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Research Article

A Survey on Process Modelling, Innovation, Design, and Material Characterisation in Additive Manufacturing

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Abstract: The unique design freedom offered by additive manufacturing (AM) technologies enables engineers to develop more innovative products with relatively lower costs within a shorter period of processing time in comparison with conventional manufacturing methods. On the other hand, the unique capabilities of AM have created a platform for researchers to combine several engineering methods with the new manufacturing technique to grow industrial applications as well as resolve the existing issues with AM processes. Understanding the research values that AM offers academic environments, this paper performs a systematic survey on AM-related research topics in the fields of mechanical engineering and materials science that have attracted much attention from research teams over the last few years. These topics, namely process modelling in AM, innovative research in AM, generative design by AM, material characterisation in AM processes, and finally, design for additive manufacturing (DfAM), are notably investigated through this study.

***Keywords*:** additive manufacturing technologies, generative design, material characterisation, computational modelling, DfAM

1. Introduction

In recent years, additive manufacturing (AM) technologies have been adopted by many different industry sectors, ranging from the automotive industry to fields including consumer products, electronics, the military, architecture, and many more [1, 2]. As an industrial example and due to some unique capabilities of AM technologies, it is estimated that there has been a reduction in the cost of 30-90%, a reduction in the build time of 77-94%, and zero inventory and warehousing by using AM technologies in the rail industry [3]. Building parts by three-dimensional (3D) printing eliminates tooling and setup costs associated with traditional manufacturing, which lowers fixed costs. In addition, the use of AM technologies has been extended to secure service parts supplies, develop tools to aid operations and

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maintenance, and improve safety and the customer experience.

The numerous applications and benefits of emerging technology discussed above were realised thanks to the key features of AM technologies that enable engineers and researchers to design customised parts, develop parts by using high-performance materials with advanced mechanical properties, and design and develop parts with higher complexity and functionality. However, despite the several advantages offered by AM technologies, some challenges have been observed over the years from the emergence of AM technologies, namely equipment cost, limited material availability, manufacturing costs, lack of in-house AM resources, limited repeatability or lack of accuracy from build to build, software development and capabilities, limited recyclability, and data storage requirements [4]. Furthermore, the low efficiency of current AM technologies in mass production, limited print bed size, limited AM expertise in the industry, lack of AM standards for different products, and additional post-processing operations can be enumerated as major challenges in this technology [5].

To address the challenges in AM technologies, a vast variety of research approaches have been conducted among the research groups; however, some of the challenges remain largely unexplored. These studies are mainly focused on process modelling and optimisation, material characterisation and development, standardisation of the design processes, and design innovation in AM processes.

To have an overview of the research works that have been carried out over the last decades, this article aims to investigate AM-related works from different aspects of mechanical engineering and materials science that have been widely researched over the last few years. The methodology that has been followed in this study has been summarised in a diagram shown in Figure 1. As displayed in Figure 1, the research areas are mainly divided into five categories, namely AM process modelling, innovative research in AM, generative design by AM, materials characterisation in AM processes, and design for additive manufacturing (DfAM). These categories and their respective sub-categories will potentially provide a suitable platform for the researchers from mechanical engineering and materials science teams to learn how to find out the existing challenges in the field of AM technologies and how to deal with those challenges, accordingly.

Figure 1. Classification of research topics in this study

Understanding the main goal of the paper, the remainder of the paper is organised as follows. In Section 2, the research on the modelling of AM processes will be investigated in detail. In Section 3, some innovative research in AM will be reviewed. Afterwards, the generative design by AM processes, material characterisation in AM processes and DfAM are investigated in Sections 4, 5, and 6, respectively. Some conclusions will be wrapped up in Section 7.

2. Process modelling in AM

Computational modelling including FEA, TA, and CFD, has been extensively used for AM process modelling and optimisation.

The process modelling and optimisation are performed through FEA, TA, and CFD to explore process deficiencies such as balling effect [6, 7], part shrinkage [8], pores and microcracks [9], and residual stress-induced defects like warpage and distortion [10]. In most cases, the numerical methods mentioned above are handy tools for engineers and researchers to shed light on key parameters of the process and eliminate deficiencies in the printed object by applying parameter tuning and optimisation

2.1 *Process modelling to improve the surface quality and mechanical properties of the 3D-printed parts*

Several studies have appeared in recent years documenting the use of numerical analysis to simulate the process before fabrication and predict the most likely root causes of deficiencies in the printed part to optimise the quality of the final product. These deficiencies appear in different forms depending on the AM techniques used for the part's fabrication. For instance, in material extrusion AM, the internal pores formed by the deposited strands will result in less mechanical strength and a lower-quality surface finish in comparison with conventional manufacturing processes like injection moulding [11-13]. To evaluate the quality of the printed part, CFD analysis is used as a tool to predict the surface roughness of the mesostructures in material extrusion AM [14]. In a different application, the nozzle dispensing method, which is classified as one of the material extrusion AM technologies, has been widely studied in the fields of additive biomanufacturing (ABM) and life sciences [15, 16]. In this regard, an FEA-based predictive model was employed to predict the height and width of a highly viscous material that is dispensed on the substrate of the build platform [17]. The results of this modelling will help set the parameters of the dispensing system to provide a uniform flow and a surface with a lower roughness. In another material extrusion AM process called fusion deposition modelling (FDM), despite the ease of handling this type of 3D printing technique, the resultant poor surface quality has not been fully explored. To investigate the effects of different parameters of the process on the quality of the surface finish, a mathematical model for the surface profile was developed based on two groups of parameters, i.e., pre-process parameters and fabrication process parameters [18]. Alternatively, in another study, the Taguchi technique was used to investigate the effect of the layer thickness parameter on surface roughness [19].

Besides low surface quality, despite the large application of thermoplastic resins in polymer-based AM, these materials have limited structural applications due to their poor mechanical properties like stiffness and strength [20]. To overcome this imperfection, some research teams and manufacturers have designed and developed 3D printing machines for additive manufacturing of composites (AMC) that offer practical solutions to improve the mechanical properties of the final products [21-24]. As discussed earlier, finite element (FE) modelling has proven to be a useful method to model the mechanical properties of products that are made of composite elastomers [25]. The mechanical properties of the final 3D-printed part in composite 3D printers vary evidently with the composition ratio and configuration of the part [26-28]. Alternatively, in the field of material extrusion AM, flow analysis was performed using an integrated FE and analytical models to investigate the printing requirements such as continuous deposit, maximum and minimum spreading pressures, and an upper limit for the separating force between the nozzle head and substrate [29]. In this context, much research can be found in the literature that has studied the flow characteristics through the nozzle and its relationship with heat transfer [30-33].

2.2 *Process modelling to predict residual stress*

In a different AM technique called powder bed fusion (PBF), the powder layer thickness can potentially influence the manufacturing-induced residual stress [34, 35], which is a common issue in PBF processes. To overcome this issue, the layer scaling method was investigated through FEA, and guidelines were provided [36]. In this line of research, a thermo-mechanical part-scale model was alternatively used to model the distortion in the PBF process by using FEA that generates an adaptive voxel mesh to reduce the complexity of the model and computational time, respectively [37]. In another study, to reduce the computational time, a calibrated analytical thermal model was proposed to derive functions in terms of an FE model [38]. Through this model, the complex evolution of the thermo-mechanical behaviour of components printed by the PBF process was captured. Presumably, this simulation could have been performed using the traditional FE model that was used for simulating distortion in welding and direct energy deposition (DED) processes, but it could introduce new technical challenges into the model due to differences in PBF bead width and welding/DED bead widths [39]. In the laser powder bed fusion (L-PBF) process, a FE model was developed for the prediction of the distortion generated in this process [40]. In this model, the accuracy of the prediction was compared between FE modelling using solid elements and shell elements. The experimental results revealed that the performance of shell modelling is more accurate except in the prediction of the buckling effect, which was captured more accurately by using solid elements. For the thermo-mechanical modelling of the DED process, readers may refer to [41], in which the comprehensive modelling was thoroughly studied.

In PBF processes, since the laser movement leaves an inhomogeneous and unstable temperature distribution in the powder, it leads to the amplification of residual stresses in the solidified layer. To model the thermal distribution, an FE model was implemented with the commercial FE code ABAQUS to take into account the effects of different parameters that could influence the temperature distribution of the laser sintering (LS) process [42]. For complete modelling, it is recommended that the powder density and specific heat be defined as functions of temperature, thermal conductivity, and latent heat in the simulation [43-45]. Similarly, a numerical model was developed for simulating the heat transfer and residual stress using the Comsol multiphysics environment to further understand the complex thermo-mechanical behaviour in the LS process [46]. The distortion due to undesirable residual stress in the LS process has most likely arisen from the presence of large thermal gradients [47-50]. Alternatively, a semi-analytical thermal model was presented to discretise the moving laser spots on a printed object to predict the temperature gradients in the selective laser melting (SLM) process and accompanying deformation [51]. To validate the numerical model and results, many studies have been performed to measure the residual stresses and deformations using in-situ techniques [52-56].

Repeatedly about residual stress, it is worth mentioning that the residual stress, in a form of tensile stress, will influence the fatigue life as an additional driving force for crack initiation and propagation [57]. In some AM processes, residual stress might cause cracks at the interface between the solid part and the support structure. To model the crack at this point, one method was developed by Tran et al. [58] for the L-PBF process to predict the interfacial cracks and consider the configurations that are most likely subjected to form a crack. In one of the studies related to FE modelling of metal LS, the location of failure due to crack was predicted in the printed components and the results were validated by experimental observation [59]. In a different AM process, named fused filament fabrication (FFF) process, by using an anisotropic cohesive zone model (CZM), the crack propagation between layers and through layers was investigated with extended finite element method (XFEM) on a printed object made of acrylonitrile-butadiene-styrene (ABS) materials [60].

A functional laser scanning strategy is a known method to improve some limitations of the L-PBF process, such as deflection near the overhang and the poor surface finish. A new laser power control algorithm was proposed by Yeung et al. [61], by which the laser power is scaled to a value called the geometric conductance factor (GCF). This method demonstrated the improvement in some limitations of L-PBF as well as the potential evolution in laser scanning strategies for similar processes. In the SLM process, the manipulation of some laser parameters, such as laser power, laser scanning velocity, and scanning pattern, will have a direct effect on the porosity level and the deformations arising from residual stress [62, 63]. In addition to the laser parameters, depending on the material conductivity, both distortion and residual stresses can be compensated by tuning other relevant parameters like the initial substrate temperature and final cooling phase [64]. In addition to the substrate temperature, the shielding gas, which is chosen for the L-PBF process, plays an important role in terms of spatter generation and oxide formation [65]. The convection heat transfer generated by inert shielding gas will influence different properties, including the microstructure of the printed object [66].

One of the main advantages of AM is that it enables manufacturers to reduce supply chain complexities and minimize the use of available resources in comparison with conventional manufacturing processes [67]. To enhance further improvements in process and supply chain, a study shows that the modelling and simulation of AM processes, in particular, the L-PBF process, can play an important role [68]. One of the common deficiencies occurring in the printed parts, especially in L-PBF processes, is warpage. The main source of warpage is the non-uniform temperature distribution in the build chamber that causes deformation during the cooling stage [69]. In addition to the temperature distribution and the surrounding temperature in the build chamber, the laser scanning pattern and speed, laser power, and layer thickness in the synthesis laser sintering (SLS) process will have a direct effect on the severity of the warpage [70]. Another study has revealed that the intermittent scan strategy can significantly reduce warpage occurring due to residual stress in the SLM process [71].

The virtual simulation could help with an estimation of the temperature distribution and melt pool size to control the quality of the built part [54]. The electron beam melting (EBM) process was investigated by using a FE model in terms of energy source and powder melting properties [72]. The model demonstrated good forecasting capability with the experimental results. To investigate the residual stress in the EBM process, the effects of beam size, beam power density, beam scanning speed, and substrate temperature were modelled by FEA only through one-pass scanning to elucidate the features of the residual stress fields both qualitatively and quantitatively [73].

2.3 *Constitutive modelling*

As it appears in some AM processes, the printed parts possess anisotropic characteristics, meanwhile, the mechanical properties like tensile strength vary with several printing parameters such as printing angle and orientation on the build platform [74-82]. According to the AM technique and 3D printing machine, some researchers attempted to develop a constitutive model to predict the structural response of the printed parts against the input force or moment. E.g., two specimens of soft polymer were printed in two different directions, and the constitutive parameters were obtained by using the experimental stress-strain data [83]. An additional FEA was performed to evaluate how far it satisfied the mechanical response obtained from the constitutive model. In a different AM technique, a constitutive model considering print angle, layer thickness, an isotropic elastic model, and a Hill anisotropic yield model was developed for a printed part through the stereolithography (SLA) process [84]. The model was validated by experimental and simulation results that satisfactorily described the mechanical response of the samples under a uniaxial tensile load.

2.4 *Modelling of large-size elements in AM*

The AM of large components using processes like wire arc additive manufacturing (WAAM) involves additional computational challenges. The weld bead is the constituent block of WAAM, as shown in Figure 2. Therefore, the shape and size of the weld bead determine the mechanical, metallurgical, and geometric characteristics of the end product. The computational viewpoint of the mechanical and metallurgical aspects of WAAM is similar to the other process variants previously discussed. However, the large size of WAAM components brings additional computational challenges. Modelling the shape and size of the weld bead is a unique aspect of WAAM. The shape and size of the weld bead cross-section are needed before printing the component to schedule the path planning. The flatness of a deposited layer (obtained by laying several beads side by side) or the lateral surface of a wall (obtained by laying several beads one over another) is a direct outcome of the weld bead shape and size (height and width). This requires that the profile of the bead be modelled.

Conventionally, the weld bead profiles are modelled by fitting standard geometric shapes such as parabola [85] or cosine [86]. The new WAAM variants, such as laser-arc hybrid [87] or twin-wire welding [88], do not fit the standard geometric shapes and require the application of computational methods to determine the shape of the weld bead. For instance, the characteristic coefficients in the following bead profile equation for laser-arc hybrid DED are obtained by a numerical method [87].

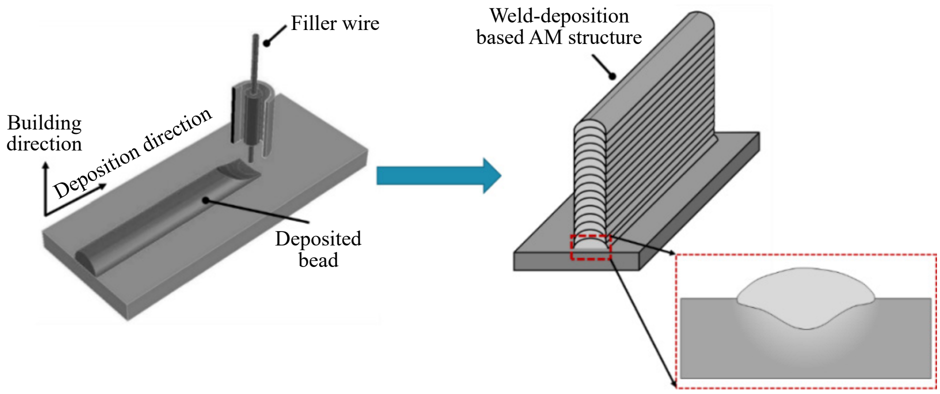


Figure 2. Role of bead geometry in the WAAM process

The welding process parameters, mainly the welding current and travel speed that determine the shape and size of the weld bead, also determine the heat input per unit volume and thereby affect the distortion, residual stress, and microstructure. The FEM-based prediction of volumetric phenomena such as distortion and residual is well documented in the literature [89]. However, local effects such as microstructure change and anisotropy are still fully captured using computational methods. One of the recent approaches paired the material hardness model with a thermal model to predict the anisotropy variation in the build direction [90]. The components produced by WAAM are computationally difficult to simulate because of their large size, which necessitates simplification in the modelling approach, for instance, the replacement of complex, distributed welding heads used in the welding process with a uniformly distributed heat source, the application of the finite difference method with a large mesh size, and neglecting fluid flow phenomena.

2.5 *Application of machine learning in process modelling*

In parallel with process modelling, machine learning (ML) techniques have been observed in many pieces of research to predict and optimise the quality of the final printed parts in some AM processes [91, 92]. E.g., thermal data from a physical-based model was used to train a neural network (NN) in terms of a surrogate model (SM) [93]. This model can unravel the coupled interactions between layers during a deposition in the FFF process and also makes it possible to be used for future applications such as in situ monitoring for closed-loop control. Alternatively, in a different process, an artificial neural network (ANN) was designed to predict the thermo-mechanical properties of NiTiHf samples built by SLM [94].

In a different framework, an optimal controller was designed by generating a set of training data from the metamodel and the auxiliary thermal model to adjust scan speed to control the temperature, which is responsible for track-to-track interactions [95]. The control variables can be chosen from across several parameters of the AM process depending on the influence of those parameters on the quality of the AM-produced part [96, 97]. In a different polymer-based AM process, digital light synthesis (DLS) is a method that allows for the fabrication of 3D-printed parts with higher speed and lower manufacturing costs [98]. Since it is classified as an ultraviolet-based AM process, the secondary thermal curing step plays a vital role in the final mechanical properties of the printed part. The negative effect of the secondary thermal curing step can be eliminated by applying optimisation to the secondary curing cycle [99]. Similarly, an optimisation framework was designed in a digital light processing (DLP) photopolymerisation process to obtain the optimal printing parameters such as penetration depth and critical energy for a wide range of materials like polymers, ceramics, and metal suspensions [100]. There is also evidence that shows that light self-trapping during the photopolymerisation process can deliver products with high aspect ratio structures with a wide range of biological applications [101]. Repeatedly, in the area of mask exposure methods, a process planning method was proposed as an optimisation method to determine the mirror's grayscale value for the digital micro-mirror device (DMD) technique, which utilised phenomenological and light-field models to predict cured heights [102]. The process planning method was applied to several lens designs, and accuracies of about 1-2% of lens dimensions along lens profiles demonstrated success in predicting part configuration and fine-tuning process plans. Further references and research in the field of ML applied in AM can be found in [103].

3. Innovative research in AM

As discussed in previous sections, AM offers some unique capabilities that set it apart from conventional manufacturing methods, however since emerging technologies have been developing, some drawbacks need to be addressed. The innovative research aims to enhance AM functionalities that are highlighted in the forms of multi-direction fabrication, conformal deposition, supportless AM, large-scale AM, and some other works that are not categorised within the mentioned fields above, yet they are considered innovative works in AM [104, 105].

3.1 *BAAM*

Concerning innovative research, research teams have focused on some areas that can be enumerated in this section. One of these areas that has attracted much interest is BAAM. Despite some common issues with the small-scale AM, this manufacturing technique claims new design guidelines and new design parameters that need to be taken into consideration [106]. Similarly, in this respect, three strategies, namely multi-resolution printing, extrusion diversion, and feedforward extruder control, were examined to mitigate the geometric deviations taking place in the printed part [107]. In previous research, the effect of material properties on the BAAM process has also been examined [108, 109].

3.2 *Robotics-assisted AM*

In recent years, multi-material additive manufacturing (MMAM) has been broadly utilised for the development of parts with higher functionality and complexity. To further develop this method, the m^4 3D printer integrates four AM technologies, namely inkjet (IJ), FFF, direct ink writing (DIW), and aerosol jetting (AJ), together with robotic arms for pick-and-place and photonic curing for intense pulse light (IPL) sintering [110]. The proposed innovative platform offers products with a wide range of functionalities and applications, like the manufacturing of soft robotics and flexible electronics for medical devices. In some studies, AM hybridisation has been reported to integrate one or two methods of AM along with a robotic arm to eliminate some limitations of the traditional AM process [111, 112]. In the field of applied robotics in AM, a robotic cell allows traditional AM for printing objects by using the sheet lamination technique to use different materials for different sheet layers as well as embedding prefabricated parts between laminated sheets [113, 114]. As another example, a robotised laser-based direct metal addition (LBDMA) was equipped with an 8-axis manipulator and a closed-loop control system to control the powder flow rate and molten pool size for achieving a uniform geometry [115]. LBDMA is classified as a DED process that has been in service by some industries like automotive, biomedical, and aerospace for both manufacturing and repair purposes [116, 117]. For further study, several applications of robotics in AM were surveyed [118].

3.3 *AM of embedded devices*

Embedded electronics have allowed the electronics industry to make billions of dollars over the past decade [119]. Recently, an innovative AM method, namely ultrasonic additive manufacturing (UAM), enables embedding features with better mechanical properties and in a more integrated manner in comparison with conventional manufacturing and traditional AM [120]. In this line of research, miniaturised engineering components like micropower sources [121] and microactuation devices [122] can be fabricated by using energetic material deposition systems. To build electronic devices by AM, three piezoelectric actuating systems were developed as key elements of an energetic material deposition system to deposit one type of nano-thermite material into small-scale electronic devices [123]. The systems were investigated in terms of the quality of drop formation and the energetic performance of the deposited material.

3.4 *Innovative switching between materials in 3D printing*

To facilitate the switching between materials through an SLA process, a leak-free fluidic cell was designed to switch between liquid photopolymers actively and quickly in a multi-material mask projection scanning-free SLA process [124]. Similar work has been done in [125, 126], but the process has to be stopped for switching between materials.

3.5 *Innovative methods for the continuous flow-feed in material extrusion processes*

The materials that are mainly used for 3D printing of biomedical and electronic devices have a high viscosity that sometimes leads to clogging the nozzle due to generated back pressure at the nozzle outlet and consequently stops the continuous flow-feed on the substrate [127-130]. To overcome this issue, an ultrasonic actuator was designed and connected to the nozzle to ensure continuous flow-feed during deposition [131]. Alternatively, to control the flow-feed in the FFF process, some works have been proposed to control the volumetric flow rate in such printing machines [132-135], but the major challenge is to use and mount suitable sensors at suitable places for real-time measurement of the actual extruder flow. To address this challenge, a low-cost USB microscope video camera was utilised to calculate the actual flow rate by measuring the speed difference between filament feed gear speed and filament speed for the closed-loop control of slippage during filament transport [136]. The volumetric flow rate of the extruded filament is one of the important parameters to ensure the accuracy of components printed by the FFF process.

3.6 *Designing of innovative 3D printers for the removal of the support structure*

One of the most popular limitations of printing layer-by-layer along the vertical direction is the need to generate support material when printing overhang structures. Some researchers have attempted to resolve this problem with self-supporting freeform structures without needing the support structure [137-139]. Alternatively, another solution is to employ a multi-axis 3D printer to print complex structures without the support structure [140]. For instance, fumed silica was used to ensure continuous material extrusion and curing through the hybridisation of two methods: FDM and ultraviolet (UV) assisted 3D printing. Another method to remove the support structure is to dynamically use re-orienting the build platform [141]. In this system, the layer-slicing algorithm and tool-path planning were used to eliminate the need for generating the support structure for thin shell parts. Some other research in the literature has focused on the support structure removal generated due to bridging and overhang features in the printed parts [142]. By using these methods, the time and material required for the printing process will be discounted accordingly.

3.7 *Conformal 3D printing*

Some research can be found in the literature about automated gas metal arc welding for 3D printing purposes [143-148]. In an innovative work, the new slicing system was developed based on handwritten G-code in MOSTMetalCura as a slicing software platform. Using the hand-writing G-code along with other configurations in a gas metal arc welding (GMAW) process resulted in three printed objects made of ER70S-6 steel with an improvement in the resolution of 1 mm bead widths [149]. Another application of G-code programming was observed in conformal 3D printing. A new method of AM, namely conformal AM, enables us to print a 3D model or perform coating on an available freeform surface. To implement this method, one algorithm was proposed in [150] to get both a 3D model and a freeform model as a substrate to generate G-code instructions as output and use the G-code for printing on a freeform surface. Alternatively, aerosol jet printing (AJP) can also be used for conformal AM on various flexible substrates [151].

3.8 *Hybrid manufacturing*

As discussed in the previous section, WAAM is a promising technique of DED in which wire is molten into the substrate by using an arc discharge as an energy source for the process [152, 153]. The surface roughness that is generated by WAAM reaches up to hundreds of microns or more. Hence, to improve the surface finish of the printed part, the material removed during the finishing process can be measured by a cooperative system, and the optimum material removal is obtained by using the measured data and the developed software [154].

Furthermore, the innovative research in WAAM is driven by the need to deposit a variety of alloys and combinations of them in multi-material components, e.g. bimetallic [155] or functionally graded material structures [156]. One of the upcoming innovations is using a multi-wire torch to deposit two feed wires of the same or different compositions to control the weld bead's chemistry or shape [157]. Theoretically, the materials that are welded can also be printed using WAAM; however, converting welding equipment into an AM machine needs several modifications, such as additive-subtractive AM, where the deposited material is intermediately or eventually machined [158]. In some research works, different welding processes were hybridised to enhance the range of WAAM, for instance, friction stir welding and arc welding [159] or laser and arc welding [87].

To wrap up this section, similar to the previous section, i.e., process modelling in AM, some innovative research has been carried out on the use of ML techniques in AM processes that can be found in [160-162].

4. Generative design by AM

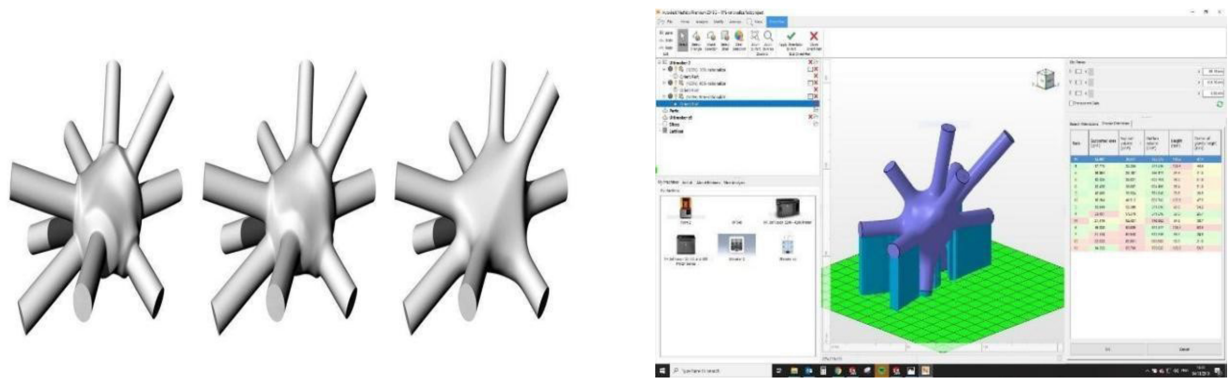
Generative design is a process that is done iteratively involving computer-aided software that generates all possible outputs subjected to real-world constraints [163]. This method will provide engineers with an appropriate platform in terms of computer-aided design (CAD) software. Combining generative design and CAD, one can create lighter parts with better structural and mechanical properties.

4.1 *The applications of topology optimisation in AM processes and industry*

Topology optimisation [164], which is known as one of the commonly used methods of generative design, has been widely explored by researchers thanks to the emergence of AM technologies. Through the literature, one can find several applications of topology optimisation that focus on the improvement of structural performance [165], heat transfer [166-169], material usage, cost, and build time [170]. However, these applications have not been restricted to the areas mentioned above and have covered a wider range in the field of engineering.

As discussed in Section 2, the residual stress-induced failure is one of the sources of distortion in the PBF process [48, 171, 172]. Topology optimisation can be used to design the support structure to mitigate the failure caused by residual stress in such a process [166, 173].

In a different application, topology optimisation has been used as a design method for generating the self-supporting structure to eliminate the need for a high-volume support structure [174, 175]. This method will help reduce the post-processing time required for the removal of an excessive support structure. In an alternative research, a topology optimisation formulation was proposed to implement a geometry filter through the optimisation process to exclude non-printable geometries that resulted in a self-supporting optimised design [174]. This method was formerly used for filtering two-dimensional (2D) geometry [176]. In the area of design for the minimum generated support structure, a rationalisation algorithm was proposed for topologically-optimised 3D-printed spherical nodal joints to control the volume of the generated support structure by a degree of rationalisation [177]. The results exhibited that the higher degree of rationalisation renders a node with smoother geometry and less generated support structure at the expense of low weight (Figure 3).



(A) (B)

Figure 3. (A) Different degrees of rationalisation for a topologically-optimised node; (B) Less generated support structure at a higher degree of rationalization [177]

Despite the appealing feature of topology optimisation, engineers and researchers cannot easily apply this method anywhere due to its manufacturing constraints. Because this method can only be realised by AM in most cases, which is neither affordable nor applicable for some manufacturers. Considering this issue, a quasi-topology optimisation method was proposed in terms of three algorithms that are seeded on a given part that is supposed to have an identical volume fraction with the equivalent software-based topologically-optimised part under the equal loading condition [178]. These algorithms can be implemented on a real part regardless of uneasy access to AM processes; meanwhile, the part can be fabricated by traditional manufacturing methods. The results also showed that the final fabricated part has better performance over the topology optimisation in terms of the less volume required for generating the support structure compared to the topologically-optimised part.

Functionally graded additive manufacturing (FGAM) is a methodology by which a variety of material compositions across a given volume can be printed using specific types of 3D printers [179]. To combine this approach with topology optimisation, the distribution of hard and soft polymers was formulated in a rectangular sample under different tensile load scenarios [180]. Multi-functionality cannot be only achieved by the FGAM approach; it can also be achieved by embedding features such as embedded sensors, circuits, or electro-mechanical devices into a given structure [112]. In this respect, a coupled structurally designed system was presented to take advantage of topology optimisation to obtain the desired structural performance on the one hand, and on the other hand, the inner structural system components and circuitry are embedded suitably into the topologically-optimised structure (Figure 4) [181].

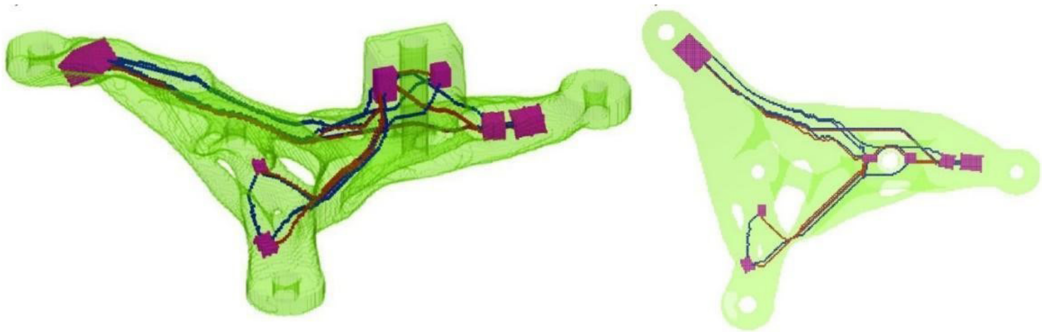


Figure 4. Topologically-optimised parts with embedded systems [181]

Porous metals have a wide range of engineering applications as they offer lightweight, high stiffness, and high damping characteristics [182, 183]. Developing these kinds of metals with chemical processes and traditional fabrication methods does not necessarily result in a product with high performance, while the performance of these parts can be controlled through AM processes. Topology optimisation has enabled us to design pore structures with optimum stiffness that are verified experimentally in terms of compressive strength [184].

To further prove the feasibility of topology optimisation to AM processes, two methods of topology optimisation for AM framework and conventional milling framework were compared to redesign a C-frame which is used in the riveting process [185]. The results of the numerical simulation revealed that the topology optimisation used for the AM solution has some structural advantages over the topology optimisation used for the conventional milling solution.

Apart from the several advantages offered by topology optimisation in AM-produced parts, some manufacturing constraints can yet be observed especially for those AM powder-based processes. One of these issues that need to be explored is the enclosed voids in which the powder is trapped. The left in the void increases the weight of the structure, which is contrary to the main objective of topology optimisation, which is nothing but weight reduction of the final part. In one of the recent studies, the enclosed voids were interconnected to generate tunnels that connected the voids with the outside boundaries of the part [186]. These tunnels allow for removing and directing the trapped powder to the outside of the part.

4.2 *Lattice structure, AM process and its applications*

Similar to topology optimisation, the main goal of designing and building parts by lattice structure is to reduce their final weight. As mentioned earlier, since the emergence of AM, these optimised complex structures, i.e., topologically-optimised parts and lattice structures, can be easily developed by AM methods compared to conventional methods. By using AM, two types of lattice structures can be built, which are volume lattice and infill lattice [187]. In the former architecture, the part is converted into a grid bounded cell with different geometries, while in the later architecture, 2D cell patterns are extruded in one direction and bounded by a solid wall. The wall in the later design assists in printing the parts with a lower wall thickness and higher resistance to deformation; in the former design, some particular cell patterns allow for high resistance to deformation as the final strength of the part is tightly dependent on the cell architecture and their grid bounds.

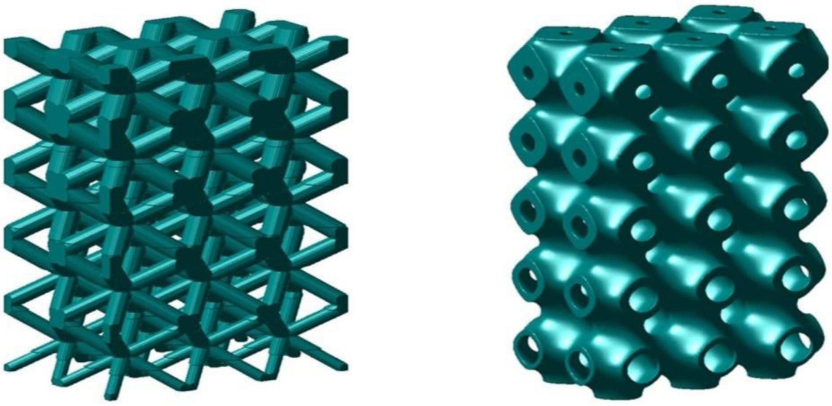
Understanding the specific characteristics of lattice structures, one can find a great number of research and engineering applications in the literature. For instance, the phononic bandgaps and their effect on vibration mitigation capability in an architected foam structure composed of hollow spheres and binders were investigated [188]. Similarly, several surface-based lattice structures were tested and developed in the form of phonon dispersion curves [189]. Through this research, it was realised that cell type, cell size, and volume fraction of lattice structures can directly influence their energy transmission spectra. For further study about passive vibration control, readers may refer to [190-192] in which the vibration control within a frequency range of interest has been broadly described for several engineering systems such as pumps, motors, civil structures, and laboratory equipment.

In a thermo-mechanical application for the parts produced by the PBF process, three types of lattice structures, namely gyroid, diamond, and Schwarz primitives, were investigated in terms of heat transfer capability [193]. As an outcome of this investigation, the material properties and volume fraction of the lattice structures were known to play an important role in this regard, however, the surface area to volume ratio that is attributed to the cell architecture can also have a slight effect on the measured conductivity.

In terms of mechanical properties in cellular structures, one study has been done showing that mechanical properties depend on some parameters such as relative density, the solid constituent, and the unit cell architecture [194]. These structures, under a certain loading condition, exhibited deformations in the form of combined bending, twisting, or stretching of the strut members. However, in a separate study, it was shown that the particular cell architecture can exhibit structural deformation due to only one dominant behaviour [195]. Apart from cell geometry parameters, similar to some AM processes of solid structures, the build orientation is an influential factor in the strength and other mechanical behaviours of the final product. An investigation was carried out on the anisotropic-induced behaviour of lattice structure during optimisation with regard to problem constraints in displacement, stress, and Euler buckling [196]. The results of this study can be used inversely to develop an algorithm for finding the optimum orientation of the part on the build platform.

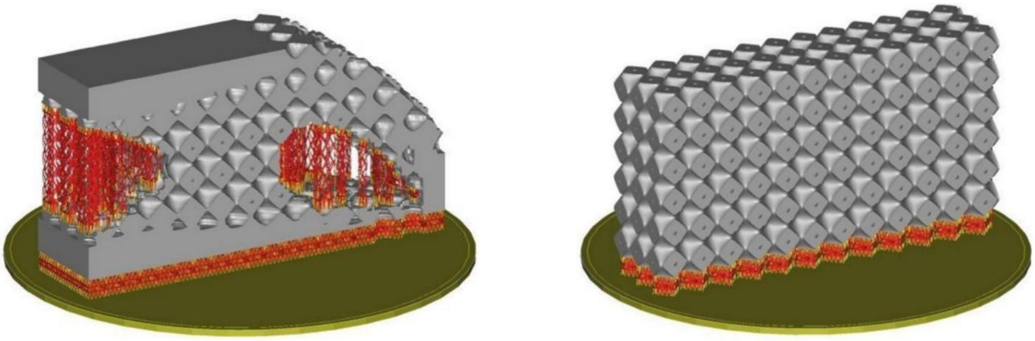
Recently, the use of cellular structures has been reported in some research related to the strength and stress characterisation of cortical and cancellous bones [197-200]. In another study, the mechanical and biological behaviour of 192 open-porous cellular structures was examined. The octahedral pillar shape was found to have the best compressive stiffness and strength, besides an increased rate of pre-osteoblastic cell proliferation [201].

In a new design method, hybrid topologically-optimised lattice structures may increase stiffness, yield strength, and critical buckling load compared to the equivalent solid structure and the pure lattice structure [202]. This methodology can also be used in functionally graded lattice structures, in which one can derive lattice structures from topology optimisation. The resultant lattice structure possesses higher stiffness when compared to the equivalent lattice structure that has not been derived from topology optimisation (Figures 5 and 6) [203].



(A) (B)

Figure 5. (A) Strut based lattice; (B) Surface based lattice [203]



(A) (B)

Figure 6. (A) Graded lattice structure derived from topology optimisation; (B) Scaled lattice structure before applying topology optimisation [203]

Finally, it is worth mentioning that the different methods of generative design are advancing through the progress in the development of CAD software, which will give more design freedom to bring a variety of design objectives and constraints into the problem to create more performative products.

5. Material characterisation in AM process

Depending on the AM processes chosen for building the parts, different types of materials can be either selected or developed [197, 204]. Since AM technologies have been advancing progress, new types of materials need to be developed to respond to the needs of the engineering world. As a result, the different characteristics of these materials need to be explored by the AM process. To explore further in this area, this section aims to cover some research works that have focused on the twofold, i.e., material characterisations and testing in some AM processes.

5.1 *Material characterisation in AM processes*

In the area of materials characterisation, a lot of experimental methods have been applied to characterise the different properties of materials in AM processes. E.g., by using one of the methods called "digital image correlation" (DIC), one of the key enablers of measuring mechanical properties such as Poisson's ratio and Young's moduli, the characterisation data like a stress-strain curve can be generated. In one study, these data were collected to improve the printing parameters of a BAAM process that was utilised for printing test coupons made of 20% glass fibre-filled ABS [205]. The strong adhesion between fibre and ABS has to be guaranteed to increase the strength of the final part [206]. The data from the DIC test is a useful measure for manipulating the print parameters and the ratio between glass fibres and ABS polymer. DIC measurements were also used to derive a 2D analytical model to relate DIC measurements to estimate planar residual stress generated by the severe thermal gradients in the SLM process [207].

Polymer-based AM has been around since the early days of the emergence of AM. In this context, comprehensive research was conducted to characterise the different properties of 3D-printed specimens such as tensile, bending, compressive, fatigue, impact, and others by using commonly used ASTM or ISO standards [82]. More comprehensively, the mechanical properties, macrostructure, and thermal properties of ULTEM 9085 in the FDM process were investigated with regard to a part orientation on the build platform [208]. The impact of part orientation and raster pattern in the FDM process was also investigated alternatively for ABS polymer [209].

Both types of polymer materials on the market, i.e., thermoplastics and thermosets, can be used to manufacture smart materials like shape memory polymers (SMP) [210]. In this respect, the 3D-printed polyurethane-based SMP specimens were tested in terms of the shape memory effect of the samples and their dependencies on the annealing heat treatment and test temperatures [211]. During the test, it was found that the annealing of the specimens at 85 °C for 2 h can improve the shape memory characteristics of those specimens.

Repeatedly in polymer-based AM, elastomeric structures are known as ideal structures to apply repetitive dynamic loading on them due to their strain-rate-dependent characteristics. The full characterisation of such structures will enable hyperelastic material modelling with viscous components [212]. This, of course, is helpful, as the experimental data for AM-produced parts is typically different from the equivalent conventionally manufactured parts [213, 214]. To further understand the strain-rate dependent characteristics and modelling, readers may also refer to [215-217].

To build composite 3D-printed objects, special printers have been developed by some manufacturers to reinforce polymers with carbon fibres. One of these printers, namely Markforged, can be used to build composites by controlling the fibre orientation, fibre type, and volume fraction. The experimental observations on tensile properties have revealed that increasing fibre content to a certain volume fraction leads to increased tensile strength [218]. These types of 3D printers have been designed and developed to address the issue called the 'stair stepping' effect that has been continuously observed in single material FDM 3D printers [219-221].

The porosity rate is one of the common defects occurring particularly in the SLM process that has a consequently negative effect on the fatigue life behaviour of components due to generated internal voids that cause stress concentration [222, 223]. In one study, the porosity rate was measured using three methods, namely the Archimedes method, the helium pycnometer method, and micrographic observations [224]. The accuracy and measurement optimality of each method were investigated and compared separately.

In alternative research, the microstructure and wear behaviours of three processes, i.e., SLM, hot pressing, and casting, for a part made of austenitic 316L stainless steel, were investigated [225]. Among these manufacturing methods, SLM was found to deliver a part with higher tribological performance. In addition to the better tribological behaviour of SLM, it was also found that there are some other advantages when compared to conventional manufacturing processes [226-229].

5.2 *Material development and recycling in AM processes*

In the area of material development, both polymer and metal materials have been developed to be compatible with the candid AM process. As the applications of AM are extended in different fields of engineering, the need for the development of materials is relatively increasing. Therefore, it yields the growth of interest in the development of 3D printable materials that are practically formulated to have a specific function, such as conductivity, elasticity, smart materials, etc [230-233]. As an example, a new type of polymer resin called ethylene glycol phenyl ether acrylate (EGPEA) was developed to be used in vat photo polymerisation processes like SLA, DLP, etc. Dissimilar to the current commercial polymer formulation, the ratio of monomers in the structure of this type of resin can be altered to achieve a wide range of elastic moduli between 0.6 and 31 MPa [234].

Plastic waste streams are the potential sources of different types of polymers in nature. However, the recycling of polymers has been a dominant issue in nature over the last few years. In some studies [235, 236], it has been shown that polymer recycling can be one of the best ways to manage plastic waste in nature other than landfilling or incineration. These materials can be recycled in different forms for use in different fields of manufacturing processes. Some of these materials, namely polyethene terephthalate (PET), polypropylene (PP), and polystyrene (PS), are processed into filaments to be used in extrusion-based AM. The blend of these materials with compatibiliser material [237-239] like styrene ethylene butylene styrene (SEBS) has returned different tensile strengths and chemical structures in terms of crystallinity in the final printed sample [240]. Similarly, the recycling of thermoplastics for use as feedstock in open-source 3D printing and the recycling of polylactic acid (PLA) for use in the FFF process was thoroughly investigated [241].

Multiple studies have been found in the literature targeting the printing of dissimilar materials such as laser-melted polymer-ceramic composites [242, 243], laser-templated ceramic-metallic nanostructures [244], and laser-processed zirconia with polymer binder [245], but the printing of metal material onto semiconductor substrates has not been fully explored. To develop a new generation of heat removal devices in an electronic package, research was carried out to bond Sn3Ag4Ti alloy to a silicon substrate by using the SLM process [246]. To increase wettability and create a strong bond between alloy and silicon substrates, a titanium-silicide interfacial layer was added.

Finally, similar to other areas of research discussed in previous sections of this paper, ML can play an important role in many applications, particularly in the prediction of part quality made via different AM methods. In one of those applications, a Bayesian network was designed to predict the quality of the part by making a relationship between four process parameters: laser power, scan speed, hatch spacing, layer thickness, and also other characteristics of the part like density, hardness, surface roughness, and ultimate tensile strength in the SLM process [247].

6. DfAM

As discussed earlier, AM technologies have enabled researchers and engineers to redesign the products with higher design freedom and customisation; however, the new technology imposes some manufacturing constraints in terms of build time, cost, build size, special materials, and pre- and post-processing operations that highlight the essential need for DfAM. In this regard, the research works can be investigated in terms of how much AM can contribute to developing more performative products compared the conventional manufacturing methods on the one hand, and on the other hand, how much AM constraints are taken into account by researchers and engineers within the design and manufacturing processes. In other words, DfAM is a process to consider the AM capabilities [248] for establishing the design rules corresponding to the manufacturing process constraints [249].

6.1 *AM: A useful tool to develop inner structures*

As it was understood, some of the existing limitations in conventional manufacturing could be overcome by using AM technologies [250, 251]. One of those limitations that can be enumerated is the need to develop parts with embedding features and inner structures. For instance, a stretchable, soft pressure sensor was built by using an in-house designed multi-material 3D printer equipped with three extrusion heads in which an ionic liquid pressure-sensitive layer was held between two carbon nanotube stretchable electrodes [252]. During the design process, some modifications were carried out on the sensor materials to adapt to the respective AM process. AM is also a suitable manufacturing method for designing and developing embedded sensors that are used as in-situ monitoring devices. However, for such flexibility, a proper fabrication strategy is required. As an example, to embed a piezoelectric sensor into a structure, the “stop and go” strategy was chosen, in which the fabrication of a part is paused to place the sensor and the remaining process is resumed to complete the final part [253]. In this process, the risk of delamination between the embedded section where the sensor is placed, and the circumference underlying the structure has to be taken into account [254]. In a different framework, to take advantage of AM in the development of an integrated part with inner structure(s), one fully integrated pressure reducer, was redesigned and developed to overcome the shortcomings of conventional pressure reducers which are currently installed on top of the end-cap of composite pressure vessels (CPVs) (Figure 7) [255, 256]. At the end of the design process, researchers and relevant industries were provided with design guides and lessons learned from the manufacturing constraints of some polymer-based AM processes.

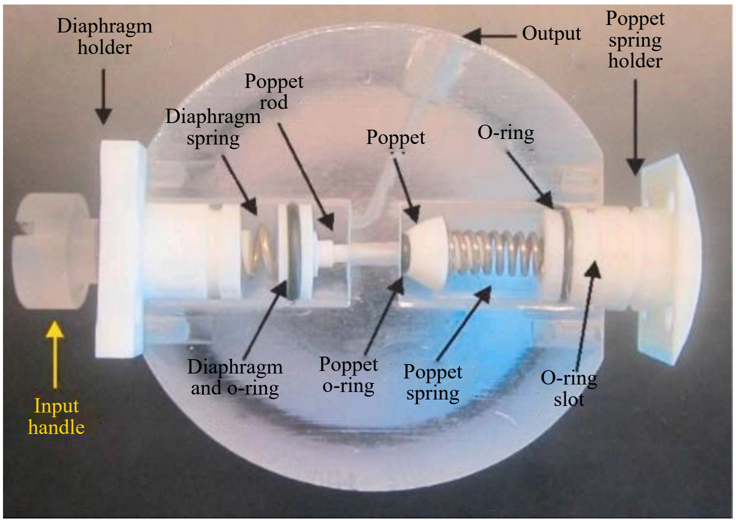


Figure 7. Integrated pressure reducer end-cap assembly [256]

6.2 *Design guides for AM processes and parts with special features*

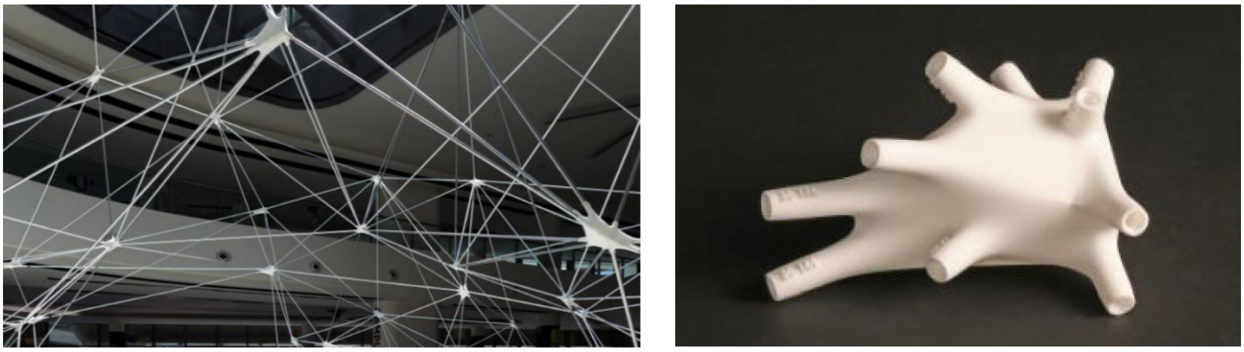
To further study, the design rules for some particular methods of AM, such as laser sintering (LS) [257, 258], laser melting (LM) [259, 260], and also material jetting [261], have been fully explored. In this line of research, a worksheet was proposed in [262] to address the common mistakes made by the researchers and engineers and to redesign the components by AM.

In addition to the manufacture of seamless parts, AM can also fabricate different types of assembly parts. In [263], AM limitations and advantages were investigated to redesign and develop non-assembly multi-articulated mechanisms in a single-step fabrication process. During the fabrication, it was understood what level of mechanical complexity could be obtained within a single-step fabrication. The development of non-assembly mechanisms has been additionally considered using different AM techniques, such as polymer-based and metal-based non-assembly mechanisms [264-266].

In a particular application, different deposition techniques, such as screen printing, spray printing, and drop casting, were investigated from the viewpoint of their influence on the resistance variation in the Wheatstone bridge of a low-cost strain sensor [267]. By using AM techniques, sensor manufacturers can produce more flexible and integrated products [268-270]. The conductive thermoplastic filaments have attracted much interest among research teams to develop printed electronic circuits in a wide range of materials with different resistivities. These materials with different mechanical properties claim particular attention and design guidelines in the design process of printed circuits [271].

Different optimisation techniques are applied to optimise the different parameters of the AM process to obtain the printed object with high quality. Hence, the weighted objective functions are one of the useful functions to define multi-objective optimisation problems. These functions can be calculated concurrently to optimise both processes and configurations. The process parameters, such as part orientation and tool-path direction, can be optimised together with the part geometry to minimise fabrication complexity in a selected AM process [272]. In the literature, a large number of research works have focused on the optimisation of AM processes to achieve different design objectives for the final printed part [273-279].

AM allows for design evolution in different industry sectors. Randomly mesh space frames are one of the structures in the civic sector that have been developed by using both polymer and metal-based AM techniques. The irregular arrangement of bars in such structures necessitates the design of nodal joints with irregular and complex geometries (Figure 8). In [280, 281], two form-finding algorithms were proposed for these kinds of nodal joints to be exclusively fabricated by the AM process.



(A) (B)

Figure 8. (A) Randomly mesh space frames; (B) Nodal joint with irregular geometry [280]

In recent years, researchers have put some effort into designing a workflow for the design and development of bio-products that are classified as ABM processes. This technique can be a potentially appropriate choice for manufacturing a complex architecture of soft tissues, particularly the breast scaffold [282]. Finally, a workflow representing a design procedure for fabricating such structures will facilitate the design process accordingly.

Considering the summary of some research works discussed above out of the myriads of works that can be found in the literature, DfAM enables us to use a set of design methods and strategies by which we can optimise the functional performance, manufacturability, reliability and the final cost subjected to the unique capabilities of AM technologies. Further methods and tools that have been used for DfAM were thoroughly investigated in [283].

7. Conclusions

In this study, the most researched AM-related works in the fields of mechanical engineering and materials science were surveyed. This paper was organised to illustrate five classes of research, namely: process modelling in AM, innovative research in AM, generative design by AM, material characterisation in AM, and finally, DfAM.

In terms of process modelling in AM, the authors attempted to provide some examples in computational modelling with a particular focus on the CAD-based models, which are considered static modelling, however, the emergence of a new technology known as "digital twins" will add extra value to the process modelling in future research and enable academic and industrial experts to have an estimation of the product's life cycle while performing real-time or dynamic analysis of the process. Combining this technology with industry 4.0 and the industrial internet of things (IIoT) will help business and industry owners to resolve some existing issues with the process modelling in AM to make it more economical and compatible with the needs of customers and stakeholders.

To investigate the importance of innovative methods in AM processes, some of the solutions were reviewed in terms of addressing the problems with the current AM technologies on the market. The research works in this area have been targeted to propose new and more functional manufacturing methods for BAAM, develop support-free objects by using multi-axes 3D printers or by adding some features to the 3D printers' software, combine AM with other forms of conventional manufacturing methods known as hybrid manufacturing, develop new forms of composite structures using multi-material AM (MMAM), and finally use robot platforms as robotic-assisted 3D printing.

In addition to the engineering applications of generative design that were reviewed in this study, future research will aim to eliminate the unnecessary operations that have been involved with the current technologies. To this end, the concept of AI-powered generative design will be a useful tool to reduce the difficulties created in the post-processing operation of 3D-printed objects that have been designed using this method.

The materials characterisation and development were briefly reviewed, through which some research works were investigated in terms of the functionality of testing methods for both polymer- and metallic-based AM processes. The structural and chemical performance of 3D-printed objects has always been a major concern of manufacturers and researchers. For this purpose, a variety of hardware and software tools will be under development by some research teams and industry sectors to create an accurate result and also evaluate the 3D printer's characteristics. Using the parameters of 3D printers together with the digital twin's technology will enable an online estimate of the different properties of the 3D-printed objects.

Finally, the DfAM topic was reviewed in terms of an investigation of some research works that were related to the creation of inner structures, assembly, and form-finding of parts with irregular geometries. Although AM can deliver higher design freedoms to the designers to create parts with higher complexity and functionality, the different aspects of AM processes have largely remained unexplored. As a result, to get the advantages of new emerging technologies, design guides and standards need to be provided.

Within this study, the authors attempted to encourage readers to get familiar with several research areas in AM technologies that contain a higher potential for exploration, innovation, and research. In addition, this article aims to improve the knowledge of both engineers and researchers who begin their research and engineering activities in the field of AM technologies and those who want to add value to the current technologies in the market.

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Conflict of interest statement

There is no conflict of interest for this study.

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