On Design for Additive Manufacturing: Review of Challenges and Opportunities utilising Visualisation Technologies

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***Abstract*—Design for additive manufacturing poses new challenges and opportunities for manufacturers to produce highly customised parts while reducing cost, production time and improving quality. Manufacturing constraints of conventional manufacturing methods, such as geometric complexity limitations and workpiece handling, have shaped the landscape of computer-aided design tools, which are therefore not suitably adapted to design for additive manufacturing. Furthermore, computer-aided design tools require a high level of training to produce appropriate models. Augmented reality and feedback technologies pose an interesting opportunity for design for additive manufacturing, whereby the interaction with 3D models in an augmented or virtual design space can provide intuitive feedback to engineers and designers, providing fast validation of designs, parametric modelling and opportunities for training and use in both professional and amateur designer communities. This paper will explore and review the opportunities this exciting new technology provides.**

Keywords— 3D printing, augmented reality, human-machine interaction, virtual environment

I. Introduction

A. Additive manufacturing: A disruptive technology

Additive manufacturing (AM) is a fabrication method, which builds objects in a layer-wise manner. This method is opposed to a number of conventional manufacturing (CM) processes, which manufacture parts by subtraction of materials, such as milling, for part production [1]. The first AM process, stereolithography (SLA), emerged in 1987 [2] and was originally used for rapid prototyping [3]. Since then, the rapid evolution of AM as an exponential technology over the past three decades has led to its adoption as a disruptive manufacturing method. AM has applications in the mainstream production of end-use functional or mass customised [4] parts and products for aerospace, medical devices and implants, and automotive industries as well as in tooling and part repair [5], [6]. The AM industry, which is comprised of all AM products and services, was valued at \$7.34 billion in 2017, with a growth of 21% in the previous year. It is expected to reach \$10.8 billion by 2020 with 80% increase in sales of metal AM systems, in part due to the uptake of affordable desktop-sized offerings and increased production capacity requirements [7].

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Though the most commonly used material in AM is still plastic, the increased interest in metal AM indicates the shift towards industrial AM as an upcoming preferred production technology. AM can be used to manufacture parts and end-use functional products using a variety of different materials including plastics, metals, ceramics and composite materials. AM utilises a broad number of technologies, from binder jetting to vat photopolymerization [8].

II. Design for Additive Manufacturing

For CM methods such as machining, material is milled from a workpiece until a solid 3D object is created. In the case of injection moulding or casting, molten material is transferred to a mould where it solidifies to create a part of a single geometry. The high cost of tooling, mould making and the customisation shortcomings for both CM processes mean that there are limitations in the complexity of designs which can be feasibly produced. Moreover, there is difficulty or impossibility in producing parts containing internal structures, of high geometric complexity or using multiple materials.

Design for additive manufacturing (DfAM) involves the considerations, which need to be made across the entire product lifecycle for manufacturing parts using AM technologies with respect to minimising cost and production time while achieving sufficient quality [9], [10]. DfAM is a branch of design for manufacturing (DfM) in which AM creates new opportunities and constraints for the design process not previously encountered with CM manufacturing processes [9]. The opportunities AM processes provide due to its layer-wise production method includes the ability to manufacture parts with high geometric complexity, production of freeform parts, entire assemblies consolidated into a single part, functionally graded parts, smart materials and even reactive shape morphing systems by the now termed '4D printing' method [11]. Though AM provides advantages compared with CM processes, it also poses new challenges and constraints. AM material feedstock, such as powder or wire, is considerably more expensive than its conventional counterpart. Part quality defects is also an issue where complex designs are tested. Those defects are usually not determinable ahead of production and there is currently much effort being made into improving standardisation of AM production and qualification methods. AM is also typically a much slower manufacturing process and is better suited to small lots of highly customised products. Conversely, mass production was previously required to achieve the economy of scale warranted to return on the high initial investment with CM, such as in mould making and tooling [12]. Furthermore, cost elements are different compared to CM [13],[14]. For these reasons, DfAM requires different approaches and tools when compared to standard DfM methods for overcoming the cognitive barriers that have gradually developed due to past CM experience [15].

A. The AM design workflow

AM part manufacture typically follows a digital workflow. In particular, the development of fast computer systems, the deployment of digital manufacturing tools and cloud computing platforms have greatly enabled the penetration of AM into the production landscape. The process begins with the conceptualisation phase where the initial idea about a part or product is developed. This phase is then followed by the detailed design phase, where a 3D model is developed, typically using Computer Aided Design (CAD) tools. Photogrammetry may also be used when a part already exists and may then be photographed, which will lead to a 3D model, which is produced from a collection of 2D photograph images. Various simulation tools, such as finite element analysis (FEA) and topological optimisation, may be used to improve the part design, analyse its expected mechanical properties and improve its expected performance. After the CAD design is generated, it must be converted to an appropriate format for slicing the layers. The formats typically used are STL, AMF, and 3MF, the former being the oldest associated with the stereolithography process. However, AMF and 3MF allow for higher fidelity and the use of multiple materials. The geometry is then sliced into individual layers to generate the instructions or machine code, typically using machine-specific software. This data is then sent to the machine and the part is manufactured. Process information, such as melt pool temperature can be retrieved from machine sensors integrated with AM equipment. This data can then be used for further development if the part quality could be improved in the future iterations by design modifications. After manufacture, post-production is usually required, which includes support removal, surface treatment, such as sanding, or coating, or treatment to improve mechanical properties such as Hot Isostatic Pressing (HIP).

As it stands now and compared to CM, the product development phases may schematically be depicted in Figure 1 where the height and width of each bar represent a rough indication of the range of options and the time requirements for development phases respectively. While more options would be available during the conceptualisation phase for products that are planned to be fabricated with AM, there would be fewer choices for prototyping and manufacturing. The number of AM materials is still limited, and the available AM technologies are capable of handling a restricted number of materials. Conversely, many different processes and materials may be utilised with CM [16].

In terms of the average fabrication process times required per piece in the development phases, the design phase could be shorter for AM since fewer constraints would have to be considered [17]. Prototyping and manufacturing with AM technologies would in principle be shorter, although the whole process and product should still be validated against technical specifications and repeatability.

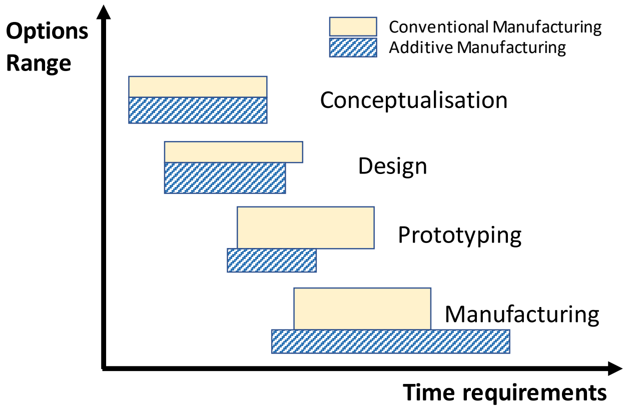

Fig. 1. AM / CM options and process time in product development phases

Industries, including the aerospace and medical devices sectors, are heavily regulated and need to validate both processes and products [9]. At the same time, AM machines in principle exhibit a higher variability, which is in most cases inherent, compared to CM processes [9].

The manufacturing process would on average be longer especially when compared with CM processes for mass production purposes, where higher degrees of automation would typically lead to shorter process times [18]. Product Lifecycle Management (PLM) strategies and platforms are continuously evolving in order to take advantage of cloud computing and manufacturing as well as of the Internet of Things technologies [19].

B. Part number consolidation and assemblies

Design for assembly seeks to reduce production costs and lead times through optimising designs for minimisation of the practical part count, assembly handling steps and includes functional analysis of parts. Standardisation of parts aids in manufacturing and assembly ease by improving repeatability and quality. Part number minimisation is desirable as it typically leads to a lower assembly cost due to consolidation to a lesser number of more complex parts. For CM processes, however, there is a trade-off between the reduced assembly cost vs the cost associated with more complex moulds and collision avoidance for machining. With AM, entire assemblies can be reduced to a single part. This can greatly lower manufacturing costs and product lead times. The GE Leap engine nozzle is an example where the metal powder bed fusion (PBF) process was used to consolidate 18 parts from an assembly into a single functional metal part. The AM part is also 25% lighter and 5 times more durable than the previous design according to GE, and can better resist clogging by carbon deposits and coking [20]. The weight reduction and increased durability are key aspects in reducing costs across the entire product lifecycle as it will reduce maintenance costs associated with clogging faults and reduce fuel consumption due to its lighter weight.

Products integrating other small parts, such as bolts and nuts or electrical / electronic components, motors, batteries and sensors have also been realised [21]–[24].

The production of assemblies with moving parts, for instance, gear trains, has also been demonstrated [25], [26]. The overall process of designing the assembly for AM is different and in the case of existing assemblies, they will normally need to be redesigned.

C. *Topological optimisation*

Topological optimisation is used to generate an optimal topology based on the solution of a material distribution problem. This problem typically involves optimising for the minimum quantity of material such that the final part will still possess the required mechanical properties. These topologically optimised designs frequently have high geometric complexity. These complex parts may be very difficult or impossible to build using CM methods due to the requirement for tool access, collision avoidance, or part removal from a mould [27]. As AM parts are produced in a layer-wise manner, the geometrical complexity of topologically optimised parts isn't necessarily a hindrance when produced by this method. AM parts can actually have a lower cost associated due to the material and process time if cavities or lesser quantities of material are used. Weight savings are typically the main goal for topological optimisation of parts rather than manufacturing costs and can have a significant impact on the product lifecycle costs, CO_2 emissions and fuel usage. This is of particular importance for aerospace and automotive applications. Weight savings of 64% have been achieved for aerospace parts designed with topological optimisation [28].

D. *Cost*

The total cost of AM part production is associated with many inputs including labor, materials and machines. Cost models should also consider the entire lifecycle costs. These include design costs, logistics, maintenance, downtime, and performance benefits. As AM parts currently have quality issues associated with defects, the build failure rate should also be appropriately embodied in cost models.

Cost models were developed for two metal AM PBF processes, Electron Beam (EB) and Laser PBF [29]. These models accounted for time, material, energy, machine costs as well as overheads, administration, utilization rates, and equipment depreciation. The cost was approximately 3 times less for the EB process due to its higher build rate. The cost of AM parts is highly sensitive to build rate. In this case, EB generally has a much higher energy input and layer thickness, 70 µm vs 20 µm for this study. Increasing feature size is, therefore, an option that could be considered by designers, where possible, as it greatly lowers the manufacturing cost.

The total size of AM parts and the performance benefits associated with their application, such as light-weighting for fuel consumption reduction, can also affect the lifecycle costs. Development costs may be too high for smaller parts to warrant design for AM, instead, CM may be less costly overall. Therefore, it is advisable to balance part sizes between small and large parts and to consider carefully candidate parts for DfAM. This is to ensure their production is not more suitable for CM [30].

A cost estimation framework was developed, which demonstrated that the AM machine G-code could be used as a reliable input for cost estimation of polymer parts [31]. This framework utilised feature vectors and a machine learning predictive model to compare similar designs and processes to estimate cost. This cost is then forwarded to the customer before the build is undertaken. This framework allows designers to quickly validate and receive feedback on the cost-effectiveness of designs. They can then be iterated such that designs which are not economically viable can be discarded or appropriately modified.

There is an endless number of combinations of designs for AM parts. Designers will, therefore, need to consider process, material and machine selection as well as part geometric complexity as each of these impact on the final part cost.

E. *Sustainability*

Sustainable product design is about creating products which, while maximizing their economic and social impacts, also minimize negative environmental impact [32]. The goal is to reduce material and energy consumption. The efficiency of converting raw material to a finished product is a key determinant of the environmental impact of the manufacturing process. When compared to AM, CM methods such as CNC milling, or tuning operations produce a significant amount of waste in the form of workpiece material and cooling/lubrication fluid. AM parts are created layer by layer and therefore produce a lesser quantity of waste material. AM waste material instead includes build supports and unrecyclable metal powder.

The design freedom facilitated by AM to the repair and reuse of parts and assemblies is a key strategy in recycling. AM processes, such as Direct Energy Deposition (DED) can repair damaged components for reuse, thus extending the overall lifecycle of a part. This method would consume only a fraction of the energy and resources required to produce new parts by CM methods [33].

Quality and consistency of AM parts depend strongly on the properties of the initial powder feedstock. The powder materials are therefore subject to stringent requirements regarding particle shape and size properties. Highly energy intensive atomisation processes are required to produce this AM feedstock powder from a bulk metal alloy of suitable quality characteristics.

In principle, AM can serve as a suitable alternative to CM and can indeed improve manufacturing sustainability indicators, especially in cases such as in light-weighting of parts used in vehicles, for reduced fuel consumption. This is a particularly important aspect in the aerospace and transport industries.

F. *Part qualification, standardisation and regulatory considerations*

The customisability of AM parts leads to challenges for standardisation, quality control, validation, testing, and regulation.

In the medical devices and implants industry, specific designs or materials used, need to meet regulatory standards according to manufacturing quality assurance. DfAM can be greatly impacted by these requirements. Material biocompatibility needs to be considered for implants, commonly, Ti-6Al-4V is used [34]. Typically, designs which are modelled from patient scans for implants, require validation [35]. Standardisation of AM processes, materials and guidelines is generally lacking, and much work is needed before they can be deemed suitable for critical industries, such as aerospace and medical devices. Standardisation of AM design guidelines is currently underway by ISO and ASTM [36]. These standards can be used to support designers and engineers for the necessary considerations for effective utilization of the capabilities of AM. Other work in the standardisation of AM design, processes and materials has been recently undertaken by ASME [37] and NIST [38].

Quality of AM parts is a major concern for designers and OEMs. The suitability of designs for AM production is typically not known before the part is manufactured. This can lead to a high failure rate for untested designs. Instead, parts are built following an open-loop control approach. This is where the part is designed and then built. Qualification and testing then follow at which defects may be found and the design may fail. Coupled with this is the difficulty in accurately correlating the process parameters with the final build quality, such that closed-loop control strategies may be implemented [39]. There is much progress required in metrology for real-time closed-loop control to be effectively realised [38]. In-situ monitoring of melt pool thermal and geometric characteristics by infrared sensors/pyrometry is frequently used for metal AM processes such as PBF [40]. This may provide a potential solution if the data generated can be analysed in real-time and corrective actions can be implemented. To this direction, a design methodology was presented for metal AM, both PBF and DED for closed-loop process control. This system integrates a fast in situ optical monitoring system with machine learning algorithms for defect detection [41].

Designers, therefore, need to consider the material, process and machine as well as the feature resolution, support method and post-processing requirements to understand the feasibility of their designs for AM.

G. Decision support systems for providing feedback to designers and engineers

The effective estimation of AM process cost, time and final product quality for determining the best AM process configuration from an array of suitable machines and available configurations for each machine is a complex problem. If this problem is solved, better product quality and allocation of resources may lead to lower production and logistics costs, lower product recalls, a higher turnaround rate and increased consumer satisfaction. Agent-based technologies could be used for integrating the design and engineering / manufacturing process. Agents are autonomous computer-based systems, which could in principle communicate with other existing software tools or systems. These include computer-aided manufacturing (CAM) systems linked to AM machines and manufacturing execution system (MES). Such agents can be used to augment the decision-making process and inform designers and engineers of the best alternative AM process configuration. User-defined product requirements, such as the part 3D model, minimum quality or feature resolution, material specifications and due date of order can be transmitted to AM machines utilising agents. The network of agents then could return to the designer or engineer the best alternative AM machine and process configuration for selection, based on the chosen criteria and their relative importance [42].

III. 3D MODELS: CREATION AND INTERACTION

A. Limitations of traditional 3D modelling approaches

One of the main limitations of AM is the gap existing between the final physical product and its 3D model. Indeed, as the 3D model used to manufacture the object exists only virtually via a CAD system, it makes interactions and modifications tedious due to the inherent difficulties of computer-based 3D modelling [43] [44], [45]. Traditional interfacing hardware (mouse and keyboard) appear to be unintuitive for creating, modifying, positioning and assembling 3D models within a virtual workspace. Therefore, there is a clear need for the development of new methods for interacting with 3D models [46], [47]. Augmented Reality (AR) and haptic feedback devices offer the most promising solutions for tackling this problem.

B. AR for better human-machine interactions in 3D modelling for AM

AR technologies, by their capability to augment the user's real world with immersive computer-generated information such as visuals, sounds and touch interactions [48], provide a promising approach for improving human-machine interactions in the context of 3D modelling for AM [49], [50]. Indeed, AR offers the opportunity for designers and operators 1) to interact in an intuitive manner, directly in their physical space; 2) to be provided with the information of the creation/production process in real-time. For instance, CAD tools can be merged with Virtual Reality (VR) or AR-based technologies, such as AR goggles, providing immersive modelling environments [51], [52] or interactive virtual assembling environments [53]. Such approaches have proven to possess significant potential for rapid prototyping of complex systems, even for non-expert users [54], [55]. Some of the possibilities are discussed in this section.

1) Virtual Environments

One of the promising approaches of AR for AM consists of the development of intuitive interfaces for novice users, e.g., based on a sketch-based prototyping tool [56] or on two-dimensional drawings [57]. Another promising approach relies on gesture recognition technologies, which can provide a new manner for interacting with 3D models [58]. Furthermore, creating models by using existing objects in the user's environment as a reference for physical guidance is also possible [59]. Nevertheless, gesture-based interactions with virtual objects can be incommodious and counter-intuitive. The use of tangible tools (such as haptic gloves or additional hardware) for creation or modification of the virtual models can make this experience more intuitive and hence, may enhance designers' productivity [60], [61].

While the 3D modelling of standalone decorative objects is a relatively accessible task, the design of fully functional artefacts interacting with other parts remains challenging. In this context, research activities have been conducted for facilitating the direct integration of mechanical or electrical components into AM parts [62], [63], [64].

2) Haptic Interactions

Haptic interfaces are devices that generate mechanical signals to stimulate kinaesthetic and/or tactile senses of the human. These devices aim at providing force feedback for improving the interactivity with a virtual environment [65].

Tactile feedback is related to sensing the pressure on the skin surface, e.g., via the use actuators for fingertips to enable tactile feedback and can thus provide a haptic shape rendering [66], [67], [68]. Kinaesthetic feedback is related to the feedback gathered from the sensors embedded in muscles, tendons and joints.

Fig. 2. Dexmo force feedback glove

This type of feedback can be used to perceive the size, weight and position of the object relative to the body, offering to the user a more realistic experience. Exoskeleton glove-based interfaces take advantage of this feedback [69], such as the Dexmo exoskeleton glove shown in Fig. 2.

Electrical muscle stimulation (EMS) is another type of interface that is based on kinaesthetic feedback that has been explored to make mixed reality experience more realistic [70]–[72].

3) Toward an integrated virtual design and physical shaping

Conventional AM is essentially a unidirectional process. First, a 3D model is shaped in the digital world. Then, the model is manufactured. While any modification of the 3D model will have an impact on the printed object, the reshaping of the physical object will have no influence on the virtual model. Experiments have been reported to provide more flexible design processes enabling bidirectional interactions between virtual models and printed goods [73], [74]. The opportunity of simultaneous 3D modelling and 3D printing by means of AR has also been demonstrated in [75].

IV. Research agenda for future progress in DfAM

Over the last years, an increasing number of research projects have emerged, attempting to streamline the process of designing and manufacturing parts and products, utilising AM technologies.

The layer-wise nature of the AM process has eliminated a number of constraints, which are typically associated with CM. This has allowed for a simpler process plan, since most, if not all production could in principle be carried out in a single 3D-printing machine. Simplified process planning further allows for a straightforward data exchange workflow and the generation of ‘digital instructions’ for the AM equipment (machine code), using off-the-shelf or proprietary CAM tools. Nevertheless, AM technologies are not expected to replace CM processes, at least not in the near future. It is rather anticipated that AM and CM will co-exist, being complementary technologies in industrial practice. Commercial hybrid AM / CM machines are already a reality and it is envisaged that AM and CM equipment will at some point be integral parts of the same production lines. This enables utilising the advantages of both technologies in a seamless manner. The higher degree of freedom provided to engineers by AM technologies for product / part design together with the maturity, robustness and high throughput of CM processes are expected to lead to the development of more complex, sophisticated and highly functional products utilising efficient production processes. Further research is necessary for effectively integrating CM / AM hybrid processes into manufacturing environments.

On the other hand, the fact, that a CAD model is normally all that is needed for producing a part with AM technologies, poses some serious risks and threats related to intellectual property protection and licensing. At the same time, ensuring that the digital model is not altered accidentally or intentionally before fabrication and that the AM process configuration retains its basic performance characteristics after it is validated, are some of the challenges that will need to be addressed by future research. AM equipment manufacturers, standardisation bodies and Computer Aided Technology (CAx) software companies have already started addressing these challenges by devising and integrating novel data protection technologies.

The development of simpler to use CAD tools allows also for the easier design of parts and products, typically utilising desktop 3D environments. At the same time, the emergence of more advanced approaches, including sketch-based modelling, gesture-based and scan-based design, and haptic interactions have proven that there are still many elements that can be improved in the process of DfM and in particular for AM.

Although these approaches and mainly the VR/AR – based ones have been under review and study for quite a long time, they still have not become mainstream and are still far from being considered widespread. Further research is required to address the lack of standard interfaces between commercial and de-facto standard CAD tools or platforms and VR/AR frameworks, libraries and external devices as well as the significant amount of time required for developing these applications, which in most cases are not generic and cannot be easily applied in different product cases or production settings.

One of the main challenges in DfAM is the significant difficulty in predicting what the mechanical and functional properties will be after AM process completion. Sophisticated web-based and cloud manufacturing technologies, including agent-based platforms, are currently being developed. These platforms can utilise more accurate models of the AM process within CAM tools. Further research into the integration of CAD and AM CAM tools is necessary to provide designers with a more precise picture of what is to be expected in AM processes with specific AM equipment.

Computing power and functionality of AR / VR equipment and devices are expected to further improve over the next years. Standardisation of software frameworks is necessary to allow for tighter integration with CAx systems. The development of software templates that could be used in specific application domains, for well-defined ranges of products and settings is necessary for further progress. These templates could help designers and developers accelerate the development and deployment of auxiliary visualisation and feedback tools. This, in turn, would reduce both time and cost associated with the overall design process.

It is important that at some point the available AR / VR frameworks achieve wide adoption and commercial success in order to extend their applicability range as well as to improve support and documentation, including the development of interfaces with standard CAD tools and platforms. A multidisciplinary approach for the demonstration of for instance haptic and visual interaction is required to increase the popularity of these technologies. At the same time, research into collaborative design, using these advanced approaches is necessary for enabling, for instance, multiple designers to interact within virtual environments. Similarly, near real-time feedback from product testers, potential buyers and consumers will provide designers with significant information that might lead to a better design for a current or following product iteration. Further development of IoT technologies will also help in that direction.

Research into the development of semi-automatic design approaches for very specific products and application domains will aid designers, where parts of the design phase will be handled by advanced algorithms. These algorithms will convert user requirements, technical specifications and users' feedback to 3D models. These will consider the technical characteristics and constraints of the AM equipment that is expected to be used for their production.

Another important aspect is the integration of diverse design disciplines (for instance, mechanical, electrical and electronic design) in the same platform. In the context of advanced visualisation and feedback technologies, future research is necessary for the development of special tools that will be capable of simulating the operation of the full product within virtual environments.

All in all, we live in quite exciting times since the available tools and emerging technologies are capable of providing designers with functionality and support that would be unheard of a few years ago.

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