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Hybrid additive manufacturing technologies - An analysis regarding potentials and applications

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- Invited Paper -

Abstract

Imposing the trend of mass customization of lightweight construction in industry, conventional manufacturing processes like forming technology and chipping production are pushed to their limits for economical manufacturing. More flexible processes are needed which were developed by the additive manufacturing technology. This toolless production principle offers a high geometrical freedom and an optimized utilization of the used material. Thus load adjusted lightweight components can be produced in small lot sizes in an economical way. To compensate disadvantages like inadequate accuracy and surface roughness hybrid machines combining additive and subtractive manufacturing are developed.

Within this paper the principles of mainly used additive manufacturing processes of metals and their possibility to be integrated into a hybrid production machine are summarized. It is pointed out that in particular the integration of deposition processes into a CNC milling center supposes high potential for manufacturing larger parts with high accuracy. Furthermore the combination of additive and subtractive manufacturing allows the production of ready to use products within one single machine.

Additionally actual research for the integration of additive manufacturing processes into the production chain will be analyzed. For the long manufacturing time of additive production processes the combination with conventional manufacturing processes like sheet or bulk metal forming seems an effective solution. Especially large volumes can be produced by conventional processes. In an additional production step active elements can be applied by additive manufacturing. This principle is also investigated for tool production to reduce chipping of the high strength material used for forming tools. The aim is the addition of active elements onto a geometrical simple basis by using Laser Metal Deposition. That process allows the utilization of several powder materials during one process what enables the tailoring of the tools materials mechanical properties. Another aspect is the possibility of Laser Alloying of the tools surface to reduce abrasive and adhesive wear. This technique is especially interesting for tools used in hot stamping production.

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1. Introduction

As the costumers desire on individual products increases, the companies offer a large portfolio of customized products [Rastogi (2009)]. To produce the small lot sizes of these parts in an economic way, the established manufacturing methods like chipping production and forming technology are limited. Especially forming processes with the need of high cost intensive tools cannot fulfil the requirements of short changeover cycles by producing affordable products. An innovative, very flexible manufacturing technology with a high degree of geometrical freedom is the additive manufacturing technology. The required part is build up by adding material. To produce a solid part the geometry is sliced into layers and by generating these layers successively the product is built up. This manufacturing technology is called a 2 ½ D-process. The principle allows an optimal utilization of material as the part can be topologically optimized on the occurring forces [Gibson (2015)]. In the last few years the researches for additive manufacturing increase conspicuously as some of the patents for Fused Depositon Molding (FMD) [Crump (1989)] ran out and so called “3D-Printers” were affordable for small costumers. A similar development is expected for machines working with selective Laser Beam Melting (LBM) as in January 2014 [Deckard (1994)] patents that protected this technology expired. Both of these and various more technologies are judged economically viable for commercial development.

2. Processes for additive manufacturing of metal

For the manufacturing of metal parts that could replace parts manufactured by forging, processes with a high amount of energy are required to process the metal material. Within the last decades several technologies for additive manufacturing of metal parts were developed and investigated. The most common ones are described in the following.

2.1. Selective powder melting

To take advantage of the high geometrical freedom of additive manufacturing the best manufacturing principle is the selective melting of the material inside a layer of loose metal powder. The process conventually is conducted inside an air dense process chamber with a building platform that can be adjusted in Z-direction. To build a three dimensional part a sequence of three steps is repeated successively. First the building platform is lowered by the height of one layer. Afterwards a closed layer of loose powder is applied by a so called recoater. The actual building of the part is conducted by melting selected areas of the powder bed with a high energy beam. Two processes are known to realize this manufacturing principle.

A laser based additive manufacturing process of three dimensional metal parts is the selective Laser Beam Melting (LBM), where the required energy to melt the metal powder is provided by a high energy laser. The laser is directed into the process chamber by a 2D scanner that allows a fast movement of the laser beam. To protect the molten material from oxidation the process chamber is flooded with an inert gas like nitrogen or argon [Meiners (1999)].

The second process that works with the same manufacturing principle but with an electron beam to melt the powder is the Electron Beam Melting (EBM). Besides the energy source the main difference is that the process chamber is vacuumed as the electrons would be distracted by air molecules or gas atoms [White (1980)].

2.2. Laser Beam Deposition Welding

Another industrial used concept is additive laser beam welding. For this principle a laser beam is focused rectangular on a workpiece surface to melt the workpiece material. The material added to the melt pool can be applied by wire, similar to a conventional welding process, or as powder by using an injection nozzle. The melting pool is protected from oxidation by an inert gas cover similar to conventional MIG-welding. The main advantage over the powder bed principle is that it is not limited on plane surfaces but the material can be applied onto freeform surfaces [Toyserkani (2004)]. Therefor the actual working unit is placed on a 6-axis robot or a 5-axis portal system.

One process working with the described principle is laser alloying. Main characteristic of this process is the addition of one single layer, thus it is designated for a surface treatment, and a highly turbulent melting pool to receive a homogeneous mixture of workpiece material with the allying elements. The turbulent melting pool is ensured by a dynamic beam oscillation, shown in Fig. 1 a. The alloying material can be added as powder [Klocke (2006)] or wire [Hofmann (2015)]. The main disadvantage of laser alloying with powder is an inhomogeneous structure formation based on a separation of the powder because of different dense of the alloying elements.

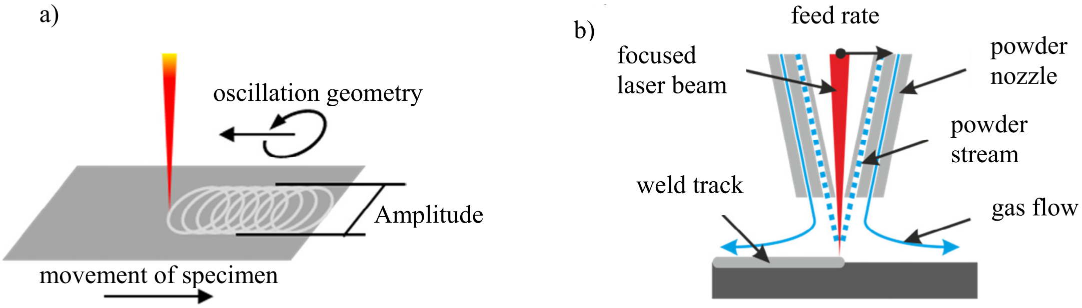

Fig. 1. (a) Movement of an oscillating laser beam producing a turbulent melting pool [Hofmann (2015)]; (b) principle of Laser Metal Deposition [Junker (2015)].

The more common process working with the laser beam deposition welding principle is the Laser Metal Deposition (LMD) that is shown in Fig. 1 b. Several companies have different names for this technology like Laser Engineered Net Shaping (LENS) from Optomec, Direct Metal Deposition (DMD) from Precision Optical Manufacturing (POM) or Laser Consolidation from Accufusion [Herderick (2011)]. Within this process a laser beam is focused on the workpiece surface through a LMD working head that is needed for the powder injection. The powder is sucked from the feeder by an inert gas flow that transports the powder from the powder tank to the powder nozzle, which focuses the powder stream on the melting pool. By using several powder tanks it is possible to mix different powder materials [Weisheit (2006)]. As the powder is injected into molten material even not meltable materials like ceramics can be processed that are used for wear reduction on forming tools. The main application of this process is coating and repeating of forming tools but also for repairing cost intensive goods like turbine blades [Rottwinkel (2014)]. Disadvantage of the process compared to the powder bed principle is the limited geometrical freedom as large overhangs do not have the support of loose powder during manufacturing.

2.3. Metal Powder Application (MPA)

A new additive manufacturing process developed by the Hermle AG is the Metal Powder Application (MPA) that is a thermal spray process. Similar to the LMD process the powder particles are transported by a carrier gas to the deposition nozzle. Inside the nozzle the powder stream gets covered by another gas flow that accelerates the particles to a velocity faster than the speed of sound. During the impact on the surface the particles energy causes pressures up to 10 GPa and temperatures temporary up to 1000°C that lead to a strong deformation of the particles and a binding contact to the workpiece. The size of the particles is with 25 µm to 75 µm similar to that used for LMD, LBM and EBM. By using water soluble filler material it is even possible to manufacture hollow geometries inside a part. The main advantage of this process is the absence of high temperatures as they exist in the laser based processes described above. That allows the manufacturing of high carbon tool steel like 1.2344 and 1.2367 as well as the combination of materials with very different melting temperatures like tool steel and copper. It is even possible to embed thermocouples or heat conductors. As the technology of MPA is patented by Hermle AG and is just offered as an industrial service the usage of this process is limited [Hermle (2016)].

2.4. Metal Inert Gas (MIG) deposition welding

Another additive manufacturing process for generating metal parts works with the principle of Fused Deposition Modelling (FDM) that is established in so called 3D-printers for the manufacturing of plastic parts and also for the production of metal components. As the laser based additive manufacturing processes are sort of welding processes the idea was to adapt the well-known conventional Metal Inert Gas (MIG) arc welding for the additive manufacturing. By connecting high electricity an electric arc arises between the wire and the workpiece melting both partners. To protect the melting pool from oxidation an inert gas covers the working area. By adapting such a welding machine on a 5-axis portal system the additive manufacturing of three dimensional parts can be realized [Dickens (1992)].

The main advantage of this technology is that MIG-welding is already known in industry for a couple of decades and therefore machines working with this additive manufacturing principle are relatively cheap compared to those working with a laser. The main disadvantages are the inadequate geometrical accuracy and the surface roughness, so a subsequent machining of the built part is recommended [Simhambhatla (2015)].

2.5. Conclusion of additive manufacturing processes of metal

Regarding the development of additive manufacturing within the last few years the variety of processes as well as the process reliability increased significantly. The high geometrical freedom, process flexibility and the ideal utilization of material are the main reasons for the rising interest of the industry. Nevertheless the technology is still faced with challenges like varying mechanical properties and surface roughness, both depending on an abundance of process parameters. Therefore the technology is in particular used for prototyping and near-net shape semi-finished products that get reworked by milling or grinding. Furthermore, the quality of the part is highly dependent on the know-how of the operator and at least the production time is very long compared for example to forming processes, consequently it is not yet suitable for mass production. The utilization of additive manufacturing of metals is restricted by the limitation of the range of materials. Especially for tool manufacturing the established materials can hardly be processed using additive manufacturing techniques as most of them are classified as difficult to weld. Thermal induced tensions, caused by the high cooling rates during welding, may lead to cracks inside the added material. Therefore the parts temperature during welding has to be regulated. On the other hand, the production of parts by using powder provides an opportunity to process alloys that are challenging to cast [Sander (2016)].

3. Hybrid additive processes

Especially for large volume the production speed in additive manufacturing does not allow an economical usage of this technology. Therefore, the inclusion of additive processes into the production chain of conventional manufacturing is part of the recent research, which concludes hybrid processes. As the additive manufacturing is a sequenced method the combined processes should be repeatable in sequences as well.

The most obvious combination is the additive manufacturing by a deposition process with a subtractive process like milling. Both technologies require a 5-axis machine for a full three dimensional processing.

Akula et al [Akula (2005)] integrated a machine for Gas Metal Arc Welding (GMAW) into a CNC milling system. For the final hybrid process a deposited layer is milled planar before the next layer gets deposited. Once a near-net shape is achieved, the required profile is milled to complete the part. By using this method the production time for manufacturing molds and dies can be reduced significantly. The latest research is treating with the utilization of an automatic tool changing system to decouple the welding tool during milling.

Kerschbaumer and Ernst [Kerschbaumer (2004)] integrated a LMD nozzle into a 5-axis CNC machining system in 2004. In their process the additively built component is machined after every few layers to allow machining access with small tools into complex internal geometries. In this study they identified that alterning laser deposition welding and machining operations do not permit the use of cooling lubricants. Furthermore it is highlighted that for the milling tools materials, which can resist machining of advanced alloys at high temperatures, are necessary. This combination of a LMD tool and a CNC milling center is nowadays the most interesting technique for a hybrid process. Several producers which are known for their competences in CNC machining centers are investigating and developing the integration of a LMD machine into the CNC setup.

The DMG MORI SEIKI AG is one of the first companies that built a hybrid machine for commercial sale by combining LMD and milling [DMG MORI (2004)]. As demonstration part they present a ready to use turbine housing with connection ports for fuel feed entirely built by the hybrid process within approximately 5 hours.

In October 2015 WFL Millturn GmbH & Co.KG presented their hybrid machine. Similar to that of DMG MORI, it uses the LMD as the additive manufacturing technology but the machine is equipped with a drill chunk that allows turning [Schöpf (2015)]. Thus milling and turning are combined with the additive manufacturing increasing the flexibility of the hybrid process. Furthermore the laser is used for surface heat treatment, like hardening. Combining all those processes the production of ready for use components can be completed inside one machine without re-clamping of the workpiece.

As mentioned above, the Hermle AG developed their own additive manufacturing principle with Metal Powder Application that is included in one of Hermles CNC milling centers [Hermle (2016)]. One of the main advantages is the significant lower temperature of the workpiece during the additive production and therefore the possibility to of conventional milling tool materials.

To face the disadvantage of a rough surface and high porosity and consequently varying mechanical properties of additive manufactured structures, the Institute of Forming Technology and Lightweight Construction at the University in Dortmund/Germany combined a hybrid machine setup of DMG MORI with a tool for incremental forming [Tekkaya (2015)]. The step of incremental forming will be investigated to compress the material after several layers and also to smoothen and strain harden the surface after the additive manufacturing.

A fully automated system for repairing worn-out dies and molds was developed by the Fraunhofer Institute of Production Technology [Brecher (2004)]. Similar to the described machine systems the setup was a combination of LMD and a 5-axis milling machine. To realize the automated production the system is also equipped with an optical measurement sensor working with laser triangulation. That allows the analysis of the worn-out tool and the calculation of the required area that has to be reworked. Afterwards the tool can be prepared for welding by milling and repaired by LMD. To compute the further milling step for surface finishing the reworked area gets scanned by the optical measurement system again.

For the technology of selective Laser Beam Melting quasi hybrid processes, where the additive manufacturing is integrated in the production chain, are developed and still part of the actual research. The main idea is to manufacture geometrical simple segments of a part by conventional processes like forging or sheet metal forming and using the additive manufacturing to add functional, geometrical complex elements onto the segments surface. An example would be an impeller designed by the Rosswag GmbH, where the main part that transfers the forces is forged. By using LBM to manufacture the blades canals could be integrated that effect the boundary layer flow [Rosswag (2016)].

4. Additive Manufacturing in Forming Technology

At the Institute of Manufacturing Technology it is investigated to combine a selective powder melting process with the conventional sheet metal forming process. Further investigations are on the added value of additive manufacturing for tool production of sheet metal forming as well as hot and cold forging tools.

4.1. Combination of sheet metal forming and laser beam melting

Powder bed based additive manufacturing (AM) processes such as laser (LBM) and electron beam melting (EBM) are characterized by advantages such as the ability to produce unique and individual geometries and being highly material efficient [Cansizoglu (2008)]. Nevertheless, these manufacturing technologies are limited in manufacturing speed and maximum geometrical size of fabricable parts. To overcome these disadvantages the aim of the research work within the Collaborative Research Center 814 is to combine AM with sheet metal forming processes. Thereby the advantages of forming such as short production time and the ability to produce large scaled parts should be merged with the benefits of AM processes. Parts manufactured by the combined processes forming and AM will further be named hybrid parts. As the alloy Ti-6Al-4V is the most important titan alloy utilized on medical applications and aerospace industry it is used within this work as exemplary material to investigate the combined process chain of forming and AM [Peters (2002)]. It is state of the art that laser and electron beam melting enable the production of dense Ti-6Al-4V parts with good mechanical properties [Scharwsky (2015)]. Until now, the combination of the AM and bulk metal has been researched considerably [Graf (2012)]. Nevertheless, for the combination of semi-finished sheet parts and additive manufacturing of volumetric elements there is a lack of existing research and knowledge. Fundamental research has been fulfilled by Schaub et al. [Schaub (2014 a)] to combine flat sheet metal with an initial thickness range from $t_0 = 1.0$ mm to $t_0 = 5.0$ mm. Within this research work it has been proven that it is possible to manufacture dense hybrid parts consisting of flat Ti-6Al-4V sheet metal and volumetric electron beam manufactured elements of Ti-6Al-4V powder. Comparable results have been presented by Schaub et al. [Schaub (2014 b)] for the manufacturing of hybrid parts by laser beam melting. Within the research it has been presented that in comparison to EBM, hybrid parts manufactured by LBM can highly be influenced by brittle oxides within the first additive manufactured layers [Schaub (2014 a)]. It is further state of the art that mechanical and metallurgical characteristics of Ti-6Al-4V manufactured by LBM is high sensitive to post heat treatment [Vrancken (2012)]. This fact has also been proved for hybrid Ti-6Al-4V parts consisting of flat sheet and functional elements manufactured by LBM by Schaub et al. [Schaub (2014 b)]. Based on the investigations deep drawing, LBM and heat treatment has been developed as a suitable process chain to realize hybrid parts[Ahuja (2015)]. An exemplary hybrid part, visualized in Fig. 2, has been produced and analyzed.

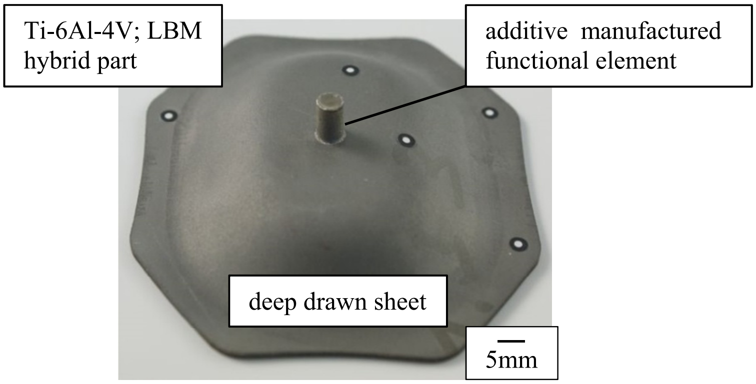

Fig. 2. Hybrid part manufactured by the combination of deep drawing and LBM.

In order to realize the combined process chain deep drawing of Ti-6Al-4V sheet metal with an initial sheet thickness of $t_0 = 1.5$ mm has been formed at an elevated temperature of 400 °C. Tool set up has been designed and implemented to clamp the formed sheet within the LBM machine SLM 280HL from SLM Solutions GmbH. The functional element is characterized by a cylindrical geometry with a diameter of d = Ø5.0 mm. Mechanical characteristics of the hybrid part has been analyzed by applying shear stress at the connection zone between sheet metal and additive functional element. With the experimental testing high mechanical characteristics of the hybrid part with shear strength of 478 MPa ± 62 MPa have been proved [Ahuja (2015)]. Further investigations of this project will focus on the interaction zone between sheets an additive element. Initial stress states and sheet thickness variation of the formed sheet are expected to be two significant parameters in this context. For further investigation of the combined process chain, a wide range of stress states will be induced in the semi-finished sheet by forming operations such as superplastic forming as well as bending and deep drawing at elevated temperatures.

4.2. Innovative surface treatment for wear reduction on hot stamping tools

Hot stamping is a suitable method for manufacturing ultra-high-strength structural steel components. The semi-finished parts can achieve an ultimate tensile strength of approximately 1500 MPa and high accuracy [Karbasian (2010)]. In direct hot stamping a blank is heated up for several minutes in a roller hearth furnace. Afterwards the heated blank is formed and quenched in the press and cut to the final geometry [Merklein (2006)]. During this process the forming tools are highly thermo-mechanically stressed which results in abrasive and adhesive wear. In order to prevent an expensive rework of the tools, a wire based laser alloying process is developed to influence the properties of the base material. The profitability can be increased and a more homogenous distribution of the alloying elements is possible by using a wire instead of a powder. By using a laser alloying process, the steps of removal of coating and adhesive layer, deposition welding and recoating can be reduced. In addition, a local modification of highly stressed surface areas is possible. The overall purpose of applying this additive manufacturing method is to increase the wear resistance of the tools. A fiber laser of IPG YLS-1000 is used in combination of a 2D-scanner. Mirrors are used to generate a circular beam oscillation. The laser beam has a maximal frequency of 1 kHz, which heats a wire-shaped filler material to achieve diffusion of the alloying elements into the base material. The laser beam is guided continuously in the laser alloying process. The welding wire 1.4430 has the necessary element composition of molybdenum, chromium and nickel to increase the surface hardness. Molybdenum improves the wear resistance at high temperatures and chromium increases the wear and oxidation resistance of hot-working steels while nickel increases the hardness [Doege (2010)]. Unlike conventional methods like powder bed fusion, the wire based method generates a constant layer thickness and ensures a higher material utilization. A gap distance of maximal 0.2 mm between the wire and the workpiece is needed to provide a sufficient amount of alloying elements [Hofmann (2015)]. Based on experimental results the material supply decreases for higher distances. A homogenous diffusion between the alloying elements and the base material is achieved by a minimum feeding velocity of 4.1 mm/s. At lower velocities the material supply is irregular which results in an interruption of a continuous element diffusion. The degree of dilution is used to describe the diffusion of the alloying elements with the base material in dependency of the line mass. The line mass quantifies the amount of alloying elements supplied per unit length. The degree of dilution is directly proportional to this parameter. Additionally, a positioning of the wire at an angle of 35° to the workpiece surface is required. A wire feed above this angle leads to process instabilities with an irregular melt flow. Two different tool steels were examined in the wire based laser alloying process: a hardened and unhardened tool steel. WP7V is a Cr-Mo-V alloyed special steel, which was chosen for the experiments because of its very high toughness and a high wear resistance at elevated temperatures [Dörrenberg]. The base material of WP7V consists of a martensitic structure after hardening while the unhardened tool steel 1.2379 is a hypereutectoid steel which ligates carbon in carbides and no martensitic structure can be formed. In contrast to the WP7V, it is possible to achieve an increased surface hardness for the 1.2379 by 40 %. The results are illustrated in Fig. 3.

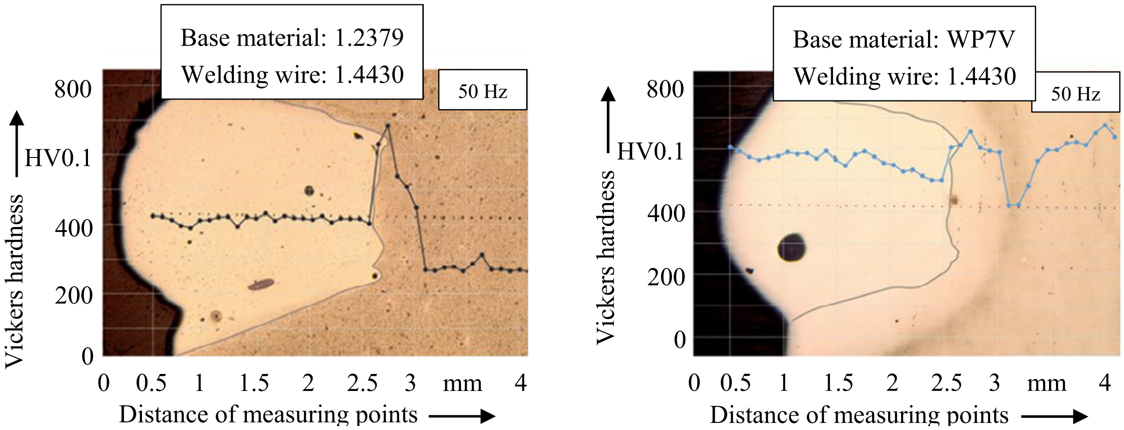

Fig. 3. Micro-hardness profile of alloyed lines and base material [Hofmann (2015)].

An improvement of the surface hardness of WP7V cannot be achieved with the used alloying elements. Due to the martensitic structure the hardness might be at its maximum level and for this reason a further increase is unlikely. The tool steel grade 1.2379 was selected for preliminary tests, but the results can be applied to conventional hot forming tool steel grades.

Combining the knowledge about the forming process with development of innovative additive manufacturing processes leads to improved tool performance. By using a wire based laser alloying process the wear resistance of high load areas can locally be increased and worn surfaces can be repaired easily. Additionally, a flexible choice of alloy composition broadens the range of possible modification of the tool surface properties depending on the parameters of the manufacturing process. Further investigation will be necessary to analyze the influence of different alloying elements on the material properties and the wear behavior during the hot stamping process. In order to develop a stable laser alloying process with constant results the process window will be examined and the effort of the rework on tool surfaces will be evaluate.

4.3. Tailored forging tools by using Laser Metal Deposition

The increasing portfolio of customized components in the industry lead to shorter changeover cycles [Rastogi (2009)], thus the costs of a tool have to be amortized with a low number of products. For parts manufactured by forging processes that trend leads to very expensive products. The state of the art in tool production is the manufacturing by milling resulting is high chipping volumes of high strength tool steel. This leads to high wear of cutting tools. To realize the mass customization, a more economical process for tool manufacturing has to be investigated. As Laser Metal Deposition is already used to repair worn-out forming tools this process is investigated for the production of active elements on forging tools. Thus the chipping volume can be reduced significantly.

First investigations were made with the low carbon maraging steel 1.2709 that is commonly utilized by LBM the production of molds for injection molding and the properties of this steel fulfil the requirements for hot forging tools. After the heat treatment for artificial ageing of additive manufactured specimens the mechanical properties were not dependent on LMD parameters but were slightly lower than those of conventional manufactured material. An analysis of cross sections built by LMD showed the existence of inclusions of TiO. As the titanium is necessary for the creation of precipitations that cause the increasing strength during artificial ageing, the fact that it is encapsulated inside the TiO-molecule leads to a lower strength compared to conventional manufactured material [Junker (2015)]. Furthermore, for the alterning load during forging these inclusions could initiate cracks that lead to tool failure. Further investigations are made with a medium-alloyed tool steel that is more common in tool production. With an amount of about 0.4 % carbon this steel is classified as difficult to weld as the structural mechanisms caused by the heat treatment during welding lead to high internal stresses. Due to the high energy input by the LMD process the stresses inside the structure resulting from the thermal gradient are moderate and defect free structures could be produced. A micro hardness measurement showed a hardness gradient in building direction that depends on the processed material and its hardening mechanism, illustrated in Fig. 4.

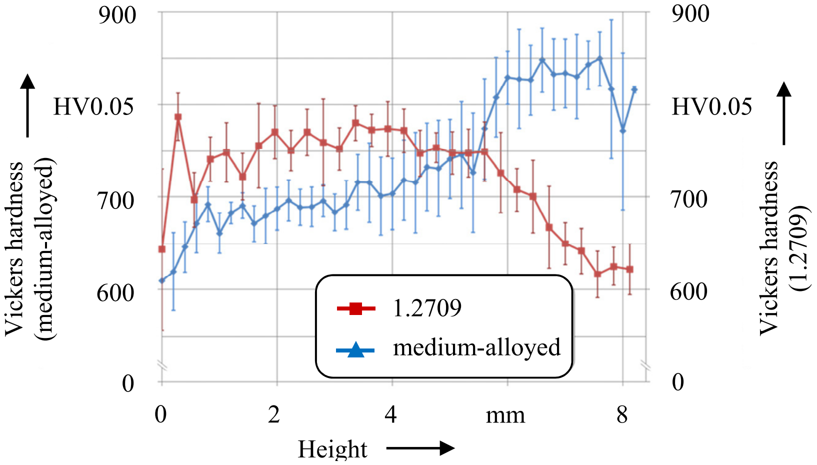

Fig. 4. Hardness distribution in Z-direction for tool steel 1.2709 and medium-alloyed tool steel after additive manufacturing using LMD.

Furthermore it could be identified that the hardness of additive manufactured medium-alloyed tool steel is measured with a maximum at about 850 HV 0.05 which is way higher than the conventional hardness of tools out of this material of about 510 HV 0.05. Furthermore the mechanical properties of the additive manufactured material show a higher strength but also a more brittle fracture behavior than conventional manufactured and hardened material. After a heat treatment the mechanical properties are similar to those of conventional material. As the surface hardness of additive manufactured parts is that high, the actual research treats with an adapted heat treatment. Additional investigations were conducted on the processing of high carbon tool steel with an amount of carbon up to 1.5 %. Unless the difficult weldability cubes with an edge length of 15 mm could be produced using LMD that reach a relative density of more than 99 %. By using an external heating further improvements of the density are suspected. The aim of the project is the additive manufacturing of hot as well as for cold forging tools. The mechanical characterization of these materials is still part of current research.

A beneficial value of the utilization of LMD for tool production is the opportunity of processing several materials within one process. The inclusion of ceramic particles like tungsten carbide into the tools surface as well as an in-situ alloying could be attractive technologies regarding tool manufacturing. Further investigations are needed to figure out the limits of LMD process.

5. Summary

The trend in industry to offer a large portfolio of products and to shorten the changeover cycles lead to the need of innovative new manufacturing processes. Facing this challenge additive manufacturing of metal as a very flexible production technology proposes new possibilities in manufacturing. The advantages of this technology like high geometrical freedom, optimized material use and easy modification of the producing part are confronted with the slow production speed of layer on layer manufacturing, inadequate accuracy and surface roughness. To solve those disadvantages hybrid processes are developed that combine additive and subtractive manufacturing within one machine setup, represented in Table 1. Depending on the requirements of the produced part, systems with the use of different additive manufacturing processes are available on the market. Aviation and space industry are focusing on the integration of Laser Metal Deposition (LMD) into a CNC milling center. It allows the use of innovative, lightweight powder materials and the production of fine structures. A surface finishing can be applied by using small milling tools. For gear shaft production the machine setup is expanded by a drill chunk and the laser used for LMD is also used for surface hardening. Thus a ready to use gear shaft can be produced without re-clamping by using a tube or a rod as semi-finished product. The gears teeth will then be applied by additive manufacturing and finished by milling. For big, low loaded tools a combination of Gas Metal Arc Welding and a CNC milling center is suitable. The deposition rate of this technology is way larger than that of LMD. For higher loaded tools like those used in hot forging the Metal Powder Deposition is an interesting alternative as the heat input is very low what results in low inner tensions.

Table 1. Categorisation of additive manufacturing processes and the combination with conventional processes.

Additive Process	Characteristic	Process Combination
Laser Beam Melting	+ high complex part geometry - limited on plane building platform - risk of powder dust by opening the machine	- integration in process chain only
Laser Metal Deposition	+ build up on any freeform substrate + multimaterial production - risk of powder dust by opening the machine	- integration in process chain - integration in CNC milling and turning centers for a sequential process
Metal Powder Application	+ small heat input - risk of powder dust by opening the machine - patented by Hermle	
Gas Metal Arc Welding	+ high build-up rate + well known process - inadequate accuracy	

Concluding the compilation of hybrid processes it can be supposed that the combination of additive and subtractive manufacturing as well as the integration of additive manufacturing processes into production chain offers a high potential for industrial utilization as many of the disadvantages of additive processes can be compensated.

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