2012). These systems include most characteristics of a smart factory, and provides a new prospective advanced interface as augmented reality. The modular production system, for example, consists of a laser cell, manual assembly workplace, robot-cell, workpiece carriers, and a modular transport system, and it is controlled by a digital product memory containing an RFID chips (radio-frequency identification) that store each order (Paelke, 2014). However, MOON project that is used for aircraft assemblies, consists of two techniques: industrial Digital Mock-Up (iDMU) and Augmented reality. The augmented reality system in the MOON project consists of three sub modules: 3D processing sub module that interprets the files provided to the augmented reality system, the 3D positioning sub module which realizes the position of the worker along with the correct placement of the virtual parts, and the information integration system that derives the needed virtual information from the augmented reality libraries (Serván et al., 2012).

A similar case-study was performed using the modular production system presented by (Paelke, 2014) and the AR system presented by (Büttner et al., 2015) on users that have no background or knowledge about the performed assembly task. The user has to do two tasks: picking the components to be assembled and assembling them. The instructions were visualized as picking instructions through highlighting the required component to be assembled and generating the needed attention even though if the component is not in the user's field of view as shown in figure (1a), and assembly instructions visualized as a 3D model, viewed in figure (1b), clearly showing the way of mounting the next part (Büttner et al., 2015; Paelke, 2014).
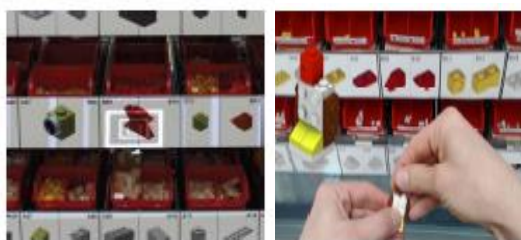
Figure 13. (a) The highlighted components (Büttner et al., 2015, p.3); (b) The visualized 3D model (Paelke, 2014, p.4).

Results showed the importance of using augmented reality systems in such applications where they can enhance the flexibility and the familiarization of the user with the environment using the modular production system (Paelke, 2014), and how useful an augmented reality system in helping the users to perform the tasks without any error (Büttner et al., 2015).

Moreover, and to directly compare the visualization of WI through augmented reality systems with the traditional documentation paper, three studies were reviewed. The paper presenting the MOON project (asseMbly Oriented authOring augmeNted reality) compared the results in regard to the WI creation time, WI consulting time, and WI maintenance time (Serván et al., 2012). However, another paper conducted the study using the HoloLens augmented reality device to perform an assembly task of Lego Blocks for 30 minutes, and it measured two parameters before and after the task: optometric measurements through Binoculus, and fatigue symptoms through Virtual Reality Symptoms Questionnaire (Drouot et al., 2021).

After conducting the MOON project in a case-study of a complex assembly process composed of mounting several fittings, bolts, and routing wires in a frame of an aircraft, the following results were viewed: the WI creation time was reduced by 90% due to the use of iDMU program that generates information directly from different phases of the life cycle; the WI consulting time was reduced by 50% due to the proper function of the calibration system in the augmented reality system that leads to directing the worker with the correct guidelines so that the user can easily understand the instructions without the need for the design or assembly knowledge; and the WI maintenance time was reduced by 90% due to the ability of a quick update of information in the iDMU program (Serván et al., 2012).

On the other hand, the other study showed no difference in the optometric measurements except for the stereo-acuity and convergence at near distance. The stereoacuity was better after assembly task using the augmented reality system, and the convergence at near distance was lower after task using the traditional documentation paper. These differences are not considered important. On fatigue symptoms level, it was obvious that blurred vision, sore/aching eyes, and headache are higher when using AR system than traditional documentation paper as shown in figure (2). These results are still fit in the slight difference category. The reasons of such results return back to the position of the AR system and the assembly task itself (Drouot et al., 2021).

However, these fatigue symptoms results were similar to the results obtained in the study conducted by (Tumler et al., 2008) when performing an assembly task using Head Mounted display, even though the studies time difference is more than ten years.

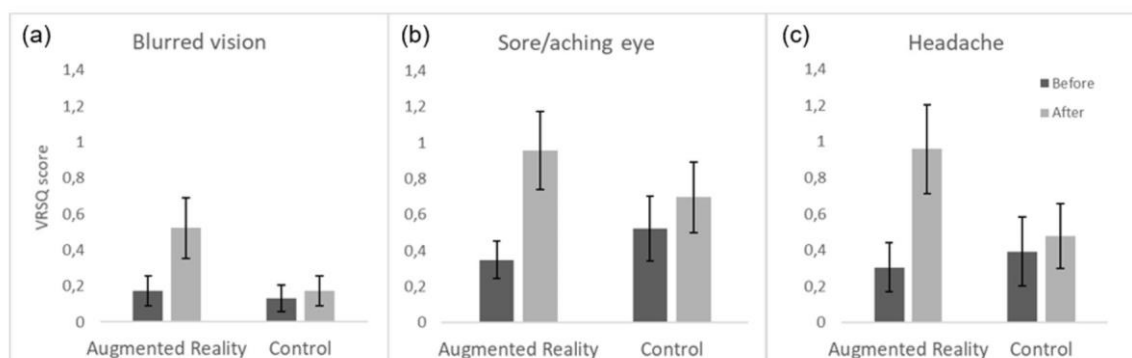**Figure 14.** Scores of (a) blurred vision; (b) sore/aching eyes; (c) headache, for augmented realty and traditional documentation paper (control), before and after the task. (Drouot et al., 2021, p. 5)

Another important comparison between the AR system and video is reviewed through a study conducted by (Loch, Quint, & Brishtel, 2016). It performed a comparison when assembling a complex Lego using AR system and

tutorial video. The study concentrates on measuring three parameters: accuracy and performance through time measurement and calculation of errors, the perceived ease of use using regression analysis, and the mental workload using NASA-TLX (National Aeronautics and Space Administration Task Load Index). Results showed a lower number of errors when using AR system with no considerable difference in consumed time and mental workload as shown in figure (3) . The measurement of perceived ease of use that expresses the level of adaptation and readiness of using new system with respect to the user, showed the high willingness by the user to use such AR systems (Loch et al., 2016).
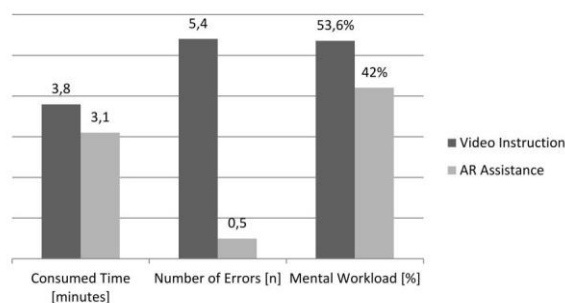

Figure 15. Measurements of the consumed time, number of errors, and mental workload, when using the video tutorial instruction and the augmented reality system. (Loch et al., 2016, p. 3)

4. Discussion

Even though the industrial manufacturing is tending to be more depending on automated assembly, the manual assembly is still a requirement in the industrial sector because of its cost-effectiveness and to utilize the mental and physical capabilities of the human. Saving the manual assembly in an almost automated environment requires the improvement of the manual assembly tasks with new technologies and techniques that supports its existence and abilities to compete in smart manufacturing. Analyzing the results of this paper, it is quite clear that augmented reality technology is a necessity as a new technique decreases the costs of a manual assembly task and assist the worker to deal better with complex tasks. It enhances the cognition of the worker and the mental networking between the worker and the spatial environment. The implementation of such augmented reality systems is time effective compared to both video tutorials and traditional documentation papers. It has no considerable regression impact on the oculomotor system, with no significant difference in fatigue symptoms compared to conventional documentation paper. The augmented reality systems discussed, such as the modular production system, showed how intuitive and useful are such systems in guiding the worker through a well-designed and clear assembly instructions. This implies in a zero-error assembly task and accurate process, despite of the experience and knowledge of the user performing the task.

Nevertheless, augmented reality systems still face some challenges in supporting the assembly of high complex models, and in making the system easier and more familiarized with respect to the beginner users. In particular, it will be more challenging in the manual assembly tasks that may be performed on different workstations which require the ability to provide the worker with the needed assembly instructions despite of the station working on. This supports the idea of wearable projectors that can replace the low disturbing glass-based and monitor-based AR systems, and more beneficial than a mounted projector. Moreover, using a more optimized augmented reality system with a more advanced calibration and integration sub-systems and a higher quality visualization hardwares, may result in a lower increase in fatigue symptoms comparing to performing tasks without an augmented reality system.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Human-machine-environment interaction

Review article

The Effective Safety of Industrial Robots with Virtual HRI environment[†]

Suwapitch Charoensilawath [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: suwapitch.charoensilawath@s2020.tu-chemnitz.de
[†] Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: Currently, a large number of industrial robots have been deployed to replace or assist humans to perform various repetitive and dangerous manufacturing tasks. However, based on current technological capabilities, such robotic field is rapidly changing so that humans are not only sharing the same workspace with robots, but also using robots as useful assistants. Consequently, due to this new type of emerging robotic systems, industrial collaborative robots, human and robot co-workers have been able to work side-by-side as collaborators to accomplish tasks in industrial environments. Therefore, human-robot interaction systems have been established for such systems to be able to regulate risks and allow human operators access to robot workspace during operation. Accordingly, this article presents a literature review of identification the essential factors for the effective safety of industrial robot with virtual reality environment. This research demonstrates a set of established metrics as well as a newly developed Kinetic Energy Ratio as an effective safety factor of Virtual Reality environment could be used in Human-Robot Collaborative strategies in the industry.

Keywords: human-robot interaction; industrial robot; safety standard; virtual environment; manufacturing.

1. Introduction

Industrial robotic play a remarkably crucial role in our society these days. Germany and European countries have been developing to obtain an advantage in manufacturing by combining the industrial robots and advanced technologies into manufacturing process (Sanneman, Fourie, & Shah, 2021). However, the human worker is still necessary to achieve some tasks that need more ingenuity and inventiveness (Oyekan et al., 2018). As a result, industrial robot or collaborative robot has been used widely in manufacturing because it is designed to collaborate safely with human operator and it can be provided with sensors or advanced visual technology for detecting humans (Sanneman et al., 2021). Nevertheless, whenever human and industrial robots work together closely, which can be defined as a situation where human communicate with robot as a human robot interaction (HRI) (Hentout et al., 2019), the accidents seem likely to be occur unpredictably. The lack of safety standard human robot interaction (HRI) in manufacturing system is an extremely concern for the operator in the shared workspace (Wang et al., 2020). The ISO 10218-1 categorized four basic type of collaborative opeerations: (1) safety rated monitored stop, (2) hand guiding, (3) speed and separation monitoring and (4) power and force limiting. Therefore, HRI becomes easier and safer interaction between robot and human (Hentout et al., 2019) as a result of this make the human safety is a essential requirement for advantageous utilization of applications based on human robot collaboration (HRC) in manufacturing industries (Ore et al., 2019).

Virtual Reality has been conducted to investigate reducing the risks to humans during experiments and human safety when working around the industrial robot. It looks like creating a digital artificial environment in which a human can be engaged in the operation. Exploiting interactive and immersive aspects of virtual reality system could enhance the perception and recognition of human (Dianatfar et al.,2020). With this system can contribute a cost effective and safe environment and also implement an opportunity to enhance human safety as well (Oyekan et al.,2018). Furthermore, manufacturing nowadays has more complex productions so that those need human safety standards to satisfy and guarantee the system. This paper aims to propose a review concept for the virtual safety environment system in the field of HRC system and discuss about the requirement of safety system of collaborative robots which can make the system safe and reliable.

2. Methods

A literature search was performed to understand the use of virtual reality environment in work safety with industrial robot. The published literatures, academic, scientific research and review articles in journal on the year from 2017 to 2021 considered on the research topic. The literatures were retrieved through reliable database such as Springer Link, Science Direct (Elsevier), Researchgate, Google Scholar. Databases were searched using the keywords: Human robot interaction, Safety standard of collaborative robots for manufacturing and Virtual reality environment with safety of human-robot collaboration. The searching criteria were established based on the all-inclusive knowledge base to identify the mainstream of industrial and manufacturing research relevant to robotic and industrial automation. The main aim is to identify the gaps in literature hence provide evidence of the future field of research. The methodology utilised to carry out the research are: planning, defining the scope, searching, assessing, synthetising, analysing and writing.

3. Results

This section proceeds to review the existing virtual reality environment research studies in Human-Robot Interaction and Collaboration which has been worked with industrial robot operating and safe areas with simulation based HRC workstation evaluation. These studies were carried out with a priority on human safety conditions in virtual environment.

There three methods to investigate the effectiveness of virtual environment of industrial robot such as analysis of realism of the developed virtual environment. A survey was collected among 22 participants using the virtual environment which were converted by scoring the reaction and attitude of participants to the robot motion in the virtual environment to study human reactions to both predictable and unpredictable of robot motion. It found that people with real experiment did not react as much as those that did not have real robot experience. The second method is analysis of human reactions to robot movement using the proposed metrics of kinetic energy ratio. An experiment was tracking among 31 participants which could be classified into three groups according to a visual observed reaction. The last method is possible correlation between human reaction and previous experience of virtual reality which was conducted in order to ascertain if there was a relationship between human reaction and personal characteristics such as previous experiment of virtual reality (Oyekan et al.,2019). The virtual environment was experienced by the user via HTC vive while interaction with elements in the environment was achieved through using hand controller which enabled the operator move freely in 3D space of real world as well as 3D space of virtual environment (figure 1).

(**a**)   (**b**)
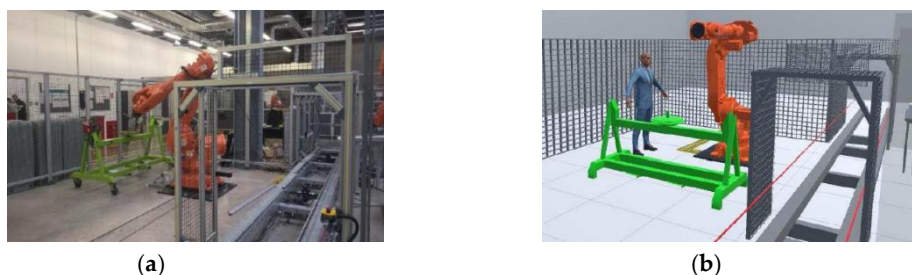
Figure 1. (a) a real-world workshop (b) workshop environment replicated in Unity. The human manikin is used as a visual aid to understand the reaction of users during playbacks (Oyekan et al.,2019).

Another research (Matsas et al., 2017) was conducted with 30 participants to collaborate with the virtual robot by using HMD (Head motion tracking) In addition, a video camera was used in order to observe, study and analyse user behaviour. The experiment shown that virtual environment could be transferred virtually acquired experience and proactive behaviour to the real environment and the real task. The Unity program has been used to describe structure of robot in 3D space and add behaviours such as pertaining to control and safety, to perform movement, to assign properties, achieve interactions, sense collision with ray-casting and other in-built algorithms. The objects of virtual scene were developed using Rhinoceros and 3ds Max software and skinned model of the avatar was created online in the Evolver avatar builder.

Likewise, (Dianatfar et al.,2020) conducted the experiment by using user, HMD and PC in virtual environment to experience safety system. The objects in the virtual environment are modeled in 3ds Max and Autodesk Maya and exported to Unity program. Additionally, forward and kinematics of the robot are simulated and scripted for vitualization of robot tasks and movements. Meanwhile, VR HMD's tracking sensors track the user's navigation. Afterward the

collected data are transferred to the Unity engine and the user 's location and navigation will be computed to display a dynamic representation of the virtual environment on the interface.

4. Discussion

From all the research which are discussed in this article. The result has been shown that virtual reality environment could provide a safe and effective environment (Oyekan et al.,2019) by interpreting both established and newly developed metrics that was collected data from participant in order to inform human reactions to robot motions. Furthermore, analysis of human reactions to robot movements using calculation of Kinetic Energy ratio was analyzed and it was demonstrated that it could accurately classify 73% of the analytical data according to the observed reaction. Moreover, the Kinetic Energy ratio correlates with acceleration and angle of lean metrics as well as the HIC-based force could be used to safely measure collision effects during human-robot collaboration session without the risk to humans. Obviously, from this result should be potential in safe human-robot collaboration factor. This investigation is particularly important because virtual reality environment demonstrates if a vitual environment is designed and developed well, the reality provided by it could be effective in understanding human reactions to both expected and unexpected robot actions.

It was also discovered that use of audio-visual aids was effective in helping user to figure out dangerous situations (Matsas et al., 2017). Although, it was shown that some users felt uncomfortable with their movement in virtual environment. However, the large majority of the users could easily avoid the moving robot as it was approaching them.

Similarly, (Dianatfar et al.,2020) revealed that a visual warning in virtual environment could be notified the user to leave the collaborative space. Moreover, an audio warning also notified the user when entering the collaborative workspace. As the result, audio and visual warning will assist the user to leave dangerous area.

5. Conclusion

The main aim of this paper is to study the effective safety of using a virtual reality (VR) environment to identify the essential factor of human-robot collaboration was carried out. In the end, a essential factor of safety has been proposed, the more accuracy of the Kinetic Energy metric, the more benchmark is able to classify human-robot collaboration as well as acceleration metric and HIC-based. Furthermore, the use of audiovisual cognitive aids was one of the effective factors which allow the user to perceive a potentially dangerous space around the robot and thus avoid collision with the robot. (Matsas et al., 2017). Nevertheless, a virtual training environment is also one of the important factors to enable the user with or without prior experience to perceive the safety system processes. (Dianatfar et al.,2020)

More studies are needed in order to follow closer to the Kinetic Energy metric and acceleration metric which could be used to control a robot's motion in the future. Furthermore, it could be used the HIC-based force as an essential factor for considering in regulation to human-robot collaboration strategies in industry as a result in the research has been shown that a VR environment is able to enable us to create an environment where has a highly skilled operation with minimal risk when robot collaborate with human.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Management and Life Cycle assessment

Review article

Life cycle assessment of hydrogen production processes†

Opeyemi Keye [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: opeyemi.keye@s2018.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Sustainability has become increasingly important for the future of mankind. Hydrogen production could play a major role in reducing environmental impact of fossils. Hydrogen; because of its properties: high energy content, combustion kinetics and no carbon emissions. Despite being considered a clean fuel, it is not a primary source of energy and can be produced in many ways. A life cycle assessment is conducted to investigate some of the production processes. The review paper compares production via natural gas steam reforming with renewable energy sources: wind, solar and electrolysis. It discussed impact categories such as global warming potential, acidification, eutrophication and wind smog effect emissions for the different processes. Study results show that using renewable energy for hydrogen production are most benign to environment.

1. Introduction

There are growing doubts over the non-sustainability of current energy systems and problems with the future supply of fossil fuels because of its related emission of greenhouse gases (GHG) (DUFOUR et al., 2009). Widespread use of fossil has had an effect more significant than first feared. There is need for a sustainable supply of clean energy. Hydrogen as an energy carrier provides a good long-term option and has the potential to decarbonize many industries. An example is the energy industry, its advantage unlike other renewable energies is that it can be supplied on demand, which is very crucial within energy transition. Hydrogen also has its use in the building sector, when mixed with natural gas, it's fed into hydrogen boilers and cells to be run through network of pipes used for heating homes. Additionally, in the transport industry, it can reduce emissions by replacing internal combustion engine (ICE) vehicles as seen with the police fleet in cities like Berlin and Osnabrück. Being an energy carrier, it needs to be obtained from primary energy sources.

1.1. Aims and Objective

The environmental performance of hydrogen strongly depends on the hydrogen donor and energy source of its conversion process in the production stage and not only on its use stage (Zhao & Pedersen, 2018). Currently, approximately 75% of the world's hydrogen production has natural gas (mainly methane; CH_4) as its raw material (DUFOUR et al., 2009), with steam reforming still the most used process. As a result of high GHG emissions, environmental issues related to producing hydrogen for example; stratospheric ozone depletion, global climate change, acid rain are caused. Its global warming potential (GWP) is around 13.7kg of CO_2 equivalent per kilogram of net hydrogen (DUFOUR et al., 2009). But with the steady fall of high costs attributed to renewable energy, there will be an increase in use of other production chains from renewable energy sources. The main aim of this review is providing a LCA of hydrogen production processes and comparing the environmental effects of the varying production processes; such as natural gas steam reforming with different manufacturing chains using renewable energy sources like solar, wind and hydrolysis. Producing hydrogen from water, either through hydrolysis or direct photochemical reactions, is the most likely long-term source. Although, with seemingly good prospects, examining the emissions from a life cycle point of view gives a clearer picture of the environmental burdens associated with hydrogen production (Zhao & Pedersen, 2018).

1.2. Basics of Life cycle assessment

Life cycle assessment (LCA) is an effective tool that has been used in analyzing and evaluating all phases of industrial activity from extraction of raw materials to processing of material, manufacturing and to final disposition. LCA

identifies key areas where process changes could be of utmost importance without necessarily changing whole production pathways to reduce impacts. Analysts use the results to decide and effect policy or technological changes. Particularly for emerging energy systems, in this case hydrogen, conducting such assessment is important (KORONEOS, 2004). The International standard organization (ISO) has defined LCA as a technique for assessing the environmental aspects associated with a product. The ISO 14040 standard, developed in 1994, which is a standard on principles and a framework defines these environmental aspects in four different phases; goal and scope definition, inventory analysis, impact assessment and interpretation. Goal and scope estimates context in which assessment is to be made, identifying the system boundary. The system boundary encompasses the important processes of product system and specifies scope of the study. Collection of data that describes the systems to be examined is termed the life cycle inventory (LCI). Inventory analysis quantifies energy, water, material usage and environmental releases. The life cycle impact assessment (LCIA) assesses human and ecological effects of energy, water and material usage and environmental releases identified in inventory analysis. Outputs with similar environmental impacts can be grouped and aggregated into a single parameter, known as impact category, for example, Global warming potential (GWP) (CO_2, CH_4 etc.), eutrophication potential which are emissions that change nutrient concentration in lakes and soil (phosphorous and nitrogen compounds). The interpretation is a comparison of results from each of the impact categories e.g., GWP of both hydrogen production through steam reforming (SR) and renewable energy (KORONEOS, 2004; Simons & Bauer, 2011). The LCA framework is shown in fig 1.
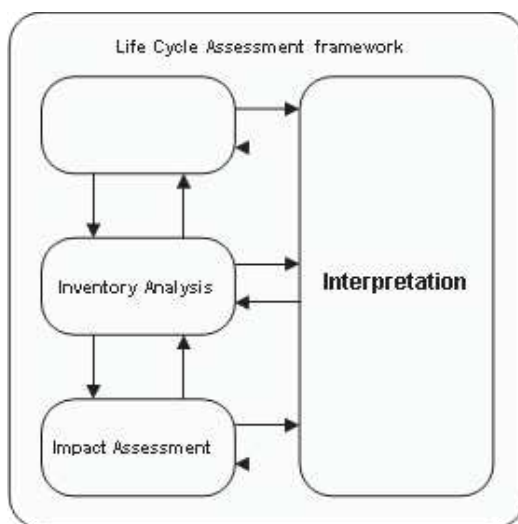
Figure 1. LCA framework.

2. Methods

The literature selected are all published scientific literature from articles in journals, conference paper, books within the last two decades. Literature was collected from database namely; google scholar, science direct and also the online catalogue of the university library (TU Chemnitz). Keywords used for literature research included "life cycle assessment", "life cycle analysis", "environmental dimension", "sustainability", "renewable energy", "hydrogen production", "hydrogen production processes". These keywords were attached in several ways with the Boolean operator "AND" to search with hydrogen production. Furthermore, the inclusion criteria after sorting by relevance through the numerous literatures found was using filters like language- English, open access, date- 2001 to 2021 and citation; with six of the selected literature having over 100 citations. Finally, I decided on the most relevant literature after reading through the abstract and conclusion. Cross-reference was also used in identifying a relevant literature.

3. Results and Discussion

This section contains the Life cycle impact assessment. Outputs with similar impacts are compared and the results for the impact categories of hydrogen production are listed in terms of cumulative quantities of specific emissions. The life-cycle impacts for each of the selected impact categories are interpreted. This provides a means of comparing the potential quantities of air pollutants emitted from different scenarios (KORONEOS, 2004). To obtain results, it is necessary to consider some of the processes involved in transformation of initial energy source. The sources; fossil fuel (natural gas steam reforming) and renewable energy are distinguished by efficiency of hydrogen production per unit of

energy consumed. A number of innovative production paths exist for hydrogen production based upon renewable energy such as wind energy, solar energy and hydrolysis to name a few (Granovskii et al., 2007).

3.1. Hydrogen production processes

3.1.1. Natural gas steam reforming

During steam reforming hydrocarbons are catalytically split in the presence of steam at temperatures of 800–900◦C. Consisting primarily of methane (CH_4), natural gas can be reacted with steam (H_2O) to form a carbon monoxide (CO) and hydrogen rich synthesis gas (syngas). Normally, the split is proceeded with nickel catalyst in gas-red ovens. This hot syngas is then fed through high and low temperature shift reactions to further convert steam and the CO to H_2 and carbon dioxide (CO_2). In a final stage, the H_2 is separated from the CO_2 using chemical adsorption and the H_2 stream is purified in a pressure swing adsorption (PSA) unit. Steam reforming is currently the main method employed for the production of H_2 (Simons & Bauer, 2011).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

3.1.2. Renewable hydrogen production

The production of hydrogen using wind energy considered here involves two main systems: a wind turbine that produces electricity which in turn drives a water electrolysis unit that produces hydrogen. The energy of wind is converted to mechanical work by wind turbines and then transformed by an alternator to ac electricity which is transmitted to the power grid (Granovskii et al., 2007)**.** The efficiency of wind turbines depends on several factors, e.g., wind velocity. Applications of wind energy normally make sense only in areas with high wind activity. The production of hydrogen using solar energy involves the indirect energy consumption and indirect GHG emissions of a photovoltaic system which converts solar energy into direct current (DC) electricity, as transformed by inverters to alternating current (AC) electricity and transmitted to the power grid. At fuel stations, AC electricity is used to electrolyze water to produce hydrogen (Dincer, 2007). Electrolysis currently accounts for the majority of production not achieved through the direct reforming of fossil fuels, and represents approximately 4% of total H_2 produced world-wide (Simons & Bauer, 2011). It also has high product purity, and is feasible on small and large scales. At the heart of electrolysis is an electrolyser, consisting of a series of cells each with a positive and negative electrode. The electrodes are immersed in water that has been made electrically conductive. The cathode (negative electrode) is typically made of nickel, coated with small quantities of platinum as a catalyst. The catalyst allows quick pairing of atomic hydrogen into pairs at the electrode surface and thereby increases the rate of hydrogen production. State-of-the-art electrolysers are reliable, have energy efficiencies of 65–80% (KORONEOS, 2004)

3.2. Comparative life cycle impact assessment

The impact categories selected for this review paper are listed in with a brief description of their environmental relevance Table 1.

Table 1. Life cycle impact categories (Ally & Pryor, 2007).

Impact category	Short description	Examples
Global warming potential (GWP)	Emissions that contribute to global warming	CO_2, CH_4, etc.
Acidification emissions	Emissions that cause acidification of rain, soil and water	S and N compounds.
Eutrophication potential (EP)	Emissions that change nutrient concentration in lakes, rivers and soil	P and N compounds.
Winter smog effect emissions	Emissions that are used for evaluating smog	Dust, SO_2.

Global warming potential (GWP) of a system is a combination of CO_2, CH_4 and N_2O emissions and can be normalized as CO_2 equivalence (Spath & Mann, 2004). Carbon dioxide makes up majority of greenhouse gases but quantifying total amount of GHG produced is key to examining different systems. Using natural gas to produce H_2 generates by far larger emission of GHG. Acidification emissions are measured as the number of protons released into the atmosphere.

The compounds mainly involved are sulphur and nitrogen compounds. SO_2 and SO_x emissions are considered to have some effect in impact category. H_2 generated from photovoltaic energy has highest SO_4 equivalent emissions. (KORONEOS, 2004). Eutrophication emissions, which cause the enrichment of nutrients in soil and water is measured by the EP impact category. An increased EP could lead to algal blooms in lakes with reduction in sunlight penetration and other adverse consequences, or similar undesirable effects on soil. Nitrogen and phosphorus are essential nutrients for the regulation of ecosystems. Enrichment of water and soil with these nutrients may cause an undesirable shift in the composition of species within the ecosystems. Eutrophication of terrestrial ecosystems is mainly due to (long distance transport of) atmospheric emissions of NOx and emissions to soil of nitrogen and phosphorus (Ally & Pryor, 2007). H_2 from biomass has the highest value of PO_4 equivalent emissions due to the fact that biomass combustion results in high NOx emissions. For evaluating winter smog effect emissions, the winter smog potentials are used for converting different chemical emissions (dust, SO_2). Solid particulate matter (SPM) is used as equivalent chemical compound. H_2 produced from photovoltaics has the highest equivalent emissions of SPM.

In this study, the Eco-indicator 95 weighting method for environmental effects that damage ecosystems on a European scale is used. Normalization is defined as an optional element relating all impact scores of a functional unit to the impact scores of a reference situation. The aim of normalization is to relate the environmental burden of a product to the burden in its surroundings.

4. Conclusion

The assessment clearly shows the relative magnitude that each process has on the overall environmental profile. Methane (CH_4) emissions, which primarily come from steam reforming of natural gas losses to the atmosphere have a negative impact on hydrogen production. The LCA of the hydrogen systems indicates that the route of production with the use of photovoltaic energy has the worst environmental performance than all the other routes. This is attributed to the manufacturing process of the photovoltaic modules. The use of wind energy proved to be the most environmentally friendly method among the examined systems for hydrogen production. The benefits of hydrogen as an energy carrier have been highlighted using the principles of life cycle assessment showing its relevance for strategic decision making to policy makers. As sustainable development is a key cog of advanced manufacturing, effort should be devoted to hydrogen production through renewable energy preferably wind. An important consideration in future work is performing a life cycle sustainability assessment; as this transdisciplinary framework includes also the economic and social impacts as well as benefits, for hydrogen production.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Liquid Metal Batteries for the Future – A Review†

Aysenur Akpinar [1, *]

1   Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: aysenur.akpinar@s2020.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Renewable energies are having a huge impact due to population and economic growth, as well as environmental issues. In order to meet the world's growing energy demand, economies are attempting to develop efficient and innovative new methods of producing and storing renewable energy. Liquid electrode-based batteries are easy to scale up, and have a low-cost and long cycle life. Liquid metal batteries are potential candidates for immense and cost-effective large-scale stationary storage; moreover, they could be crucial components of future energy systems based primarily or entirely on intermittent renewable electricity sources. Despite the benefits, liquid metal batteries have several drawbacks. These drawbacks are high operating temperature, low energy density, high self-discharge rates, and low equilibrium cell voltages. This review aims to explain the state of the art of liquid metal batteries, and proposed studies for reducing the operating temperature and increasing the low equilibrium voltage.

Keywords: liquid metal batteries; renewable energy; grid storage technology; liquid electrode-based batteries.

1. Introduction

Due to widespread concerns about environmental issues, renewable energy sources are in high demand and serve a critical role in reducing emissions while also achieving the goal of sustainable development (Li, Yin, et al. 2016). Low-cost, long-lasting, and high-efficiency energy storage technologies are essential for developing renewable energy and smart grid applications, as the integration of more renewable energy into the grid demands the utilization of large-scale energy storage technologies (Li, Yin, et al. 2016). Rechargeable batteries have essential characteristics such as high efficiency, a long life cycle, and flexibility, making them an important storage technology; various types of batteries have specialized for applications in many industries, including portable devices, electrical vehicles, and grid energy storage (Dunn, Kamath, and Tarascon 2011). Liquid metal electrode-based batteries offer a solution to the future aims of integrating renewable energies and enhancing the grid technology (Li, Yin, et al. 2016). They are easily scalable, low in cost, and have a long life cycle due to the conductive and flexible structure of the liquid metal electrode (Li, Yin, et al. 2016). Na-beta alumina batteries and liquid metal batteries are two types of available batteries that use liquid metal electrodes (Li, Yin, et al. 2016).

A liquid metal battery (LMB) is made up of two liquid metal electrodes that work as negative and positive electrodes. They are separated by a molten salt electrolyte, which self-segregates into three layers based on density and immiscibility (Kim et al., 2012). During the discharge, the negative electrode metal A is oxidized to then dissolves in the molten salt and alloys with positive electrode metal B.

In the charging process,   is oxidized back to   at the positive electrolyte;   is reduced to A in negative electrode (Li, Yin, et al. 2016). Overall process can be expressed in equation as (Li, Yin, et al. 2016):

Positive electrode: $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (1)

Negative electrode: $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (2)

Overall cell reaction: $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (3)
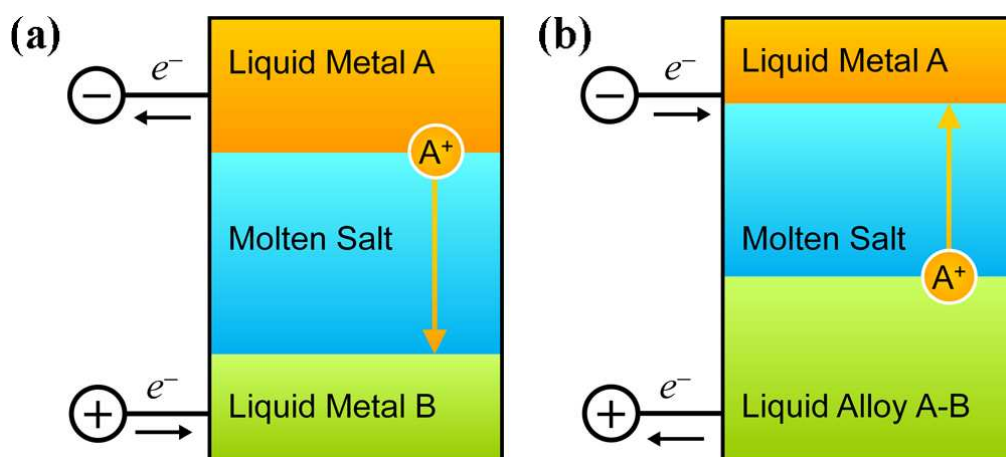
Figure 16. Illustration of liquid metal battery in the (a) discharge and (b) charge processes. Adopted from Liquid Metal Batteries: Past, Present, and Future, Chemical Reviews, 113(3), 2075-2099

The liquid metal electrodes are generally chosen based on the three conditions described below (Kim et al. 2012):
- The melting temperature should be less than 1000 °C and the boiling point greater than 25 °C
- Must be electrically conductive
- Must be nonradioactive

The following factors should be considered when choosing a molten salt electrolyte (Kim et al. 2012; Li, Yin, et al. 2016):
- Low melting point
- High ionic conductivity
- Suitable density

The original idea of developing LMBs for large-scale energy storage was to exploit electrolysis cells to generate and store electric energy, so for that goal, Donald Sadoway began to explore LMB at MIT in 2005. The MG||Sb alloying system was the first one examined (Kelley and Weier 2018; Weier et al. 2017).

Because many of the potential electrode materials are widespread and affordable, LMBs are considered low-cost. Thanks to the fast kinetics of liquid electrodes, LMBs have a high recharge rate and a long lifespan (Kelley and Weier 2018). Furthermore, using liquids allows self-segregation and provides for easier and lower-cost cell construction compared to conventional batteries (Kim et al. 2012). In comparison to liquid electrode-based batteries, liquid metal batteries are a relatively new invention. However, all the listed properties make LMBs top candidates for grid-scale storage and have recently risen in importance. Yet, LMB still confronts several material and engineering hurdles (Kim et al. 2012), which will be introduced further in this review paper.

2. Methods

A secondary quantitative research model was adopted in this review to acquire a deeper understanding of the state of art of Liquid Metal Batteries. Existing scientific research, review papers and works of literature were collected from 1998 to 2021, with databases such as Science Direct, Research Gate, and Springer being used. In total, within the given time frame, 20 papers were examined; however, in order to give the most recent findings, the emphasis was placed on articles published after 2005. Manual online searches using keywords, language, abstracts relating to the theme, and cross-reference analysis were used to find similar papers.

3. Results

Liquid metal batteries are important competitors in grid storage applications due to various of advantages like low cost of materials, long life cycle, simple assembly, and superior kinetics and transport properties (Kim et al. 2012). Despite their attractiveness, liquid metal batteries have certain key drawbacks that make them unsuitable to be used in portable applications (Kim et al. 2012; Li, Yin, et al. 2016). High operating temperature, low specific energy density, low equilibrium cell voltages, and high self-discharge rates are examples. However, due to space limitation, issues including

low output voltage, energy density, and elevated operating temperatures (Kim et al. 2012) will be addressed in this review.

Liquid metal electrodes must operate at temperatures greater than the melting point of the cell components to maintain the liquid state; therefore, LMBs are best suited for high-temperature applications (Weier et al. 2017). Nevertheless, high temperatures accelerate chemical reactions, cause cell immobility, and eventually material damage (Li, Yin, et al. 2016; Weier et al. 2017). As a result, more studies are required to discover a method for LMBs to function at lower temperatures (Weier et al. 2017). To accomplish this, ionic liquids were used instead of molten salt for the first time (Lalau 2019). The experiment was carried out at 160 °C, which was an unusually low temperature considering that LMBs generally work at temperatures ranging from 450 °C to 700 °C. Galvanostatic charge-discharge experiments were done at   for a predetermined time of 13 hours, yielding a discharged capacity of 63 mAh on the first cycle, corresponding to around 50% depth of discharge (Lalau 2019). The released data indicated encouraging results along with good electrochemical performance, and the findings should be considered when determining how to manufacture liquid metal batteries that suitable for low-temperature applications (Lalau 2019).

Additionally, because bimetallic electrodes have the limitation of electromotive force, LMBs have a low energy density (Kim et al. 2012; Li et al. 2018). However, as high energy density batteries are crucial for a wide range of power storage applications, there is a demand for LMBs that can be adapted for high specific energy applications (Li et al. 2018). In accordance with this, an experiment was carried out to investigate the feasibility of using the metalloid tellurium (Te) to boost energy density; Tellurium was coupled with Sn as the positive electrode in the experiment, and Li was employed as the negative electrode. Experiment results revealed that The Li ‖ Te-Sn LMBs have the highest discharge voltage and energy density of any available LMBs (Li et al. 2018).

Table 1. Cell characteristics and energy densities of the Li‖Te-Sn cell were compared to those of previous published LMB systems (Li et al. 2018)**.**

LMB System	Achieved capacity (Ah)	Discharge voltage (V)	Energy density
Li-Bi(Wang et al. 2014)	48.8	0.55	148.5
Mg-Sb	2.5	0.46	24.58
Li-Bi-Pb	1.5	0.62	86
Li-Te-Sn	2.0	1.50	495.5
Li-Sb-Sn(Li, Wang, et al. 2016)	1.4	0.80	193.8

The data leads to a better understanding as to why tellurium is a strong competitor for high-energy-density LMBs. The studies examined in this review are significant in addressing challenges that prevent liquid metal batteries from being used in the future. However, the results' generalizability is limited due to not enough conducted experiments for each stated approach.
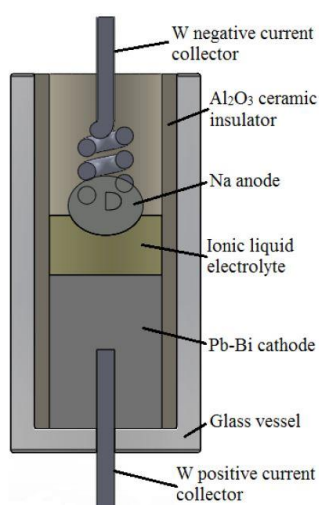

Figure 2. The experimental structure adopted for electrochemical characterization of the Na‖Pb-Bi cells for low temperature liquid metal batteries. Adopted from Sodium-bismuth-lead low-temperature liquid metal battery.

4. Discussion

This review describes liquid metal batteries, which are designed to provide a low-cost, long-life technology in large-scale energy storage applications. Based on quantitative analyses of publicly available data, it can be concluded that liquid metal batteries are a potential storage alternative with various advantages that will most likely assist in expanding the use of renewable energy applications in the future. Recent studies have been conducted to develop high voltage and low-temperature liquid metal batteries using various alloying techniques, as well as an alternative electrolyte to molten salt. Related to low energy density, an experiment was conducted to propose Li||Te-Sn LMB configuration where Te was alloyed with inert Sn as the positive electrode. As a result, high performance was recorded with 1.6 V of discharge voltage and of energy density; the highest values amongst the recorded LMBs. Another study suggests a method for high-temperature LMBs by substituting ionic liquid with molten salt. The experiment was conducted out at 160 °C, which is lower than the temperature at which LMBs typically operate. After three charge-discharge cycles, the cells stopped working due to the combined effect of the formation of a solid phase on both electrodes, which inhibited electrochemical reactions. Despite the promising preliminary results, more research is required to sustain the system and improve the cyclability of the cells. Liquid metal batteries, without a doubt, are a technology that bridges the gap between sustainable energy production and consumption. As a result, further tests should be conducted to carefully study the issues in order to improve batteries while also expanding their use.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Life-Cycle Assessment of Electric Vehicles: Are they the Solution?†

Kaan Engin Bilge [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
[*] Correspondence: kaan-engin.bilge@s2019.tu-chemnitz.de
[†] Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Sustainability is one of the emerging topics in today's world. When we compare the top global risks in terms of impact and likelihood for the past few decades, it is possible to say that environmental risks have become the main issue. Earth has a capacity to regenerate itself at a certain pace but as we exceed this pace, we are harming the environment. What the humankind can do is to minimize the resulting carbon footprint and environmental impact as much as possible. One topic that might be familiar to most people is electric vehicles. In the public eye, they are the ultimate way for an individual to help and save the environment. They are more expensive, but that seems to be the extra price to be an environmentalist. While this perception has a truth to it, the topic is more complicated than this. The aim of this paper is to review the existing literature on the life-cycle assessment of electric vehicles, summarize their findings and indicate the aspects where research or studies are lacking.

1. Introduction

All species on Earth reach equilibrium with the environment and have a natural balance with other living creatures around them, but that is not the case with us. With developing technologies and industrial revolutions, we were able to manufacture, use, travel and unfortunately pollute more than before. After subjects like sustainability, the environment and phenomena like global warming have become more popular, efforts to reverse or minimize the human impact on the earth have increased. However, sometimes solutions are just so in appearance and in many cases, problems are just shifted from one place to another. This might be intentional and aim to just create an environmentalist image without really having a significant environmental impact. In other cases, businesses might try and reduce the impact of a product or service in some way, but indirectly cause the impact to replenish or even exceed the previous amount in another area. Therefore, it is necessary to assess all relevant areas while considering this. In many cases, the environmental impact of a product is not limited to a single life phase of the product, such as the use phase. This is valid for personal vehicles as well. It is estimated that there were roughly 1 billion personal vehicles in use in 2010 (Sousanis, 2011). Considering the number of vehicles that are used globally, it is evident that both their cumulative impact and the potential to reduce this impact is very significant. To do so, it would be necessary to take into consideration all life phases of a motor vehicle. This allows us to evaluate the validity of current and future mobility solutions. Another benefit of this assessment is that it depicts the impact of different life phases separately, therefore areas with potential or need to decrease impact can be identified and allow businesses to focus on them. As stated before, EVs might be the first thing that comes to mind when environmentalism and reducing carbon footprint is mentioned. Although electric and hybrid vehicles are just starting to increase their presence in the motor vehicle market these days, it already existed as a concept back in the 90s. EVs had a 2% global market share in 2016 and it is expected to be 22% in 2030 according to the CB Insights Research (2020). Although this seems promising in terms of environmental efforts, it also highlights the importance of what the actual impact of EVs is. This paper reviews the existing publications on this subject, what kind of assessments are made, and which tools and methods are used while doing this. They are also reviewed based on how the existing works correspond to Life Cycle Engineering (LCE) and which dimensions are covered and which are not. This way it is aimed to highlight the deficits or shortcomings in the existing research to fulfil them in the future.

2. Methods

When searched online, it is possible to find many publications about the Life Cycle Assessment (LCA) of EVs. Several of them were found using the TU Chemnitz library database, Scopus, Google Scholar and Science Direct and reviewed to see how comprehensively EVs have been assessed until now and what are the approaches of the researchers, what are their methods and what are the shortcomings or obstacles, if any. The literature survey was directed towards journal articles and conference papers.

Many existing publications have different approaches and different scopes. While some of them compare EVs with hybrid and/or internal combustion engine vehicles (ICEV) with LCAs, some of them only focus on the LCA of EVs or even only the LCA of a battery pack. Although the approaches or scopes of the papers might differ, there are some common conclusions. Ellingsen et al. (2013) made an LCA only for a lithium-ion battery pack, instead of the whole EV. EVs do not have any tailpipe emissions but as stated in this paper as well, the production of the batteries is a problem on its own (Ellingsen et al., 2013). Therefore, a life cycle perspective is required to avoid shifting the problem.

Egede et al. (2015) proposed a framework to consider all the influencing factors for the LCA of EVs. The aim was for this paper to be a guide for all future LCAs regarding EVs. An EV was defined as a system which is affected by both internal and external factors. Also, the energy consumption in the vehicle was separated into the different devices in the EV. All these factors and components combine to create the proposed framework to be used for the LCA. Figure 1 depicts the suggested LCA framework (Egede et al., 2015).
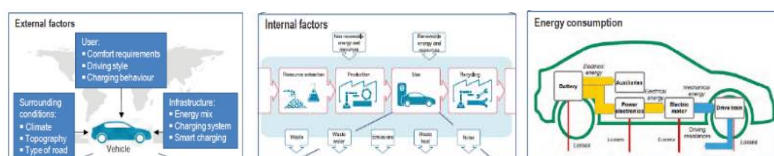

Figure 1. Life-Cycle Assessment framework for electric vehicles. (Egede et al., 2015)

The focus is more on the use phase, and the environmental aspect to be more precise. The LCA method is used for the quantitative ecological assessment and observe the environmental impact of EVs. Additionally, a case study was used both to demonstrate the proposed framework and depict the effect of the influencing factors using different cases that reflect different realistic scenarios. It is accepted that EVs, like others, have an environmental impact during the manufacturing phase, although it is not the focus of this study. Instead, the focus is on the potentially high or low additional impact that will occur throughout the use phase, which is affected by all the identified internal and external factors related to the EV. An array of results can be reached based on the case and the factors effecting the use phase of the vehicle. The first internal factor is the vehicle itself. These are the characteristics of the vehicle like weight, frontal area, aerodynamics, efficiencies of components and the use of impactful materials like lithium, manganese, cobalt, and neodymium (Egede et al., 2015). The next factor is the user of the vehicle. The driving style, charging habits and use of auxiliaries like heating and cooling all affect the energy consumption during the use phase and affect the overall life cycle impact of the EV. An external factor is the infrastructure which refers to the energy mix used in that area and the ratio of renewable and non-renewable energy sources. This is a very significant factor that affects the impact of the vehicle potentially both in the manufacturing and use phases. Also, the charging systems that are used and the availability of systems like smart charging are considered. The last factor is the surrounding conditions. This refers to variables like climate, topography, type of road, etc. The climate affects the use of heating and cooling which affect the energy consumption drastically. The topography and road type affect the driving style and affect the use of acceleration and braking. This is also the case for when the vehicle is used in a city or in highways instead. Therefore, the surrounding area where the vehicle is used significantly affects how much energy is consumed by it regularly. Later, a case study with three scenarios was carried out where the driving behavior, desired temperature, topography, and type of road were variable. Each case yielded a different result for the energy consumption per 100 kilometers. The final step of the study was to consider the use of steel and aluminum to produce the vehicle which have different initial impacts. However, the study showed that both materials could prove to be the better choice in different circumstances. Therefore, there is no single right answer for EV production and various factors should be taken into consideration.

Faria et al. (2012) provided an economic and environmental comparison of electric and ICEVs. In this paper, the Well-to-Wheel methodology was used. It was also used for the LCA by Nordelöf et al. (2014). This method was carried out while considering different energy supplies and vehicle technologies. Both non-renewable and renewable energy sources were used for the study and the differences between battery EVs, hybrid EVs and plug-in hybrid EVs were analyzed and depicted. As in many of the other publications, some assumptions such as the current average mix for EU

was assumed here. A DAQ system was used to identify the main contributors to the overall energy consumption, costs, and emissions. This paper distinctly provided an analysis of all the subsystems of EVs where energy losses occur. System efficiencies were calculated using efficiency values for each component and relevant formulas for global efficiencies. This way minimum and maximum global efficiencies for the WTT (upstream stage) and TTW (downstream stage) systems were provided. Many performance values such as resultant pollutants and plant efficiencies were given for different fuel types. Based on current values and future trends, a cost of ownership calculation was made for all vehicle technologies. Additional figures show the breakdowns of these costs. Therefore, this paper gave more depth to the economical dimension. Like Egede et al. (2015), the impact of driving style and several real-life scenarios on the energy consumption was investigated. However, the method was distinct compared to other studies. A DAQ system was installed to a Nissan Leaf, which was used to test the energy readings for different road types and driving styles. Therefore, Faria et al. (2012) used experimental data to reach conclusions. Nissan Leaf was selected as the representative for battery EVs, and some other specific car models were selected for other technologies for the cost of ownership analysis.

The Nissan Leaf was also used by Hawkins et al. (2013), while analyzing the use phase energy requirements of an EV compared to that of an ICEV. The study included the production, use and end-of-life phases for both vehicles, the other vehicle was selected as Mercedes A Series to make the cars similar in functionality. This was a distinct approach, because other studies like (Faria et al., 2012) assumed vehicle models based on the best option for the corresponding vehicle technology available on the market. Inventories for all considered vehicles were constructed and the vehicles were modeled to have setups that will have equivalent performances and functionalities. The use phase analysis was based on some assumptions such as existing industry performance tests and considered five different driving cycles, while adopting average European conditions and import mixes for the gasoline, diesel, and electricity inputs (Hawkins et al., 2013). Additional assumptions such as component wear and tear were based on existing publications. Finally, the end-of-life phases were assessed after the treatment and disposal of the vehicle and batteries was modeled.

3. Findings

The problem with many of the studies is that some aspects are ignored to simplify or isolate the findings. Ellingsen et al. (2013), for example mainly focuses on the assessment of the battery pack rather than the whole EV. They state that the main problem is the lack of transparency in the sector. Therefore, most studies are based on secondary data, and it becomes harder to provide a full and open inventory for these products. Ellingsen et al. (2013) aim to provide an inventory for a lithium-ion battery and report its cradle-to-gate impacts. The study is defined as a process based attributional LCA. The GWP of a battery with a specific capacity and weight was found this way. Additionally, most of the production impacts were found to be related to battery cell manufacture, positive electrode pastes and negative current collector and their corresponding production chains. These three production chains make up 56% to 87% of the total impact of the battery (Ellingsen et al., 2013). Contribution and structural path analysis were used, and this was helpful for the identification of the most impactful processes and value chains. This paper also provided a sensitivity analysis which showed the effects of varying life cycle numbers on the use phase impact and the used electricity mix on the production impact. The findings of the study were compared with previous studies and the results were in the same range as the previous reports. This paper was focused on the environmental aspects and the detailed explanation and analysis of a battery pack. However, functional, and economical aspects were not covered as much.

The impact of the EV is much more than just the production of the vehicle and the battery pack. The use phase is just as significant if not more and is generally studied in the papers with the help of different methods such as case studies and sensitivity analysis. The end-of-life phase however is not given emphasis as much as the other phases. As stated by Hawkins et al. (2013), more in-depth analysis led to distinct results compared to the preceding reports. Another issue is that most papers are not based on experimental data or data acquisition and depend on existing test results and studies. Almost all LCAs use some average energy mix values, fuel, and electricity prices, etc. valid for a specific country or region. Although these assumptions and the results they lead to are very significant and beneficial, they apply for specific cases and might provide false conclusions for other real-life scenarios. For example, the average energy mix for the European Union is assumed in many papers. However, this is not the case in many countries around the world. Therefore, the impact of the production, use and disposal of EVs might be much higher in the countries that currently depend on more non-renewable energy sources than renewable energy sources.

Hawkins et al. (2013) provided a comprehensive figure for different impacts of vehicle production was. The figure below (Figure 2) depicts the GWP and other impacts of the process. All results were normalized to the largest total impact, and they compare different vehicle technologies. This study estimated that the GWP impact of EV production is almost twice the impact potential reported by preceding studies.
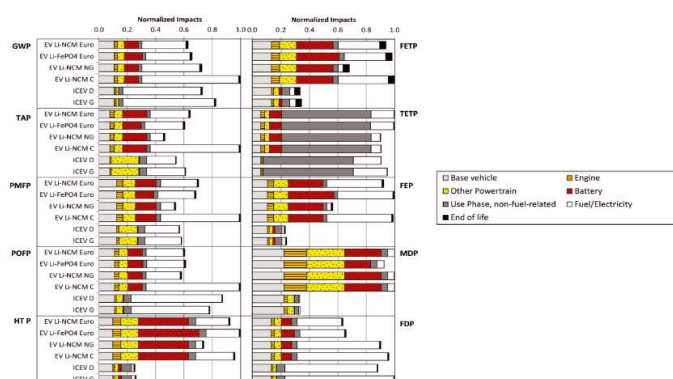
Figure 2. Normalized impacts of vehicle production. (Hawkins et al., 2013)

Publications cover the environmental aspect of LCE, and it is possible to make conclusions about this dimension. Life Cycle Costing (LCC) is also carried out, in varying depths and details, and provides conclusive information regarding the economic differences of owning vehicles with different technologies. However, the technical and social impacts of the vehicles are not emphasized and therefore it is not possible to make conclusions for these dimensions of LCE.

4. Discussion

As stated before, one of the main issues with the LCA of EVs is the lack of transparency in the industry. That is the case for both the vehicles as a whole and the battery packs used in them as well. This has several reasons such as competitive reasons or inability to comply with standards and regulations. LCE methodology presents results clearly and transparently to decision-makers. Therefore, the initial requirement for more accurate, comprehensive, and reliable studies coherent with LCE is the availability of transparent primary data from manufacturers. The material and energy flows for the entire product system must be included for the LCA. Also, the life cycle impact assessment should always include all the relevant impact categories and GHG emissions because excluding some gives false conclusions.

Studies make critical assumptions which narrow down the validity of the findings of studies. Instead of assuming average values for energy mix, fuel prices, inflation rates, etc. additional sensitivity analysis should be made. Ellingsen et al. (2013) verify that the choice of different materials to produce the vehicle such as aluminum and steel also depend on the drive cycles of the vehicle and the current energy mix of the country that is considered. Therefore, there is no universal correct answer when it comes to which option has less impact regarding the dimensions of LCE. So, the studies in the future should also focus on the identification and specification of these boundaries. If the material choice for the vehicle is considered, a comprehensive study that indicates in which conditions which options are preferable, a universal conclusion would be possible. This could be said about other assumptions as well. For example, fuel and electricity prices are much higher in developing countries compared to Europe and there are no incentives for EVs. Therefore, these countries do not fit into the LCC in these studies. A detailed and comprehensive process-based model could be used to analyze these cases as well. Or the assumptions could be set as variables in the sensitivity analysis, and it would be possible to see the effect of these elements on the preferability of different options. Visuals like CLUBE mapping and Ternary diagrams could be used for the decision-making process.

LCE seeks sustainability as well. Existing studies consider only the finite life cycle of a vehicle. A cradle-to-cradle approach is preferable than cradle-to-gate and cradle-to-grave approaches. This promotes sustainable production.

The last issue is the social aspect of LCE. Although sustainability concerning other dimensions are often analyzed, studies frequently neglect the social aspect. It is difficult to consider social aspects because there is no clear way to digest social information in terms of the products or processes involved in many cases. Therefore, to fully incorporate LCE and cover all its dimensions, methods to indicate the social impacts should be developed.

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Review article

The Circular economy: Potential alternative for linear economy†

Prabal Dhawan [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
*   Correspondence: prabal.dhawan@s2019.tu-chemnitz.de
†   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Increasing the use of natural resources and at last disposing them as a waste has affected our environment badly, so there is a requirement for some change. Our current economic model i.e., linear model which is take-make-use-dispose need for a transition. Circular economy which is quite in discussion now days could help us not only in environment but also for the growth of the economy and benefiting the society. This paper reflects how transition from linear economy to circular economy can help in reducing environment problems and the transition is possible or not. Furthermore, the paper focused on how recycled products could help in economy growth and discussed about the problems while implementing the circular economy. Moreover, it also includes business model PSS (product service system) in reference whether it can achieve resource efficiency through circular economy. However, there are certain barriers such as technical, market, institutional and social could prevent in implementing the circular economy which have also been discussed.

Keywords: Circular economy; Sustainability; LCA (Life cycle Assessment); DTs (Digital Technologies).

1. Introduction

Over the past decades, the use of natural resources has been increased rapidly and we are reaching the limits. This is mainly due to our current economic model i.e., linear economy (Take-make-use-Dispose) (kannikar et al., 2021) in which products end up as waste and this model is unsustainable. Historically, the linear model benefitted the creative, manufacturing, retails, power supply and raw material industries such as mining industry and oil industry. However, on the flipside an untold amount of waste was sent to landfills or combusted as waste (Andrews, 2015). To face this challenge of sustainability there is a serious need for the transition of an economic model, which should have less wastage and the end products could get recycled. Improvement is needed in the way we extract, use, and deplete renewable resources. Circular economy could be the alternative one(Andrews, 2015). Circular economy is restorative by design and intention, relies on renewable energy, which minimizes, tracks, and eliminates the use of toxic chemicals and eradicates waste (Michelini et al., 2017). Circular economy will not only boost the economy, but it is also beneficial for the environment by reducing the use of raw material and converting the waste which is being dumped till now can be reuse, remanufacture, re-cycle for another use and creating employment opportunities which are valuable for the society. Bringing circular economy into place of the linear economy will help world with rethinking and reengineering complex issues (Kannikar et al., 2021).

Circular economy is considered as a way to enhance Europe's effort in achieving the UN sustainable development Goals (SDGs)(Kannikar et al., 2021). According to the Brundtland Commission sustainability is the development that meets the current demand without jeopardizing future generation's ability to meet their own needs. (Geissdoerfer et al., 2017). The circular economy contributes directly or indirectly to many of the 17 goals. Goal 12 which focuses on sustainable consumption and production has the greatest impact, while goal 7,11,13,14 and 15 on clean energy, climate action, sustainable development, the oceans, as well as terrestrial ecosystem are indirectly affected (Kannikar et al., 2021).

According to EU Action plan 14, the industrial sector would gain approximately 600 billion euros if the circular economy model is put into action. However, certain barriers could affect the implementation of the circular economy such as Technological barriers, market, industrial and cultural, or social. Lack of knowledge about the circular economy concept and its benefit is the major barrier to the implementation of this model. Customers need to know about the difference between the linear economy and circular economy. This comes under the social barrier. Lack of up-front cost, lack of access to funding, cheap virgin materials come under the market barrier. Lack of eco-management tools for SMEs, poor institutional cooperation across the international supply chain, weak policy, and obstructing the

implementation of laws and regulation are considered under institutional barriers. Technology barriers such as lacking skills and investment in circular economy product design, lack of focus on end-of-life design, difficulty in separating waste (lack of ineffective technology), and price and quality of material both are unknown. (Grafström & Aasma, 2021). In recent years, certain companies are working to overcome these barriers such as ZenRobotics. They use the AI algorithm which helps in recycling the product such as sorting the waste material (one of the most important processes for recycling) and sending them for further process (Uçar et al., 2020).

In this paper, life cycle assessment, which is a standardized process used for analyzing the impacts associated with a product's life cycle or service has been discussed. LCA can be used in a circular economy to assess and measure the efficiency of an individual system to ensure the right decision are made. And this paper also assists in understanding the environmental indications of circular economy strategies (Peña et al., 2021).The circular economy model is being researched on currently and is being implemented in the industry slowly.

2. Methods

All the reviewed literature was acquired from the search engine namely google scholar with the help of search terms like circular economy, sustainability development, circular economy barriers, etc. and after combining, these terms were put together for the relevant literature and using the option of advanced search to filter only recent data. All the papers discussed in this article were published after 2013. Later collected papers were briefly reviewed and the paper which includes an appropriate approach for the topic such as transition of the linear economy, R principles etcetera, and standardized data were chosen, and the paper and the number of references were finalized.

3. Results

3.1. Life Cycle Assessment tool

3.1.1. PSS (Product Service System) model

As our current economic model i.e., linear model which is based on the manufacturing of goods and their disposal by consumers. Our current economic model is unsustainable because our current economy focuses so little on environmental and social concerns (Michelini et al., 2017). Many authors recommended the PSS model for the circular economy. PSS is an environment-friendly model that uses both sustainability themes and business models. It emphasizes reuse, repurpose, remanufacturing, and recycling at the end of life of products. By doing so, PSS can reduce resource consumption and waste production. Businesses will be encouraged to prolong the product life and construct them as economically and environmentally efficient as possible under the PSS business model for circular economy. To implement PSS model companies, need to consider extending product lifespans and promoting cost and material efficiency. (Michelini et al., 2017).

There are 3 types of PSS models:
1. Product;
2. Use;
3. Result-oriented.

However, only result oriented can help in achieving the resource use efficiency, since customer pay for the service rather than products, so the circularity of the product can be gained while the product oriented do not alter the incentive to maximize the sales, and the use oriented might encourage less careful use and prevent circularity. Unless intentionally designed, PSS is unlikely to reduce environmental impacts, so it's application must be with careful consideration that is why life cycle Assessment is considered important tool for designing PSS business model (Michelini et al., 2017)

3.2. Business Model Canvas

BMC is an easy and collaborative way to approach to define the business model's elements. Three different cases were studied to define the relation between circular BMC and DTs (Digital Technologies) (Table 1). Three cases are:
- Alpha case: In this case DTs like IoT (Internet of things) and big data where IoT provides knowledge on the location and condition of the product which helps in value creation activities like repairing, maintenance services etc. IoT that creates the value proposed by PSS, which is primarily a resource of intelligent products as well as revenue streams. Thus, alpha and the user build a long term relationship by preventing careless usage of appliances (Uçar et al., 2020);
- Philips citytouch case: In this case all the lightings was connected to the platform, where the authorities and Philips were able to communicate and control the system via lighting management software which leads to the controlling

energy consumption of the lightings and stakeholders can conserve energy and material, and generate more revenue from the remanufactured resources (Uçar et al., 2020);

- ZenRobotics case: The company uses AI algorithms to separate the waste materials that can be recycled to achieve high rate of pure secondary material. Moreover, with AI it becomes easier to use recycled materials to make recycled products which could benefit the environment (Uçar et al., 2020).

Table 1. Relation between circular BMC and digital technology

Cases	Functionalities (cases)	Digital technology
Alpha	monitoring product location, condition, availability	IoT
	optimizing energy consumption	IoT and big data analytics
	monitoring product	IoT
	Predictive preventive maintenance	IoT and big data analytics
	Creating the intelligent products	IoT
Philips	monitoring product	IoT
	optimizing remanufacturing, energy consumption	IoT and data analytics
	Virtual communication	IoT and Cloud
	Creating intelligent product	IoT
Zen-robotics	optimizing recycling	artificial intelligence

4. Discussion

In this paper, it was discussed about the transition of the current economic model i.e., liner economy to circular economy. To stop the end-product to be waste it was really important to bring some changes for the environment, economy, and society. Through reuse, re-manufacturing, recycling, waste reduction, and other practices, the circular economy seeks to reduce the environmental impact of raw material and to reduce waste at the end of the life of the product. Despite the hype of this concept, still, the companies, governments, and businesses are not cleared with the conceptual concept between sustainability and circular economy. They need to understand the similarities and differences between these concepts and how they are related to each other.

However, there are certain barriers those need to be studied well for future research. There should be some campaigns for the customers about giving them knowledge about this model, how this model could help in reducing the environmental problem and boost the economy, and certain companies are working on reducing the technical barriers using some algorithms for separation of waste that could go for the recycling process. When social aspects are discussed in circular economy, they are usually restricted to creating jobs, since it is unclear to what extent CE can contribute to society.

To define the relation between the circular economy and DTs, three case studies were studied, where two main roles for DTs were identified i.e., enabler and trigger whereas enabler explains how DTs can help in development of CE and trigger can lead to innovation process. The results presented in the reviewed literature are based entirely on theoretical concepts. There is no certainty if the methods presented will help achieve circular economy and require more testing. However, more research needs to be done to validate the findings. There are some important tools such as life cycle assessment which help in designing business models for the circular economy. LCA analyses the product and all their impacts, including both the use of materials and resources, as well as all other impacts relevant about the life cycle of the product.

At present circular economy seems to be challenging but it will be useful for the people, nature, and economy. So as a consumer it is our responsibility to choose the product and services that are environmentally sustainable, or that can be recycled.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Lean Six-Sigma: The breakthrough strategy revolutionizing automotive component assembly†

Frranc Steeve Ignatius Sundar Raj Margret [1,*]

¹   Chemnitz University of Technology; Chemnitz; Germany
*   Correspondence: frranc-steeve.ignatius-sundar-raj-margret@s2020.tu-chemnitz.de
†   Presented at the 1ˢᵗ Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: This article gives a synopsis of how the concepts of lean and six-sigma if combined, can provide a game-changing strategy for component assembly in the automotive industry. The lean six-sigma (LSS) can yield higher profits, customer satisfaction and an efficient production process through its emerging strategies. Case studies and articles of the LSS approach from different parts of the world are analyzed in detail to understand its implementation and effectiveness in achieving sustainability across the mentioned industry. In addition, a glimpse about the scope of readiness of small, medium and large European enterprises to adopt LSS in their processes is also discussed.

1. Introduction

Currently, many challenges are being faced by the automotive manufacturing industry. These challenges are mainly attributed to the emerging advanced manufacturing techniques, which makes the current technology outdated. In addition, the nature of expectations from the consumer has also dramatically changed in recent years. Hence, this industry needs to adopt the necessary tools and strategies which help to sustain themselves in the current scenario. Keeping in mind the customer's need, the prominent tools Lean and Six Sigma has been used for achieving low waste, low cost and improve sustainability.

Lean practices emerged from the automobile industry, more specifically from the Toyota Production System (TPS) with efforts of Taiichi Ohno (Ohno, 1988) in Japan. Lean manufacturing helps to enhance the production processes and gives importance to customer satisfaction. In Lean framework, 'waste' is a non-value-added activity involving transportation, inventory, motion, waiting, over-processing, overproduction and defects which does not benefit the customer. Overall, its objective is to produce products of the highest quality at the lowest possible cost in the least time by eliminating waste in the production system. Therefore, lean manufacturing techniques have become vital for manufacturers as they can act as a survival strategy and have a higher competitive edge over non-lean practitioner. Lean implementation has been adopted in the following steps: (i) identification of wastes in the present system (ii) identifying wastes that can be present in the organization (iii) performing root-cause analysis to find the solution (iv) testing and implementing the solution to the entire system. However, lean manufacturing has its own limitations. It has a very low margin for error. Being too aggressive during scheduling can lead to systematic bottlenecks. Equipment or labor failure can lead to significant irregularities and make the entire operation fall behind. Using lean methods to squeeze more economy from production can often lead to worker's dissatisfaction thereby rejection of the methods by the workers.

The six-sigma methodology is a customer-focused continuous improvement approach whose goal is to minimize defects and variation towards the accomplishment of 3.4 defects per million opportunities (DPMO) in areas like administration, product design and production. The Motorola Corporation developed this process in 1986. Six-sigma goals are directly and quantifiably connected to business goals**.** The method describe, evaluate, examine, develop and manage the quality and efficiency of any product, process, or service (Magnusson, K et al., 2004). It aims to improve process performance and achieve high levels of quality by determining the source of defects and reducing product and process variability. Unlike Total Quality Management (TQM), it takes a more prescriptive and methodical approach to process improvement by placing a higher emphasis on responsibility and customer's satisfaction. Multiple companies use six-sigma management to improve efficiency, cut costs, eliminate defects and reduce product variation, thus increasing their profits. The six-sigma problem algorithm consists of five phases: Define, Measure, Analyze, Improve and Control

(DMAIC). Many studies indicate that adaptation of six-sigma had a significant beneficial effect on sustainability performance. However, the inspection of business processes and generation of large amounts of data have been carried out minute-by-minute, leading to time-consuming and increase of overall cost.

Indeed, in spite of the fact that Lean and Six-sigma have impediments, the adaptation and integration of both the methodologies have been the most popular business approach. This has been accomplished for deploying continuous improvement, achieving operational and service excellence thereby to improve product quality, reduce production cost and enhance customer's satisfaction in automotive organization. Integrating these two approaches gives the organization superior performance faster than the implementation of each process in isolation. LSS uses the DMAIC methodology via combination of applicable tools from the Lean toolkit such as Kanban system, 5S, Just in time (JIT), value flow mapping (VFM) etc. and Six Sigma tools such as Cause & Effect Analysis, 5 Why Analysis, Pareto Chart, Hypothesis Testing etc. at each phase of the DMAIC process as seen in figure 1. Furthermore, DMAIC serves as a framework and a solid foundation for effective LSS deployment. The main objective of this article is to check for the readiness and effectiveness of implementing the LSS strategy in automotive component assembly in manufacturing organizations by analyzing the case studies.
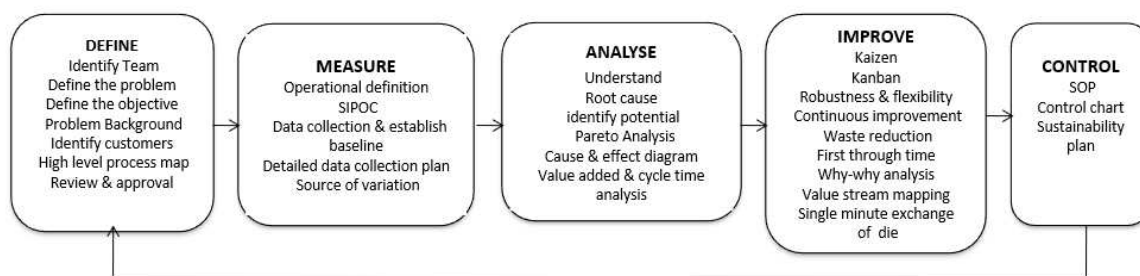

Figure 1. LSS methodology.

2. Methods

The present work was a systematic review of lean six-sigma and its impacts on the companies utilizing this methodology as described in the available literature. The detailed literature survey was carried out from reputed academic journals and proceedings of lean six-sigma from leading databases and publishers such as Scopus, SpringerLink, ResearchGate, Taylor and Francis, Emerald Insight, Elsevier and Inderscience. Keywords such as "Lean Six-sigma"," automotive industry", "DMAIC", "Integration of lean and six-sigma" etc. had returned many literatures in the last 20 years. However, to understand the latest trends and evolution of the LSS methodology and its implementation in the industry, literatures from the year 2015 were only considered. Since there were many literatures from the Indian industries, the author tried to diversify his search and included research articles from other parts of the world such as Brazil, Malaysia and Europe. Finally, eight literatures were shortlisted based on the author's objectives that reflects the purpose of this paper to analyze current scenarios using LSS in automotive industries. This may help companies understand the significance of LSS in determining project success rates.

3. Results

3.1. LSS adoption and its readiness

(Panayiotou, N.A. et al., 2020) had discussed the adoption of lean six-sigma (LSS) in European organizations. Large companies as well as small and medium enterprises (SMEs) almost equally adopted LSS principles with 54 and 46 percent respectively. Even though there were thirty-one literatures found for the dominant sector like manufacturing in adopting lean sigma strategies, no more than three literatures were available concerning the automotive industry. Moreover, the survey found that the overall percent of documents generated by all European countries is too low and that more LSS publications are needed to follow the advancement of this scientific field.

(Shokri et al., 2016) had investigated precisely in Germany, people's readiness to commence LSS projects in large and small-medium enterprises (SMEs). A set of hypotheses were made using regression and correlation analysis to look at the extent of agreement between individual's vision, culture and competence for LSS readiness within SMEs. This study had analytically verified human and behavioral factors are essential when executing LSS in manufacturing SMEs. The fundamental values of individuals, education level and the vision of continuous quality improvement were identified as the critical variables for promoting LSS readiness in these manufacturing SMEs.

3.2. Case Studies

(S. Krishna Priya et al., 2020) had discussed on implementing lean six-sigma in an automotive assembly plant that focused on reducing or eliminating non-value-added processes within the production line. Different non-value-added waste and defects were identified during the assembly processes and the DMAIC procedure was followed to solve the issues. Lean methods like just in time (JIT) and six-sigma analysis techniques such as fishbone, 5 why's, problem tree were implemented. These have resulted in a substantial reduction of futile activities expending a 37.2% defect ratio and 19 minutes of work time.

(Basant Chaurasia et al., 2019) had explained in their work to enhance First Through Time (FTT) and reduce scrap formations using the LSS DMAIC strategy. High rejection and rework in the product were identified as the main problem for scrap generation. By using value stream mapping, the problem quality rating of the product was found to be 77%. Analysis was done using Pareto chart, validation of potential defect cause, fishbone diagram. Kaizen (lean tool) was utilized to improve the FTT to 21.21% and the scrap was reduced to 12.80% in the assembly process. In 15 months, the quality showed an improvement from 71.79% to 93%. The study concluded that implementing DMAIC lean six-sigma in companies could make the automotive production to eliminate waste, reduce variation or disability and make the process more feasible.

A study was carried out in an automotive factory in Brazil (Siqueira, 2020) using DMAIC method to minimize daily defects. The occurrence of hood gaps (problem of body geometry) was identified using a weekly defect per unit (DPU) Pareto chart. The hood assembly was a manual process and the company had an acceptable capability index greater than 1.0. All the process variables and factors were considered and analyzed using the Ishikawa cause and effect diagram. It was found that the hinge of the hood wasn't able to support the hood weight since the device attachments were far from the fixing point. So, an attachment was introduced touching the hinge, which supported the weight of the hinge. After ten weeks, the DPU of hood gap defect reduced from 0.064 to 0.004, which generated an expected savings of 44,815 Brazilian Reis of rework.

(Ben Ruben et al., 2017) had discussed the implementation of lean six-sigma in an Indian automotive transmission component manufacturing firm with environmental considerations to improve its operation and environmental performance. Ecological impacts for the manufacturing process were drawn based on the data such as power consumption, raw material consumption and water consumption. It was identified from Pareto analysis that the defect bore diameter oversize by 0.050 mm - the most significant defect for the main housing component of the transmission system, among other identified deficiencies. Process Capability Analysis was conducted to check whether the process was statistically capable of performing within its specifications. Tools like Kaizen, Design of Experiments and other process improvement techniques were employed for planning the improvement activities related to productivity and quality. In order to minimize the primary resource consumption, efforts were taken to reduce the overall environmental impact. As a result, the cost of the component for manufacturing reduced significantly. On completion of this project, the firm improved its overall sigma level from 3.60 to 4.06. The rejection cost was reduced from 914 USD to 343 USD, thus providing a comprehensive total cost saving of 2000 USD.

(Che Ani, 2016) had identified suitable practical tools based on the DMAIC model for automotive component manufacturing factory in Penang, Malaysia. The company selected for the study was a car audio supplier to different automotive manufacturers. SIPOC (supplier-input-process-output-customer) analysis was done in the define phase and the goal was to reduce the defect rate from 0.8% to 0.4% at the end of the improvement phase. A Pareto chart was plotted to identify the high numbers of reject rate. Process mapping was applied to figure out what process contributes to the defect. Analyzing the possible root causes was done using the Ishikawa cause and effect diagram, multi-voting and brainstorming to identify the possible solutions. A hypothesis test was done from the three possible solutions to validate the same by comparing defects between current and proposed practices. In the control phase, scatter plot and process capability study of the implemented solution was performed to check the quality standards of the company. It was reported, after the implementation of the proposed solution that the rejection rate was reduced to almost 50% from the current process.

The study by (Sousa et al., 2015) focused on a production line in a motorcycle component company that manufactured shock absorbers for two primary customers: Yamaha and Moto Honda. A SIPOC diagram had been developed to illustrate the manufacturing processes of the assembly line. The daily production was approximated to 2200 units/day compared to the production line capacity of 2352 units/day. The collection of data such as quality, adjustment, damage, material delay was collected for six months. A Pareto chart was plotted and thereby concluded that the most significant losses of production capacity emanate during the taping and drilling operations. The Sigma (ratio between non-produced units and the total production) was calculated as 2.48. After diagnosing the factors that influence the processes, the cause-and-effect matrix of excessive stoppages was developed. Two improvements were suggested - (i) single

minute exchange of die (SMED) methodology, (ii) exchange of model technology in a new computer-controlled machine with higher productivity and reduced setup time. Later, the exchange of model technology was selected after assessment and was checked for its sustenance and improvement. The rejection rate decreased from 3.9% to 1.9% and the latest production capacity increased to 3035 units/day. This has also eliminated the necessity for a third shift curtailing the number of employees from 21 to 16. The number of non-produced parts reduced from 387 175 in 2352 opportunities to 78 in 3035 opportunities, corresponding to a new sigma level of 3.45. Total cost savings of € 365904 were reported.

4. Discussion

The study discussed the human and behavioral factors necessary for people's readiness to pursue LSS projects, especially in European companies. It also reported that the literatures of LSS case studies were very few in Europe compared to the rest of the world, especially in the automotive sector. As seen from the case studies, LSS can be a groundbreaking strategy for eliminating defects and variation in the manufacturing process. So, automotive companies shall adopt this methodology, take advantage of its benefits, implement and publish literature to broaden the scope and track its progress in this scientific area.

The article summarizes the impact of adopting DMAIC lean six-sigma in automotive component manufacturing industries. It concluded that adopting the LSS methodology greatly improved the process parameters by reducing rejection rates up to 50%, achieving operational excellence and generate enormous savings ranging from $ 2000 to € 365904 for different companies, as seen in the case studies. However, most of the LSS case studies were carried out, focusing on the problems occurring in one industry. This can be a limitation since the scope of the work is carried out at a single organizational level. Moreover, most of the case studies didn't discuss other external factors such as risk posed by LSS quality improvement project due to poor execution, training of employees in LSS, resistance to change in process by employees or managers, problems in the identification of priority areas in improvement, etc. However, the benefits of this methodology outweigh the other factors and yield sustainability. Another limitation of LSS is its lack of assessment with regards to life-cycle of the product. Although, there are studies such as 'Lean and Green' which is of interest to researchers and industrialists worldwide focusing in reducing environmental impacts, it somehow lacks a corresponding framework to track this progress in each phase of the product's lifecycle. Future studies can be extended by focusing on these external factors when implementing the LSS project. Thus, lean six-sigma methodology, if appropriately implemented in an automotive industry, can benefit the customer and the company to compete with the ever-growing global market.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Optimization of Sustainability Through Quantitative Models; Linear Programming†

Daniel Eduardo Téllez Iracheta [1,*]

[1] Chemnitz University of Technology, Chemnitz, Germany
* Correspondence: teld@hrz.tu-chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Sustainability is an essential concept in the manufacturing industry, especially in the automotive industry, because it is a requirement of international standards and also assures the diversity of economic and ecological systems. The main purpose of this scientific review is to evaluate the Linear Programming (LP) tool to optimize sustainable indicators and green innovations in the industry. Inside the review, it is possible to observe the limitations of LP and its susceptibility to the human factor; the user. Despite that, it shows the feasibility of the tool through related examples of LP and demonstrates the improvements through optimization of resources and key performance indicators.

Keywords: Sustainability; Optimization; Linear Programming; Applications of Linear Programming; Key Performance Indicator.

1. Introduction

Sustainability is a topic that has become important relevance in the organizations, governments, educative institutions and the automotive industry in the recent years with Kyoto Summit (1995) and COP21 in Paris (2015) (Gohoungodji, N'Dri, Latulippe, & Matos, 2020).The sustainability "Maximize degrees of freedom and potential self-realization of all humans without any individual or group adversely affecting others." (Ben-Eli, 2018,p.6). It is important because has a huge relevant roll in the society as; guarantee the diversity and variety of ecological and economic systems (Ben-Eli, 2018). For this reason, it is significant to improve the sustainability in companies as well as the industry.

Though the global automotive industry is a leader of natural resource consumer how raw materials, energy, fossil fuels and also the cause of many air contaminants, its efforts to become sustainable cannot be imaginable without the assessment of sustainable Key Performance Indicator (KPI) (Vikas Swarnakar,A.R. Singh,Anil Kr Tiwari, Swarnakar, Singh, & Tiwari, 2021). According to (Stoycheva et al., 2018) and the triple bottom line approach to sustainable development (environmental-economic-social considerations) have established environmental impacts through the specific metrics: Resource Usage (Water usage, raw material usage, energy consumption), Impact on Species, Emissions (Atmospheric Impact, Aquatic-Marine impact and Land Impact).

But how this metrics can be improved, which method or procedure can be followed.
With the review article "What is stopping the automotive industry from going green? A systematic review of barriers to green innovation in the automotive industry" of (Gohoungodji et al., 2020) has identified 7 main barriers to become innovations in the automotive industry, regarding with technological barriers the study assures that the lack of method or procedure is a relevant factor to get sustainable innovations in the process.

For this reason, the purpose of this paper is to review the method LP, analyze its feasibility and show some examples as well applications to minimize the environmental impacts and maximize the sustainable KPI. Having an important significance regarding the implementation of green innovation in the automotive industry (IGIAI) (Gohoungodji et al., 2020).

2. Methods

The sources to access this information was supported through the following databases; Springer Link, Scopus, and DBIS Database Information System. One of the important websites to search scientific articles was Science Direct and one the most frequent Journal was Journal of Cleaner Production. It is essential to mention that the most information that was obtained about LP was gained thanks to the class of Optimization Methods by Dr. Heriberto Garcia Reyes in the Tecnológico de Monterrey (5 Years ago).

The keywords used to find these papers were; "Sustainable Factors", "Quantitative Methods in Sustainability", "Quantitative Model to solve Problems"," Linear Programming Applications"," Linear Programming in Automotive Industry"," Linear Programming Optimization Case of Study".

On the other hand, the strategy to classify the scientific articles used in this paper was illustrated in (**Table 1**). The scope to select most of papers was mainly that includes a strong relation with sustainability or environment and improvements through Mathematic model or LP. Whereas for the Sustainability it was agreed to look for sustainability and automotive industry or industry relations. It was not neared in years but always searched for scientific articles.

Table 1. Classification of consulted and cited scientific articles.

	Sustainability	Key Performance Indicators	Quantitative Methods LP	Applications and Examples	Others
Cited	2	2	2	2	-
Consulted	7	6	5	7	3

3. Results

In this section the main purpose is to review what is a Mathematical Model LP and review two examples of LP applied to sustainability of natural resources. "A mathematical model is a mathematical representation of an actual situation that may be used to make better decisions or simply to understand the actual situation better." (Winston & Goldberg, 2004). According to Winston and Goldberg (2004) the different types of models (**Table 2**) and which are the essential characteristics of a mathematical model must include:

1. Objective function;   Set of values that satisfy the given constraints. Maximize or minimize the function.
2. Decision Variables;   Variables that are under influence and plays an important role in the system.
3. Constraints;   Restrictions to the system. Only specific values in decision variables are possible.

Table 2. Type of LP models and description.

Type of Model	Description
Static	In which the decision variables do not involve sequences of decisions over multiple periods.
Dynamic	Is a model in which the decision variables do involve sequences of decisions over multiple periods.
Linear	The decision variables are always multiplied by constants and added together.
Nonlinear	The decision variables are multiplied or added to another variables. And raised to different powers.
Integer	If one or more decision variables must be integer.
Noninteger	If all the decision variables are free to assume fractional values.
Deterministic	For any value of the decision variables, the objective function satisfied or not the constraints with certain.
Stochastic	If we don't know with certain if the decision variables satisfy or not the constrains.

According to Winston and Goldberg (2004)LP is a tool for solving optimization problems developed in 1947 by George Dantzig with the simplex algorithm. And his main purpose is to give a mathematical representation to understand situations in the real life. Meanwhile the user ensures that the mathematical input reflect the real-life problem and verify that the numerical result has a strong relation with context. So that the risks of LP describes as follows;

The risks of the LP are:

- Infeasibility; There are not points that satisfy the object function and constraints.
- Unbounded; There are many or infinite points in the feasible region.
- Wrong or unclear selection of decision variables; If the user misunderstands the mathematical model.
- Incapacity to transfer the necessity into a mathematical model; When the problem cannot be described in a mathematical model.

Heriberto Garcia-Reyes and Cesia de la Garza Garza (2015) assure in his scientific article that are 3 systematic factors to solve one mathematical model; 1) Require sufficient information (Indicators, statistics and metrics). 2)Formulate a mathematical model of the problem to be solved. 3)Analyze the results to implement actions.

In the following equations (Figure 1) it is show how it can be computed an objective function (1), decision variables (x_1, x_2) and constraint (2) in LINDO Software, that is a general example of optimization model (LP):

$$z = 3x_1 + 2x_2 \qquad (1)$$

In the objective function the maximum profit of z is determined by sum of the triple of x_1 and the double of x_2 units. And in the first constraint it is required two units of x_1 plus one unit of x_2 to satisfy the restriction of less or equal to 100 units (2). At the end with these 2 equations, it is possible to represent a basic optimization model.

$$2x_1 + x_2 \le 100 \qquad (2)$$

Constraints (2)–(4) yields the following optimization model:

$$\max z = 3x_1 + 2x_2 \qquad \text{(Objective function)} \qquad (1)$$

subject to (s.t.)

$$2x_1 + x_2 \le 100 \qquad \text{(Finishing constraint)} \qquad (2)$$
$$x_1 + x_2 \le 80 \qquad \text{(Carpentry constraint)} \qquad (3)$$
$$x_1 \le 40 \qquad \text{(Constraint on demand for soldiers)} \qquad (4)$$
$$x_1 \ge 0 \qquad \text{(Sign restriction)}^\dagger \qquad (5)$$
$$x_2 \ge 0 \qquad \text{(Sign restriction)} \qquad (6)$$

"Subject to" (s.t.) means that the values of the decision variables x_1 and x_2 must satisfy all constraints and all sign restrictions.

Figure 1. LP example with objective function, decision variables x_1 and x_2 and constraints.

LINDO Software is a computer software that helps to solve LP problems and an essential tool to perform the optimization calculus, giving a familiar interface to compute the needed information and excellent report to understand the maximum or minimum results of the optimization (Figure 2).

"LINDO (Linear Interactive and Discrete Optimizer) was developed by Linus Schrage (1986). It is a user-friendly computer package that can be used to solve linear, integer, and quadratic programming problems." (Winston & Goldberg, 2004).

```
MAX       5   X11 + 6 X12 + 8 X13 + 8 X21
                           + 7 X22 + 10 X23
SUBJECT TO
          2)   X11  +  X12  +  X13 <=    10000
          3)   X21  +  X22  +  X23 <=    10000
          4)   X11  +  X21       >=     6000
          5)   X12  +  X22       >=     8000
          6)   X13  +  X23       >=     5000
END
```

```
LP OPTIMUM FOUND AT STEP              5

           OBJECTIVE FUNCTION VALUE

      1)   128000.000

VARIABLE        VALUE          REDUCED COST
    X11      6000.000000          .000000
    X12          .000000         1.000000
    X13      4000.000000          .000000
    X21          .000000         1.000000
    X22      8000.000000          .000000
    X23      1000.000000          .000000
```

(a)   (b)

Figure 2. Example of how it can be computed and reviewed the information in LINDO Software; (**a**) Description of the objective function with the constraints; (**b**) Description of how is the report of the optimum solution to the LP problem (Objective function value and its variables of decision values).

One of the examples of LP to reduce the use of water to produce energy or as a component in the cleaning production process for chemical-manufacturing industry and assure water to future generations it is reviewed in the scientific article from Budak Duhbacı, Özel, and Bulkan (2021) seeking the optimization of problems related to the water network through mixed-integer nonlinear programming and nonlinear programming. On the assumptions of the model uses a single as well as multiple contaminants getting 65% of the studies with significant improvements (Reduction of 22% freshwater consumption-Chemical Manufacturing 2018 and Minimization 236,520 m^3/y in consumption of clarified water for replacement-Petrochemical Industry 2018).

On the other hand, a traditional industrial production-distribution enterprise focus in minimize the carbon emissions with a single machine and multiple-vehicle setting, through a PL. The research displays a problem of production and distribution where with a sustainable scheduling method (switching off machine in a period between 2 consecutive workpieces) can avoid carbon emissions. The results present that with a multi objective optimization the highest reduction kilograms of carbon dioxide is 22.01% (Wang, Yao, Sheng, and Yang (2019)).

4. Discussion

The study discussed two different cases of LP; One to optimize the usage of water as a fundamental source of energy production and as a component of industrial processes. The second study displays the strategy to use LP to minimize the carbon emissions in the atmosphere in a traditional production-distribution system on a single machine and multiple-vehicle setting. Regarding the first study as in other studies, it is significant to administrate, as well as delimit the number and type of variables that the model requires. If it is not the risk of bias and nonrealistic model is taken. In this particular case was relevant to define which kind of contaminants will be present in the model. On the other hand, in the second study, it is a common problem in production but it is harder because the multiple scenarios that could be followed are quite a lot. Nevertheless, the most relevant point with this study is that in many cases a sustainable improvement has a strong relation with economic transformation and this could be a determining factor for managers and chief executives to improve the sustainability in their companies aided with LP.

The article summarizes; what is a mathematical model and its characteristics, goal and risks of the model, type of models and its systematic factors as well as general overview how to compute a objective function on LINDO Software. The risk of information bias, can be influenced due to optimization literature and LP tool, used to solve optimization problems during one university class from the author; Optimization Methods.(Heriberto Garcia-Reyes and Cesia de la Garza Garza, 2015). Despite the two selected examples of LP-Sustainability reviewed in this article, specific KPI can be reviewed in the future, as well as illustrative examples of LP. It can be concluded that different kinds of real representations through LP can be established to optimize sustainable indicators but is not mandatory to find always one best solution attributable to infeasibility or unbounded. Another possible limitation of LP is located on the mathematical model. This is created and administrated by a human. As a consequence, it could be misunderstood, misinterpreted or not be able to be structured due to complexity of variables. Despite of those limitations LP can be used to breakdown the technological barriers to develop sustainable innovations in the industry; maximizing and minimizing KPI. Future studies could focus on; which type of models are more acceptable regarding the industry, number and type of decision variables.

LP is an effective tool to improve the sustainability and make profitable the manufacturing industry, as other analysis and methods such as Life Cycle Assessment and Life Cycle Engineering respectively but the key factor to improve the sustainability is our human behavior.(Human behavior > 45% of barriers among empirical articles) Gohoungodji et al. (2020).

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct (https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Fuel cell electric vehicles – life cycle, current state and future prospects in Germany†

Pratik Shriraj Gandhi [1,*]

[1]   Chemnitz University of Technology; Chemnitz; Germany
[*]   Correspondence: pratik-shriraj.gandhi@s2019.tu-chemnitz.de
[†]   Presented at the 1st Advanced Manufacturing Students Conference, Online, 15–16 July 2021.

Abstract: Transport sector is one of the major contributors of greenhouse gas (GHG) emissions in Europe. Fuel cell electric vehicle (FCEV) is a promising technology for emission free mobility of the future. Being in early development stage, there is utmost need to assess life cycle of fuel cell powered vehicles. Promising targets for FCEVs have been set for the upcoming decade in Germany. Currently, FECVs face two major problems as high fuel cost and unavailability of refueling infrastructure. A continuous life cycle assessment (LCA) is necessary as technology is improving rapidly. Uniform guidelines are important for equal evaluation and for setting benchmarks for upcoming LCAs. Multi-dimensional factors act towards and against the development of fuel cell vehicles in Germany. In this paper, a Comprehensive review about FCEV life cycle and the situation in Germany is summarized.

Keywords: Life cycle assessment; Electromobility; Fuel cell electric vehicles; Hydrogen; Germany.

1. Introduction

Decarbonisation of the transport industry has become a top priority for many countries including Germany (Wong, Ho, So, Tsang & Chan, 2021). Fuel cell electric vehicles are powered by electric motors and are driven by polymer electrolyte membrane fuel cell (PEMFC) generate electricity while being in motion using electrochemical reaction of Hydrogen (H_2) and Oxygen (O_2) (Evtimov, Ivanov, Stanchev, Kadikyanov & Staneva, 2020).

Life cycle assessment (LCA) is a significant tool to evaluate any product or service from cradle to grave during its lifespan. High carbon footprint (CF) in their life cycle at production phase makes it necessary to analyse and target areas where carbon footprint can be reduced (Usai et al, 2021). The accuracy of life cycle assessment will depend on completeness and availability of information of CF from raw material, components, assembly to fuel phases (Wong et al, 2021). Globally standardized LCA method is suitable to assess emerging technology such as FCEVs. Currently available FCEV models on the market and studies by prominent institutes reviewed to obtain better insights on the topic. Three different scenarios were studied and additionally a sensitivity analysis was checked concerning previous LCA studies (Usai et al, 2021).

In Germany, BEVs are currently the best alternative to replace ICEVs but the environmental impact (EI) during production and total cost of ownership (TCO) of BEVs are still higher than ICEVs (Bekal & Pauliuk, 2019). Some studies had compared CF for foreign auto brands such as Tesla Model 3 EV and Toyota Mirai FCEV and had highlighted lack of German brand FCEV model in the market (Wong et al, 2021). Taking the ongoing energy transition and automotive trends in Germany into account; multiple studies have addressed isolated aspects of the current state of electric vehicles (BEVs and FCEVs) but, a review specifically about FCEVs in Germany was rarely found. Previous studies in life cycle inventories addressed particular cases and features while excluding some aspects. Due to fast development rate of PEMFC application in e-mobility, a continuous and a broader generalized assessment is necessary. In this review paper, an attempt has been made to get an overview about life cycle of FCEVs in Germany.

2. Methods

Literature of different types such as published journal articles, research papers, technical reports and review articles for the past 10 years were considered as time window for finding data for this topic. Multiple open access databases were accessed through the intranet of Chemnitz University of Technology as well as public databases, which include Scopus, SpringerLink, Science Direct and Google Scholar. A number of keywords were used to find articles for e.g. hydrogen, fuel cell, life cycle assessment, Germany, Electromobility, etc. The search strategy also included related words

such as vehicles, life cycle cost, electric vehicles that resulted in a large number of published articles, which were sorted based on relevance to the topic and open accessibility, was also considered while eliminating some papers from the literature review. This topic is being recently developed and documented, thus cut off limit of year 2015 was set. Citavi referencing and citation software was used to conduct this review. After reading through the abstracts and conclusions of these papers, a total of seven papers and reports were finalized from a shortlist of 10 items for a detailed review.

3. Results

The studies reviewed in this paper elaborate a list of predefined criteria for evaluating the status of FCEVs in Germany. They include existing car park; road map for FCEV; government policies for OEMs, infrastructure and customers; deployment as of 2015 from manufacturers, fuel stations and sales point of view (Brunet et al, 2015). LCA process referred ISO: 14040 and ISO: 14044 for standard procedure of conduct. Six different phases of products systems namely vehicle production, electricity generation and distribution, charger production and EV charging, hydrogen supply infrastructure, vehicle use-phase and end-of-life treatment were individually assessed. The study considered hydrogen stations in Germany and a pictorial summary of electricity losses at various stages for FCEVs (Bekal & Pauliuk, 2019). A detailed description and a flowchart of working of polymer electrolyte membrane fuel cell for FCEVs is given (Wong et al, 2021). This study examines in detail the electric energy requirement not only for hydrogen gas but also for the fuel cell vehicle structure production (Evtimov et al, 2020). A detailed modelling of different cases concerning following components is done in this study - Platinum (Pt) loading as catalyst, polymer membrane thickness, Gas diffusion layer weight, material of bipolar plates, membrane electrode assembly (MEA) composition and production of hydrogen tanks. The paper also compares two modelled development scenarios for the year 2020 and 2025 using data points predicted in previous studies (Usai et al, 2021).

3.1. Present and future scenario of FCEVs in Germany

Studies show that the passenger car market in Germany will saturate and fleet size will reach a max and then fall in near future. In 2011, the government had set ambitious target of one million EV on German roads by 2020. National organization for hydrogen and fuel cell technology (NOW GmbH) was set up in 2008 to support and promote this technology in Germany. A target of 1.8 million FCEVs by 2030 is set for small mass market. An objective of 400 hydrogen-refuelling stations (HRS) by 2023 and 100 HRS by 2030 has been set under hydrogen road map. National innovation program (NIP) for demonstration projects of hydrogen in transport sector is being promoted by the government. Company initiated partnerships such as H_2-mobility in which members consisting of Air Liquide, Daimler, Linde, OMV, Shell and Total are coordinating for developing German hydrogen refuel network. From funding perspective, the German government has set aside a budget of €1 billion over a 10-year period for FCEV. Introduced in 2009, the annual circulation tax (CO_2 tax) applies to petrol and diesel vehicles and exempts ZEVs for a 10-year period. EVs have some benefits namely free parking spots, access to city center, permit to use bus lanes, etc. to promote ZEVs (Brunet et al, 2015).

The so-called chicken-egg dilemma is more significant in case of FCEVs as mass production of vehicles and infrastructure deployment are dependent on each other. Solutions to counter this problem include implementing a pilot fleet to simulate real world situation and public subsidies based on push strategy. German companies are also signing international agreements for joint developments in fuel cell systems. Sales from the past few years have shown increasing trends in both BEVs and FCEVs. The author argued that the target of one million EVs could only be reached with financial and non-monetary support from government (Brunet et al, 2015).

3.2. Life cycle assessment

The following subsections discuss in brief the standards and guidelines that can be referred for LCA studies. A short overview of two sample models named ReCiPe 2016 and GREET is also given. Finally, it concludes with a discussion of two studies, which focused on environmental aspect in their research.

3.2.1. Framework and references for performing LCA

Melideo et al. (2019) states that the project FCH – HyGuide gave two LCA guides: one each for hydrogen production system and fuel cell system based on framework as Figure 1. The projects had primary work in various life cycle phase such as H_2 production, distribution, use and purification. The joint research center (JRC) has published the international reference life cycle data system handbook (ILAD) to assist ISO 14040 and ISO 14044. More studies are conducted to evaluate hydrogen production using electrolysis concerning the source of electricity. Hydrogen projects focusing not only on mobility, but also on stationary power need LCA evaluations. The properties for the product under

evaluation must be quantifiable and predefined at start of LCA. The quality of primary and secondary inventory data is important.

20 factors were evaluated under the study conducted by Trencher & Edianto (2021) and they were classified in four subcategories- vehicle supply, refuel infrastructure, vehicle demand and institutional issues. The data collection for this evaluation of factors was done via three methods namely expert survey, expert interviews and document analysis. The supply side has two drivers - EU environmental regulations and government schemes to promote R&D. On the other hand, production cost, future demand and personnel availability for after sales act as barriers for the supply side. From infrastructure point of view 6 of the 7 factors act as a barrier - profitability of fuel station, building cost of HRS, network of HRS. From demand side, government and industry incentives drive FCEVs forward, while low number of private owned FCEVs and lack of German brand in the FCEV market act as barriers. Standards and regulations along with absence of knowledge sharing network contribute to barriers for institutional issues.
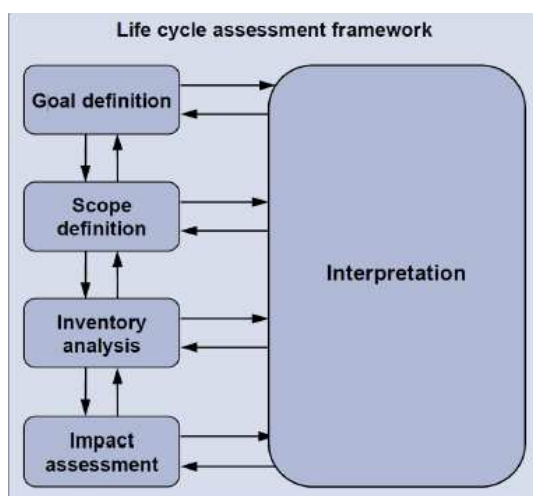

Figure 1. Framework for Life cycle assessment (Melideo et al, 2019).

3.2.2. LCA using ReCiPe 2016 and GREET models

LCA done by Bekal & Pauliuk (2019) based on ReCiPe 2016 method was divided into 2 sub-parts namely life cycle impact assessment (LCIA) and life cycle costing (LCC). LCIA was composed of base case analysis, which stated that FCEVs have reduction potential of around 50% for global warming potential (GWP) but have higher impacts in other categories. Another aspect of LCIA was infrastructure that concluded FCEVs have higher impact than BEVs in all 4 impact categories under consideration. Producing hydrogen onsite or off-site had little impact on the infrastructure evaluation. Three separate scenarios with said assumptions were elaborated in scenario analysis of LCIA. The other sub-part of LCC studied infrastructure costs and concluded that FCEVs have 48% investment cost and 52% operating costs. Three different fuel price cases resulted in total cost of ownership for FCEV ranging from 124900 € to 130100 €.

The work of Wong et al. (2021) use GREET (greenhouse gases, regulated emission and energy use in transportation) model to compare CF of BEV with FCEV as per Equation 1. Consideration is done in manufacturing and consumer usage stage for FCEVs. GREET model analyzes fuel cycle emissions FC_{GREET1} and vehicle cycle emissions VC_{GREET2}. GREET1 is well-to-wheel (WTW) energy use and emissions while GREET2 focus more on vehicle manufacturing.

$$FC_{GREET1} = FC_{Fuel\ Production} + FC_{Fuel\ Consumption} \quad \& \quad VC_{GREET2} = VC_{Vehicle\ Production} + VC_{Vehicle\ Operation} + VC_{Vehicle\ End-of-Life} \tag{1}$$

Toyota performed LCA for its model MIRAI and provided detailed figures only for fuel production and fuel generation phase. Most manufacturers of FCEVs report emission studies in product use phase but it does not reflect full cradle-to-grave life cycle. Toyota reports have shown a wider scope in terms of reporting emission in various phases. GREET1 analysis conclude that fuel production affects CO_2 emission as source of electricity can either be natural gas reforming or electrolysis backed by wind power. Green hydrogen (produced from renewable electricity) supported by national energy strategy reflected in 320 green H_2 production demo projects globally. Germany's national hydrogen strategy, launched in June 2020, is aimed to have 5 GW H_2 production capacity by 2030.

3.2.3. LCA focusing on environmental aspect

Evtimov et al. (2020) described a model to investigate the energy spent by FCEV in life cycle Taking energy losses and generated emissions into account. Mathematical formulae for the energy spent and CO_2 emitted are described in

detail in this study. Using these formulae, LCA of FCEV was done for four cases – Bulgaria, Poland, Norway and mean values of EU-28. The study found out that increasing the contribution of renewable energy produced electricity in the energy mix for hydrogen production could make FCEV a good competitor for IC engine vehicles. Comparisons have been done for the primary energy consumed for producing hydrogen via three different ways. Electrolysis method shows highest CO_2 emission unless the electricity for it has been produced by renewable sources as in case with Norway. Table 1 shows percentage distribution of various energy sources in the energy mix of Germany.

Table 1. This Distribution of energy sources in the energy mix of Germany for the year 2015.

Country	Share of total production, %				
	Nuclear energy	Thermal Power plant			Renewable energy
		Solid fuels	Natural gas	Crude oil	
Germany	19.8	35.9	5.3	3.0	32.5

Recent study conducted by Usai et al. (2021) focused on tanks, catalysts and auxiliary fuel cell components which have higher carbon footprints in production phase and thus possess significant global warming potential (GWP) that needs to be addressed through advanced manufacturing. The paper also depicted a comparison of contribution analysis for several other potentials as in fossil depletion (FDP), freshwater ecotoxicity (FETP), human toxicity (HTP), terrestrial acidification (TAP) and a few more. This study not only compared the GWP for two scenarios of 2020 and 2025; but also displayed how previous results from other studies stand in comparison using a cradle-to-gate approach. FC auxiliaries are one of the top contributors to environmental impacts. Sensitivity analysis performed to analyse impact of increase in material demand.   It concluded that 10-20% change of weight in auxiliary parts would result in minor difference in overall impact. The paper also projected and compared possible impact reduction percentage in different potentials namely GWP, FDP, HTP, ATP, etc. in scenario 1 and 2. Scenario 1 preferred technical development in near-term while scenario 2 focuses on reduction in environmental impacts. It also highlights the importance to have continuous update of data for LCA at current stage. Tanks made up of carbon fibre have existing technical constraints - capacity and strength. Thus, material innovation for tanks has high potential to reduce CF.

4. Discussion

At current state, BEVs are eco-friendlier than FCEVs in terms of GWP and other impact categories. Manufacturing improvements are necessary for FCEVs to have cost competitiveness with BEVs in Germany. The data for energy consumed and CO_2 released displayed the ecological benefit of fuel cell vehicle technology highlighting the importance of renewable electricity in the energy mix (Evtimov et al, 2020). Increasing demands for detailed studies for FCEV life cycle make it necessary to consider fuel production and vehicle use phase equally. Institutional support in green energy-produced hydrogen could assist manufacturers in lowering PCF across life cycle (Wong et al, 2021).

A considerable number of LCA studies have been published until date focusing on various life cycle stages of H_2 production and FC stack system. Although this highlights the significance of hydrogen technology, a lot of work is still necessary to address unexplored gaps and new systems from environmental aspect. For the uniformity of results, it is highly recommended to follow FC-HyGuide framework for LCA. The authors cite a need for harmonization effort and inventory database to have comparable outcomes in future studies (Melideo et al, 2019). The dependency on assumptions and research scope set makes LCA and LCC vulnerable regarding their results and thus should be properly interpreted. The inventory of data should be published on a regular basis to have up-to-date information for future assessments. Based on individual ranges, it is recommended to use BEVs for short distances and city transit while FCEVs for long- range passenger and goods transport. Segmentation based on range will optimize the advantages of both types. Bigger hydrogen gas stations can be installed on highways to have economies of scale (Bekal & Pauliuk, 2019).

Future research can be focused on hydrogen supply infrastructure and more efficient electrolysers for producing hydrogen economically. The excess renewable electricity in Germany can be utilized for hydrogen electrolysers that will bring down the cost of fuel. Scientific work can focus on assessing and comparing new ways to produce hydrogen and standardizing reporting practices for LCA studies. Efficient and carbon-neutral production processes will assist in future developments.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Life Cycle Assessment of Renewable energy sources, storage systems and alternate fuels[†]

Chaitanya Mahajan [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
[*] Correspondence: Chaitanya.mahajan@s2020.tu-chemnitz.de
[†] Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: The energy situation on this planet is changing rapidly, alternate sources have come to the forefront and are now the biggest priority of almost all nations who want to decouple from carbon-based fossil fuels and have a smooth transition into the new energy paradigm. Renewable energy is the future; there are no two ways about it. However, what needs to be done is to analyze these sources and their manufacturing and operations closely to get a better understanding of how they impact the planet. Life Cycle Assessment analysis on Li-ion, Vanadium redox flow batteries and alternate fuels was also carried out to cover the whole renewable energy ecosystem. The analysis pointed that we needed more collaboration between the producer, user, and reprocess stages. To improve the quality of our Life cycle assessment system, boundaries need to be changed to include more systems and the quality of data should be used during input should be precise.

Keywords: Life Cycle Assessment (LCA); Global Warming Potential (GWP); End of Life (EoL); Multi-energy System (MES).

1. Introduction

Energy derived from sources that are perennial and inexhaustible is classified as renewable. Harnessing this energy from sources such as the Sun, wind, biomass, etc., is at the forefront of every nation in the world today. This desire to enlarge the portion of renewable energy in the energy pie of a country and the planet is prodded on by Climate change, global temperature rise and melting of polar ice caps causing the irreparable damage to flora and fauna. Our over-dependence on fossil fuels is destroying our planet at an alarming pace. Since that realization, governments and corporations across the world have invested huge amounts into the research and development to increase the accessibility of various renewable energy sectors such as solar, wind, biogas, and energy storage systems such as Li-ion and vanadium redox flow batteries. Solar panels, wind turbines have become a common sight and huge sustainable transformations have happened. However, we need to mindful as we move towards a new energy paradigm, that we do not make the same mistakes we made last time with fossil fuels and for that reason calculate the impact the whole process of generating energy from renewable sources is having on our environment. This is when Life Cycle Assessment comes into the picture, the analysis of a process or a product from the extraction required for its materials to the end of its use. Hence, we look at life cycle assessments of a range of renewable energy sources and selective renewable energy storage systems as well.

2. Methods

Google Scholar and Science Direct were used to access most of the literature for this paper. Filter was put in place and papers were shortlisted from 2015 onwards. Databases were searched using the keywords, "Life Cycle assessment of Renewable Energy"," and Life cycle assessment of Renewable energy storage systems". Papers were decided by first checking the year of their publication so that most of the literature was recent and to keep up with emerging methods. The second reason was the number of citations and the journal in which it was published. Lastly, abstract was the key in finalizing literature its reconciliation with what this review paper hoped to achieve. These papers were selected because they further the intent to study about life cycle analysis of renewable energy sources and storage systems since the latter two are the piquing sectors in the energy market right now.

3. Results

The current Biogas production levels in Europe were analyzed and the consequences that it is causing on the environment due to Greenhouse gases(Luo, n.d.,2020). It performed a full LCA on 15 biogas plants and determined that all had lower GHG when compared to similar projects. It worked by defining the goals of the study which was to cut emissions and revise the understanding we have on LCA studies on biogas. Life Cycle Inventory (LCI) was compiled with all inputs and outputs in the system. These inputs and outputs were then transformed into equivalent environment impacts and this was done during the Impact Assessment stage. Further classification and characterization were done by keeping the initial goals in mind(Hijazi, Munro, Zerhusen, & Effenberger, 2016). Wind is one of the biggest contributors to alternative sources of energy and so an LCA was performed on on-shore and off-shore wind energy plants finding that off-shore plants have a higher environmental impact due to more material and equipment needed and transportation of that equipment on site. Also, direct-drive generator technology is less harmful to the planet than small geared turbines. Further, 20-30% savings can be made using recycling at the end-of-life stage. This study helps in making designs more sustainable and innocuous. The end of life despite being tentative is a vital stage since capital is saved by more recycling thus paving the road for a more circular financial system(Bonou, Laurent, & Olsen, 2016).

The easiest available form of renewable energy source for almost every country on this planet is the sun and so solar panels are among the biggest drivers of renewable energy. Among the early successes of renewable energy these panels have been deployed almost everywhere now and so; we must look at their impacts through LCA. Silicon thin-film, dye-sensitized solar cell, quantum dot sensitized solar cell (DSSC) were analyzed using the system boundaries from the extraction of materials to make the apparatus to the discarding of the parts. Energy supply, wires, and inverters, etc. influence the production stage. Preparing the ground or fields, taking the parts from the manufacturer to the site contributes to environmental impact during construction. Lastly, maintaining the panels, fixing damages, and keeping up with fluctuating demand fall in the usage stage of the LCA. DSSC was found to be environmentally benign because it had lower energy needs, low costs, and higher compatibility, whereas mono-Si had the maximum energy intensity and sizeable GHG emissions during purification and manufacturing(Ludin et al., 2018).

The three studies we have looked at focus on one energy-producing source, and so to further enhance the scope of our study we look at an LCA for a renewable Multi Energy System (MES). This study also begins with keeping the energy consumption, cost, and eventual emission for the whole process in focus. The MES has two parts, active and passive consisting of biomass-filled combined cooling heating and power system (CCHP) and Building Integrated Photo Voltaic (BIPV) and wind power respectively. CCHP is the main provider of energy which makes up the active part of the MES. A building in the U.K. is taken for demonstration and MES, CCHP, and a conventional separate system (CSS) which is a natural gas-powered boiler, supplies heat. It is found that the lifetime cost of MES is higher than the conventional system due to greater costs of BIPV, solar cell, and wind power. Conversely, the energy consumed by MES is less than that of the conventional system. Additionally, weather plays a big part in the study and so 5 different locations across the United Kingdom namely London, Efford, Cardiff, Birmingham, and Aberdeen. Biomass consumption, electricity taken from city grid and energy devices and their sum is the yearly energy usage, emissions, and economic cost. Biomass, power from the city, and component cost are the contributors to the emissions, etc. from CCHP. Natural gas and the boiler used on it are the emissions causers in CSS apart from city grid electricity(Luo et al., 2020). Further looking at 'mixed' energy-producing systems we look at an LCA and a life cycle cost analysis model for a hybrid system.

The aim is to develop a tool with which we can appraise sustainability in a systematic method based on LCA and Analytical Hierarchy Process (AHP). AHP is a technique that employs mathematics the preferences of a person or the concerned party in coming to a decision. Identification of the hierarchy and then reviewing elements keeping the controlling element in the spotlight and getting the suitable substitute was done. LCA coupled with AHP was applied to a novel compresses air energy storage system in a small scale stand-alone renewable power plant. Inculcating the perspective of all the concerned stakeholders was the objective. LCA was done for the environment, society, and economic reasons to have a collective effect on the results in the hope that each factor would help in reducing other impacts. The process is recursive, and we can generate different answers using multiple inputs. Coincident assessment of the environment was done using both qualitative and quantitative approaches. SimaPro software was utilized, and the outcomes were weighed with AHP using a fluctuating weight analysis. To analyze various LCAs all outcomes were weighed against the same criterion(Petrillo et al., 2016). All this renewable energy will not be useful if cannot be stored, Energy storage systems help big time in this by storing the energy generated so that it can be used at another time when no energy is being produced. They are playing a big role in the renewable revolution by giving us a chance to store energy that we are producing in our wind power plants or from solar panels, but we need to look at their 'footprint' on our planet. Analysis of Li-ion and Vanadium redox flow batteries and their subsequent effects using an LCA was conducted. Again, as with others, LCA was done from the 'cradle' to 'grave'. Their acceptability is going up due to

durability, low costs, and easy transportability to different locations. LCA framework consists of primary assessment in the supply phase on extraction, manufacturing, and assembly of components. This is collated with additional components, replacement, or repair in the use phase. SimaPro and Ecoinvent 3.6 were used in this. ReCiPe 2016 Midpoint (H) calculation methods were used for both batteries using Global Warming (GW), Terrestrial Acidification (TA), Fine Particulate Matter Formation (FPMF), Mineral Resource Scarcity (MRS), Fossil Resource Scarcity (FRS), Human Toxicity (HT) and Cumulative Energy Demand (CED) as markers as shown in Figure 1. It was summarized that just manufacturing and transporting causes 50% of the damage in all markers not including CED which had a 30% contribution. 95% material in both batteries was recycled so End of Life did not have much effect. Vanadium redox flow batteries are the most benign for the planet but if the distance of their fabrication and use is too far their impact can increase. End of life is also linked to the distance between usage and recycling.

Also, the proportion of energy supplied to both these batteries is important since wind is better suited than solar when compared(da Silva Lima et al., 2021). Finally, we look at alternate fuels and their impact on different vehicles. An Internal Combustion (IC) engine was investigated using fuels such as gas, diesel, LPG, methanol, CNG, hydrogen, and ammonia. A hybrid vehicle was filled with 50% gas and 50% electricity and an only Electric Vehicle (EV) was used. These were selected so that we can get as real a situation as possible. Two methods were using a fuel cycle and a vehicle cycle. In the fuel cycle, we count the energy used from the fractional distillation of CNG, the refining of crude oil to get diesel, and emissions when they were being shipped. In the vehicle cycle, we use software called GREET (Greenhouse Gases Regulated Emissions and Energy use in Technology model) developed by Argonne National Laboratory (ANL) to check the various combinations of fuels and vehicles. The impact from drilling for oil then oil reaching the gas station and then from the station to the car is also added. SimaPro was used to get the results. It was concluded that hydrogen is the 'greenest' fuel; ammonia has the lowest GWP after EV. EV manufacturing and end life affect human toxicity. If we can achieve renewable electricity charging stations to charge EVs we can further cut down on environmental impacts(Bicer & Dincer, 2018).
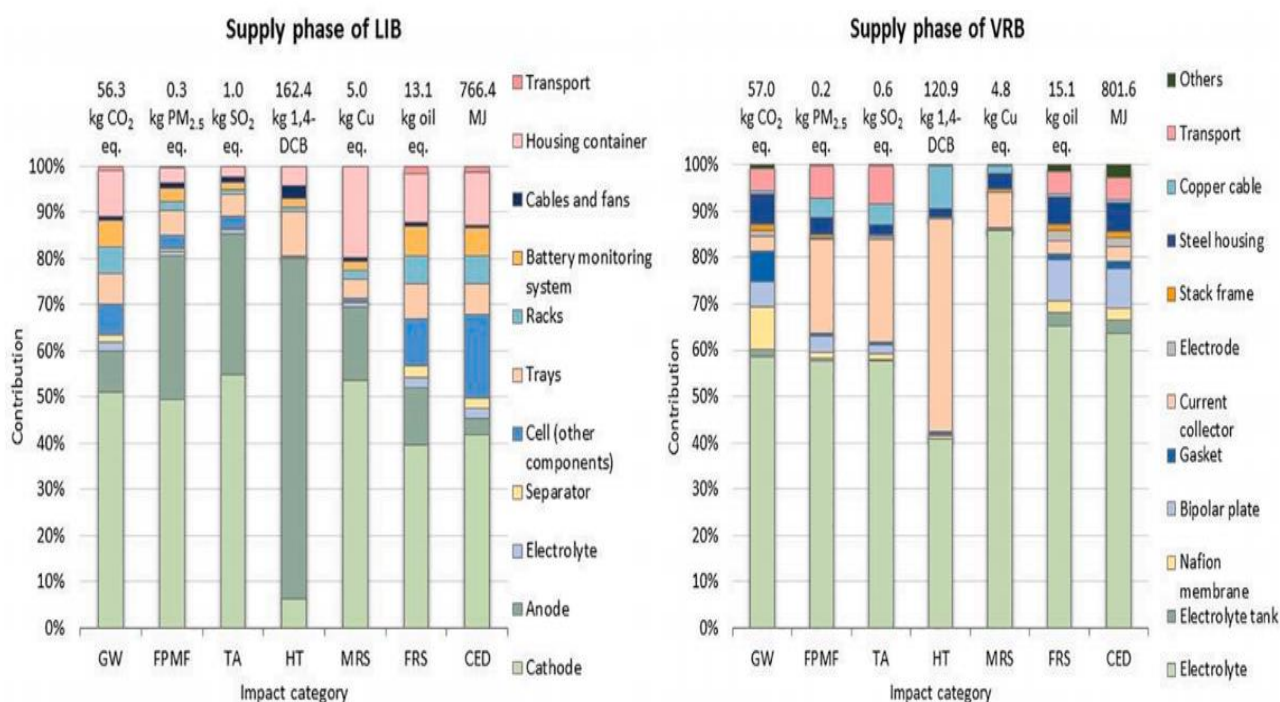

Figure 1. The impacts caused by the delivery Li-ion and Vanadium redox flow batteries together with their shipping and in-situ function(da Silva Lima et al., 2021).

4. Discussion

All in all, we have analyzed the life cycle assessment methods used on different renewable energy projects, storage systems, and alternate fuels. Various techniques were used to evaluate the effects these energy sources had during their lifetime and how we could best understand the challenges that come with a new energy shift. Foremost priority should be given to more concerted efforts between the supplier, the user, and the disposer. All studies point that this collaboration can help us reduce the overall impacts by substantial margins. Another focus point is the end of life procedures

for various components which are not yet in vogues such as blades of a wind turbine and associated parts because when this is practiced in the case of (da Silva Lima et al., 2021) the recycled materials used in both types of batteries makes an impact at the time of their disposal very small. LCA studies in (Bonou et al., 2016) didn't include backup and energy storage systems, and hence expanding system boundaries to include more factors in LCA is a possibility. LCA studies start from the extraction phase and so the value of inputs increases manifold, different inputs will provide different results in (Petrillo et al., 2016), and also when assigning weights to different factors we get different outcomes. End of life is dependent on the transportation of the component from the user to the site where it can be recycled. If this distance is large the effect in LCA due of end of life goes up and so we have to strive to keep this distance as low as possible. Wind energy systems face a lot of problems in this regard as from their manufacturing to installation to disposal there is a lot of energy spent on moving the components and construction of foundations etc. Working with new materials and developing new ways of powering the planet we need to be careful that this new technology does not cause more harm than benefit because as demand for renewable materials will shoot up in the coming years the extraction for their raw materials will go up and hence the emissions will rise. The equilibrium between our needs and wants must be managed responsibly.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct ([https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf](https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf)), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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Review article

Robot-Assisted Disassembly of Electric Vehicle Batteries for Remanufacturing Ends†

Gerardo Palacios Barraez [1,*]

[1] Technische Universität Chemnitz; Chemnitz; Germany
* Correspondence: gerardo.palacios-barraez@s2020-tu.chemnitz.de
† Presented at the 1st Advanced Manufacturing Students Conference, Online, 15-16 July 2021.

Abstract: The increasing number of Electrical Vehicles (EVs) in the markets due to environmental awareness has led to a rising number of batteries reaching their End of Life (EoL). To make this relatively new technology economically and environmentally sustainable is necessary to remanufacture batteries rich in lithium, aluminum, and copper. For this study, a scientific paper search was conducted through Google Scholars, and the bibliography of the most suitable papers for this contribution was revised. The batteries are composed of cells that need to be disassembled to extract the valuable resources. Challenges are evaluated, and two types of disassembly outlay are proposed, a semi-automated for complex varieties of batteries and a fully automated for less complicated battery montages. Although the proposal seems to be economically and environmentally feasible, since the technology is relatively new, more tests and studies are required to implement such a technology on a big industrial scale.

1. Introduction

The application of lithium-ion batteries as an energy provider for the drive of vehicles has increased and gained relevance in the past recent years, increasing the number of sales and number of companies that now offer alternatives of EVs (Jens Markowski, 2014) (Jürgen Fleischer, 2021) (Lluc Canals Casals, 2017). Due to environmental awareness, Germany, for example, has a goal of having one million EVs by 2020 and more than 6 million by 2030 (Kathrin Wegener, 2014). Nevertheless, a more significant number of EVs on the roads also increase the number of high voltage batteries. Therefore, an increasing amount of end-of-life (EOL) high voltage batteries must be processed. Most of these batteries are lithium-ion high voltage batteries, which contain precious and contaminating materials such as lithium, cobalt, nickel, and copper, making these batteries economically and environmentally attractive to remanufacture and increase independence from imports of raw materials (Jürgen Fleischer, 2021) (Qingdi Ke*, 2020). However, the remanufacturing process comes with several challenges to consider if a solid, durable, and large-scale system is to be achieved. To this end, many disassembly tasks are necessary, which therefore require automated solutions. With the automation, several advantages surge. Complex technological requirements can be done with consistent quality, the harm to humans is reduced, a constant plant operation is possible, and an inexpensive adaptation for the production is viable (Jürgen Fleischer, 2021).

Automation, however, comes with burdens, one of the main ones is attached to the design of the product. A higher-level study reveals two different types of battery categories. The first battery one is represented by complex products with poor disassemblability and a high number of connections. The second battery consists of standardized and less complicated products with good disassemblability and a reduced number of connections. The first category can be disassembled by semi-automated systems such as Human-Robot configurations and the second one by fully automated systems (Jürgen Fleischer, 2021) (Eduard Gerlitz, 2021). Therefore, this contribution aims to describe options of the automated and semi-automated disassembly process of EVs batteries according to their level of complexity. The first alternative, where the battery is categorized as less complex, the fully automated robotic outlay takes care of the discharge and disassembly process, recycling metal content, and recycling non-metal components (Jens Markowski, 2014). In the second alternative, semi-automation, the human performs the more complex tasks. He reacts to unexpected problems that may occur while the robot performs simple, repetitive tasks like removing screws and bolts.

2. Methods

Since the area of research is relatively new, due to the increasing environmental awareness in the current decade and therefore the development of the EVs technologies, the search of material through Google Scholars did not come up with several accurate research. Accordingly, after finding three valuable papers of relevance in the mentioned portal, their bibliographies were closely revised, coming up with more accurate research, a total of ten, located in Research Gate and Science Direct. Afterward, the investigations were filtered by relevance ending up in seven papers to be studied. However, a further dissertation was required in some documents. It was not necessary to limit the search by date to find updated materials. Due to the relatively new field of study, all the research dated after 2014.

According to the APA standards, the software Mendeley was used to collect the publications and as a tool to organize and manage the citation and reference process.

Although several studies in German were found, they were discarded due to language barriers. It is recommendable for further studies to take this into account if the researchers are German speakers.

3. Results

3.1. Battery description

Li-ion batteries can be categorized into three ranked levels, battery systems, modules, and cells. Cells, contains valuable materials to be extracted, such as lithium, nickel, cobalt, aluminum, and copper (Jürgen Fleischer, 2021).
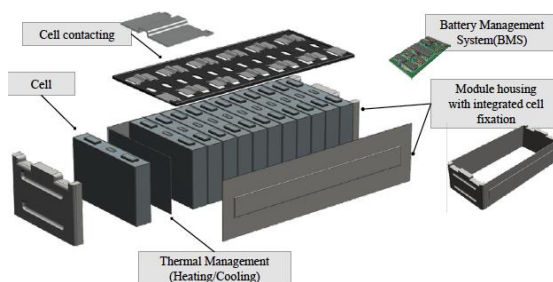

Figure 1. Example setup of battery module with prismatic cells (Jürgen Fleischer, 2021).

The module of figure 1 consists of cell, cell contacting, thermal management, module housing, cell fixation, and battery management systems. The disassembly of systems into sub-systems can potentially increase the concentration of the portion allowing the extraction of functional components for remanufacturing ends (Jürgen Fleischer, 2021) (Wegner, Chen, Dietrich, Dröder, & Kara, 2015).

3.2. Disassembly process

The first task is to discharge the battery to reduce the potential danger of a high voltage (up to 400 V). After the discharging process, the battery is disassembled, followed by an abrasive shredded process. Next, the shredded material is separated where one part is treated or recycled, and the other is subject to fine crushing. Afterward, the materials are separated again before they are also treated or reused. The objective is to obtain raw materials that can be reused or remanufactured to produce new batteries or different industrial products (Kathrin Wegener, 2014). The process is summarized in the following figure 2.
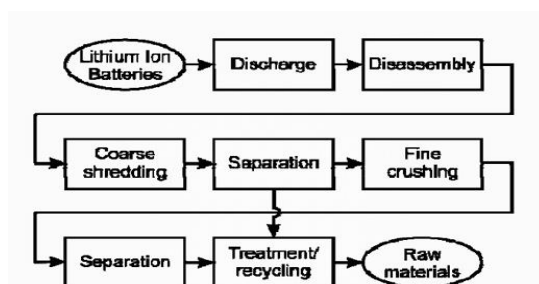
Figure 2. Recycling process chain for lithium-ion battery modules/stacks (Kathrin Wegener, 2014).

3.3. Challenges

Due to the great variety of batteries, the non-existing standards in battery design, and the lack of detailed designs available for the recycler, EVs batteries are currently manually dismantled. Nonetheless, labor is one of the most expensive phases in the recycling process of the Li-ion batteries and dangerous due to the high voltage and chemicals contained in the batteries. Therefore, a partially automated or fully automated system is required (Wegner, Chen, Dietrich, Dröder, & Kara, 2015) (Kathrin Wegener, 2014). This contribution proposes using a partially automated method for complicated battery assemblies and a fully automatic system for less complex systems.

One possible task for the robots is the remotion of screw and bolt fasteners or unscrewing. Several variants of EV batteries are montaged by many screws and bolts. Unscrewing is a simple task that is repetitive and little interesting for humans. Thus, the potential of robots to take over this task is considerably high (Jens Markowski, 2014) (Kathrin Wegener, 2014).

3.4. Proposed solutions-different outlays

3.4.1. Robot Container Disassembler

The entire disassemble unit is built in a container, where a barrier against the environment is ensured. First, the battery container is opened by the robot through a non-conductive tool. Second, the housing is opened for further disassembly. An especial table for the discharging is installed, where the batteries are set up and drained. The design of the table allows several batteries to be discharged simultaneously. Third, the Lithium cell block is dismantled as the significant component, and the resting fractions are separated. A hydraulic press-out unit was built for continuous disassembly of the cellblock where the cathode/ anode windings are compressed out abruptly and under elevated mechanical pressure from their respective housings. Subsequently, the components can be prepared separately (Jens Markowski, 2014). In the following figure 3, the layout is illustrated. The figure was translated from German to English.
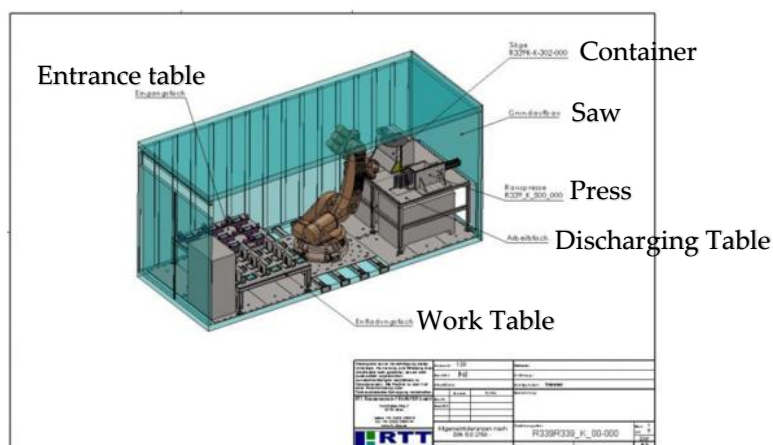

Figure 3. Conception and Design of the robot workplace for battery disassembly (Jens Markowski, 2014).

3.4.2. Hybrid human-robot disassembler

Both human and robot need access to the object for disassembly. The human and the robot share a space due to simplification matters of space. The human and the robot also require access to their tools. For the human the supplies

could be: screwdrivers, hammer, and cutting tools. The robot could be different sockets wrench bits for its unscrewing tools. Humans carry more complex tasks such as prying apart pieces joined with snap fits or glue and pulling out or cutting cables. The location of the screws and bolts could be taught manually or detected by a camera to the robot. The robot should be lightweight to minimize the risk associated with collisions. It should have sufficient load capacity and equilibrate the forces and torques generated from handling an electric screwdriver and loosening screws. One of the robots to fulfill this characteristic is the KUKA Lightweight Robot (LWR). The LWR is a seven-degree-of-freedom robot with torque sensors in each articulation. The stiffness of the automat could be adjusted if required (Wegner, Chen, Dietrich, Dröder, & Kara, 2015) (Kathrin Wegener, 2014).

The robot tool comprises primarily of a screwdriver, including a DC motor and a chuck. This subassembly was modified and mounted on the robot flange. Through a designed mechanism, the robot can change sockets wrench by itself. The torque and rotational speed can also be adjusted via microcontrollers (Wegner, Chen, Dietrich, Dröder, & Kara, 2015) (Kathrin Wegener, 2014)—next, outlay illustration in figure 5.
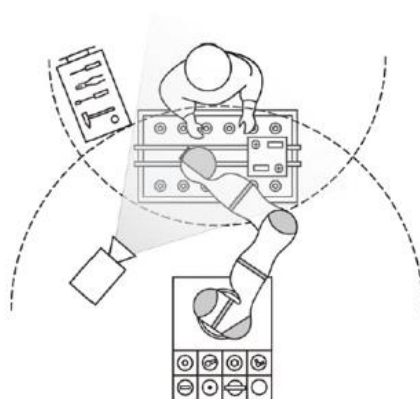

Figure 4. Disassembly workstation (Wegner, Chen, Dietrich, Dröder, & Kara, 2015)

4. Discussion

The second life of EVs batteries is closer to be a reality in a big scale manner. Usually, electric vehicles reach the EOL when their battery loss only gets between 20% or 30% of their capacity (Lluc Canals Casals, 2017). Therefore, it is economically and environmentally feasible to remanufacture this equipment. Even though when different layouts of batteries exist, they all can be classified into three main components, where the main element of interest is the cell, obtaining from them the valuable components to be reused (Jens Markowski, 2014) (Jürgen Fleischer, 2021) (Qingdi Ke*, 2020). Moreover, the disassembly procedure is also standardized, consisting of basic tasks such as discharging, crushing, separation, shredding so the product can be finally reused (Jürgen Fleischer, 2021) (Kathrin Wegener, 2014) (Lluc Canals Casals, 2017). How and by whom this disassembly is made, is where this paper contribution proposes two different mechanisms, depending on the complexity of the equipment. An entire automated system is recommended for simple assemblies, economizing, and speeding up the procedure (Jens Markowski, 2014) (Jürgen Fleischer, 2021). For more complicated bodies, a semi-automated is of greater use. The human, in this case, takes care of the complex manual tasks while the robot conducts repetitive and simple tasks such as unscrewing (Wegner, Chen, Dietrich, Dröder, & Kara, 2015) (Kathrin Wegener, 2014). These studies, however, are yet on an experimental phase and have not been applied on a significant industrial scale. Therefore, it is recommendable to conduct more experimental tasks on a bigger scale. It is also recommended that the EV manufacturers provide their battery outlays so remanufacturers can design faster and more efficient disassembly systems.

5. Conclusions

Environmental awareness has caused an increment of electric vehicles. Therefore, the rising demand for Li-ion batteries has increased **t**he interest in their recycling, where disassembly plays an important role (Wegner, Chen, Dietrich, Dröder, & Kara, 2015). This paper describes the battery components, defines a clear path for disassembly, explains the challenges attached to the process and proposes two different mechanisms, automated and semi-auto-mated, to approach the disassembly according to the complexity of the battery. The results indicate that a complete automatic layout is feasible when the batteries have a simple montage, whereas, for more complex montages, a semi-

automated is required (Jürgen Fleischer, 2021) (Kathrin Wegener, 2014). However, more studies and tests are necessary to get these studies to an industrial level.

Declaration: In preparing this scientific paper, I followed the DFG Code of Conduct ([https://www.dfg.de/download/pdf/foerder-ung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf](https://www.dfg.de/download/pdf/foerderung/rechtliche_rahmenbedingungen/gute_wissenschaftliche_praxis/kodex_gwp_en.pdf)), which describes the essential standards of good scientific practice.

Conflicts of Interest: The authors declare no conflict of interest.

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