ADDITIVE MANUFACTURING / 3D PRINTING TECHNOLOGY: A REVIEW

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ABSTRACT

Additive manufacturing (AM) also known as three dimensional (3D) printing is an important advanced manufacturing method that will change the way machines and consumer good are made. This technology is where the human creativity meets technology. AM allows product to be fabricated from the 3D computer aided design (CAD) model of the part, no matter the complexity, through addition of materials one layer at a time until the building is completed. In this article, the seven classes of AM, the advantages in the additively manufactured products as compared to the existing counterparts are highlighted and some of the research efforts in this technology are presented. Some of the problems and the future research need in this field are also presented.

KEYWORDS: AM, Laser metal deposition, Selective laser sintering, Sheet lamination, Stereo lithography.

1. INTRODUCTION

Additive manufacturing (AM) is an advanced method of manufacturing that builds up components into complex shape by adding materials layer after layer. This is unlike the traditional manufacturing process that involves a number of manufacturing processes including material removal to achieve the complex shape desired. The first AM technology appeared in the 1987 when stereolithography was invented by Hull of 3D systems [1]. The next challenge for the researchers was the development of materials for the new technology. This resulted in the development of acrylate resins by 3D systems in conjunction with Ciba-Geigy in 1988 [2].

Similar technologies were also commercialized by NTT Data CMET in Japan and Sony/D-MEC in 1988 and 1989 respectively. The technologies were called solid object ultraviolet plotter (SOUP) and solid creation systems (SCS) by NTT and Sony respectively. In 1988, the first epoxy resin used on stereolithography machine was developed by Asahi Denka Kogyo [2]. Also, in 1989, Japan synthetic Rubber and DSM Desotech produce resin for the stereolithography equipment [2]. Through research and developments, a number of resins have been developed for the system. Another important AM technology, namely fused deposition modelling (FDM), was commercialized by Stratasys in 1991. Solid ground curing and laminated object manufacturing were commercialized by cubital and Helisys respectively. Selective laser sintering and solid form stereolithography system were commercialized by DTM and Teijin Seiki respectively in 1989 and 1992 [2], [3].

In 1998, Optomech commercialized its laser engineered net shaping (LENS) which was based on the technology that was developed at Sandia national laboratory in the mid-nineties. Many additional AM technologies have been introduced since then and before the end of last decade, over thirty AM technologies have already appeared [4].

A number of modified AM technologies have been developed and, with patents' expirations, the prices of AM equipment have witnessed a downward review making them more and more affordable. The large number of AM technologies was beginning to confuse the user which resulted in the classification of AM technologies into seven classes [5].

In this paper, these seven classes of AM technologies are presented. The advantages in the AM products over those manufactured through existing manufacturing processes are highlighted. Some of the research works in AM technologies are presented. The current problems and the future research needs in this field are also presented.

2. CLASSIFICATION OF ADDITIVE MANUFACTURING TECHNOLOGIES

Additive manufacturing technologies are grouped into seven main classes namely: binder jetting, direct energy deposition, material extrusion, powder bed fusion, sheet lamination, vat photo-polymerisation. Each of these classes of AM technologies is briefly explained in the following subsections.

2.1. Binder Jetting

Binder jetting is a class of additive manufacturing where the technologies in this group create three dimensional (3D) objects by placing a binding agent on powder stock material in order to join the powder particles together. The powder materials used in this class of additive manufacturing include metals, polymers and ceramic materials [6]-[11]. The AM technologies that belong to this class include 3D printing, ink-jetting, s-print, and M. print. The schematic diagram of this class of additive manufacturing processes is shown in figure 1.
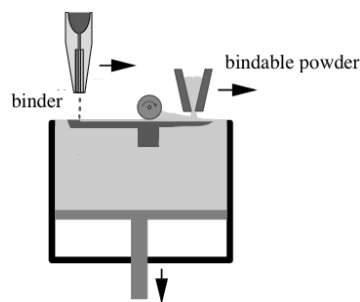

Fig. 1. Schematic diagram of Binder Jetting

2.2. Directed Energy Deposition

Directed energy deposition is a class of AM technologies that produces 3D object by using thermal energy to melt or fuse materials together following the path dictated by the 3D path. The thermal energy first creates a melt pool on the surface of the substrate material, and then the deposited material is introduced into the melt pool. The materials used in this class of AM technologies include powder and wire of metals, and ceramic materials [12] - [19]. The AM technologies that belong to this class of AM technology include: direct metal deposition, laser metal deposition process, electron beam direct melting and laser consolidation. The schematic diagram of the process is shown in figure 2.

2.3. Material Extrusion

Fused deposition modelling is an additive manufacturing that belong to this class of AM technology. It creates 3D object by ejecting material through a nozzle and depositing it layer after layer to

produce the solid object desired from the 3D model of the part. The materials used in this class include polymers and metals [20] - [23]. The schematic diagram of material extrusion class of AM technologies is shown in figure 3.
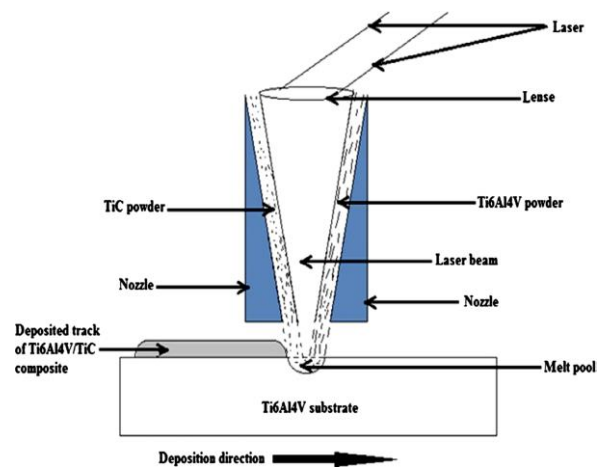

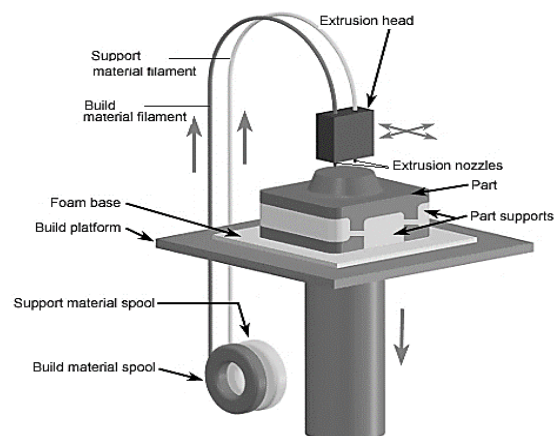**Fig. 2.** Schematic Diagram of Directed Energy Deposition Process [19]

Fig. 3. Schematic Diagram of Material extrusion

2.4. Material Jetting

Material jetting produces 3D object by depositing small droplets of build material that is then cured by exposing it to light [24] - [28]. This process is repeated layer after layer until the part building is completed. The materials used in this class of Am technologies include photopolymer and wax. A photopolymer is a type of polymer that changes its physical properties when exposed to light. The AM technologies in this class include polyject, ink-jetting and thermojet. The schematic diagram of material jetting is shown in figure 4.

2.5. Powder Bed Fusion

This class of AM technology produces 3D objects by preplacing powder on the build platform called the

powder bed, and then the thermal energy is used to fuse or melt the powder together along the path of the thermal energy. The materials used in this class of AM technology are metal, ceramic and polymer [29].
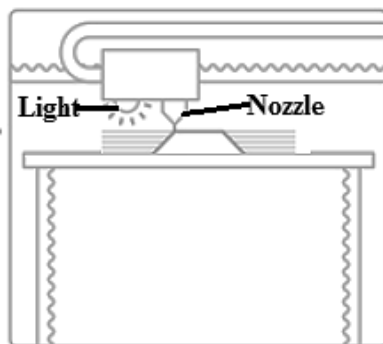

Fig. 4. Schematic diagram of Material jetting

The AM technologies that belong to this class of AM technologies include: direct metal laser sintering, selective laser melting selective laser sintering, electron beam melting [30]. The schematic diagram of powder bed fusion is shown in Figure 5.
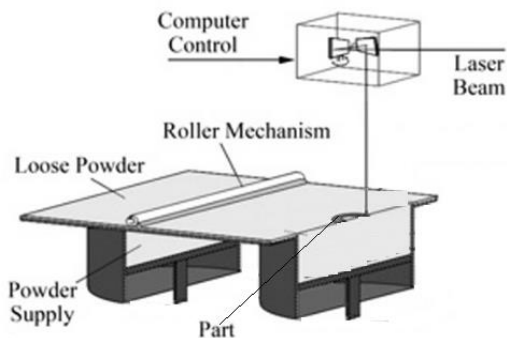

Fig. 5. Schematic diagram of powder bed fusion

2.6. Sheet Lamination

This class of AM technologies produces 3D objects by binding material together in layers and trimming the sheets as required, to produce the complex shape. Materials used in this class of AM technology include metals, ceramic, wood and paper [31] – [40]. The AM technologies that belong to this class of AM technologies include laminated object manufacture and ultrasonic consolidation. The schematic diagram of the sheet lamination is shown in Figure 6.

2.7. Vat Photopolymerisation

Vat photopolymerization is a class of AM technologies that achieve building of 3D parts by selectively curing layers of photopolymer materials based on the path dictated by the 3D model of the path. The AM technologies in this class of AM technologies include stereolithography and digital

light processing [41], [42]. The schematic diagram of vat photopolymerisation is shown in Figure 7.
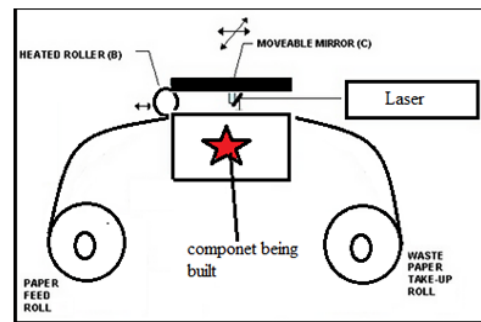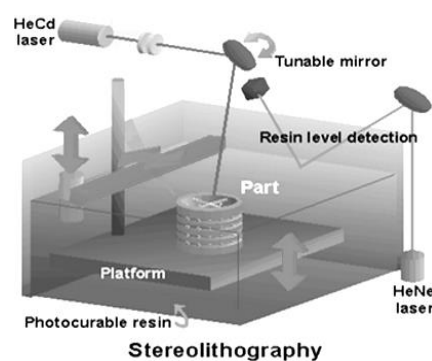

Fig. 6. Schematic diagram of sheet lamination

Fig. 7. Schematic diagram of vat photopolymerisation

3. 3D PRINTING USED IN PRODUCTS AND EQUIPMENT MANUFACTURING

A typical car is made up of over 30,000 different parts that are made using different manufacturing methods. This occurs as a result of available traditional manufacturing processes which necessitated the breaking of a complex part into smaller parts resulting in a large number of parts. With additive manufacturing technology, a complex part can be produced as a single part. Other benefits of employing the AM technology for production of car parts include the reduction in weight due to elimination of additional materials used for joining and assembling of parts. Reduction in material loss is another important benefit.

The actual materials needed for the part are used, since the part is built up by adding material layer after layer. It also makes it possible to create customized 3D printed car parts. It offers the opportunity to easily replace spare parts and saving time in part production. The unibody of a car is the spine of any car. It is the part of the car that absorbs pushes and bumps that the car may experience.

The complex manufacturing methods that were used in producing the unibody makes it difficult to repair, hence additive manufacturing is an ideal manufacturing process for the unibody because of its ability to replace damaged parts. AM processes are

also used to produce Interior parts such as dashboard, gauges, dials, switches, air conditioner vents, door handles, floor mats, and seat belts which can fully be customized. Porsche is using additive manufacturing process to manufacture its rare vehicle's spare parts. Because these vehicles are customized and the original spare parts are not being produced any longer, they are now produced by additive manufacturing technology. Porsche finds the use of additive manufacturing process more economical. Rolls-Royce is also taking advantage of additive manufacturing technologies for the production of their customized luxury cars that will allow drivers to completely personalize their cars. The Rolls-Royce 103EX has design that will allow for the inside and outside to be customized by the driver.

The mass customization advantage that is offered by additive manufacturing technologies [43] provides the enabler technology for the automobile industries to satisfy their wide range of customers' need. BMW creates customized service for BMW MINI users where they can indicate the options they will like to have implemented or specific parts of the BMW MINI. A host of other automobile manufacturers are also taking advantage of additive manufacturing technologies for the production of their car parts.

Fig. 8. Titanium based-alloy satellite bracket made by Additive Manufacturing [44]

The light weight offered by the additively manufactured part, a typical part as shown in figure 8, contributes immensely to the low fuel consumption in any moving or flying parts, hence reducing the carbon footprint of these industries. Aerospace industries are greatly benefiting from additive manufacturing technologies because parts can now be produced with improved buy-to-fly ratio. Additive manufacturing technologies are now being used to produce aerospace engine, turbine parts and cabin interior components. AM technology can be used to produce cost effective functional parts with complex shapes that comply with aerodynamic properties. Leading aerospace companies like Boeing has integrated additive manufacturing into their production run. The aerospace industries are able to achieve up to 60% weight reduction in their parts produced using

additive manufacturing technologies. The medical and petrochemical industries are also having their fair share of additive manufacturing technology. The highly customized medical implants are produced at no additional cost using additive manufacturing technologies making the technology the number one choice of manufacturing in the industry.

4. RESEARCH ADVANCEMENT IN ADDITIVE MANUFACTURING TECHNOLOGY

Currently, there are a number of research works in additive manufacturing technologies. Most of these research works are carried out for better understanding additive manufacturing processes while orders are aimed at solving problems that are preventing a number of AM technologies to pass certification processes. Some of these research efforts are presented in this section.

The challenges of most AM parts include porosity and defect. Zanini *et al.* [45] used Micro X-ray computed tomography to study dimensional evaluations, porosity analysis and surface topography measurements of AM parts. The authors carried out experimental investigations on different selective laser melted of Ti6Al4V. The results revealed that the thickness analysis was found to be sensitive to the surface quality. The search angle optimization was also found to improve the surface topography and the thickness analysis samples. The investigation also revealed that for larger pores it was possible to evaluate internal porosity with diameter below 5 μm and for volume below 5 %.

Gao *et al.* [46] presented the barriers, evolution and future research trends in additive manufacturing. The research revealed that additive manufacturing has the potential to re-imagine current research and provide new avenues for research exploration.

Yadollahi and Shamsaei [47] also presented the various mechanical characteristics of metallic parts produced using additive manufacturing and the challenges and opportunities in fabricating materials using AM technology with increased fatigue resistance. The study suggested that standards for mechanical testing methods, specimen design procedures, and post manufacturing treatments need to be revised for AM parts.

Stavropoulos *et al.* [48] presented a roadmap for the industrial application of AM by addressing the challenges that hindered it with a Hybrid of solution framework that is tailored to the industrial need.

Ford and Despeisse [49] studied the sustainability of additive manufacturing processes and found that additive manufacturing has benefits in product and material life cycles due to product and process redesign. The authors highlighted the advantages and challenges of additive manufacturing on sustainability.

Krujatz *et al.* [50] conducted a review on the

historical background, their current implementations and some of the major challenges of AM in biotechnology/bioprocess engineering. The capability of additive manufacturing technologies in handling more than one material at the same time gives rise to the opportunity of manufacturing components that are made of composite and functionally graded materials (FGM). This huge benefit is achieved in a single manufacturing run. A number of research works on composites and functionally graded materials using AM technologies are reported in the literature. Some of the works include those of: Obiolodan and Strucker, [51]. These authors studied the fabrication of composites of 10 and 5w%TiC /Ti6Al4V using laser metal deposition process.

Popoola *et al.* [52] studied alloys of TiC/Ti6Al4V composite at various TiC compositions. Wang *et al.* [53] also investigated additive manufactured TiC/Ti6Al4V composite at different TiC compositions. Ochonogor *et al.* [54] studied the effect of the TiC ratio on the wear resistance performance of Ti/TiC composite, using laser metal deposition. Some authors have also studied functionally graded Ti6Al4V/TiC composite [51, 55, 56]. The importance of producing functionally graded parts directly from the 3-D CAD model in one single step has been the driving force for the research interest in FGM, by using laser metal deposition (LMD) process.

The earlier works tried to establish the feasibility of making FGM through the LMD process [57]. In a study conducted by Zang *et al.* [56], functionally graded Ti/TiC was deposited on a Ti6Al4V substrate. They first established the processing parameters for various volume fractions of Ti/TiC composite in their preliminary works. They used the results from their preliminary work to successfully deposit a thin wall of functionally graded material – by adjusting the processing parameters during the deposition process. They showed that the wear-resistance performance of the Ti6Al4V substrate was improved with the addition of TiC. They also showed that FGM can be produced with LMD without a discrete interface. In their preliminary studies, the method used to obtain the optimal process parameters for the various premix of Ti and TiC was not clear. Also, premixing the powder before deposition can result in having the powder with higher density to be deposited first, before the less dense powder. And this could affect the results (density of Ti is 4.5 g/cm^3 and that of TiC is 4.93 g/cm^3). This could be one of the reasons why they observed cracking in the deposit at 40% TiC.

In another study performed by Wang *et al.* [55], a functionally graded material of Ti6Al4V/TiC was deposited. They used Ti6Al4V wire and TiC powder; and the two materials were fed simultaneously. They achieved the compositional grading by keeping the wire feed rate of Ti6Al4V constant; while they varied the TiC powder feed rate. Also, other processing parameters were kept constant. They did not consider the effect of processing parameters on the resulting deposit properties. Liu and DuPont [58] successfully deposited functionally graded material of Ti/TiC composite using LMD. They relied on the controller in LENS, which monitors the melt pool area and controls the laser power to achieve a constant melt pool area, for the deposition of their FGM. The melt pool area control in LENS is intended to control the dimensional accuracy in the deposited part. Shah [59] deposited functionally graded material of Inconel 718 Nickel alloy and Ti6Al4V using the laser-metal deposition process. The effect of the laser pulse parameters and the powder flow rate on residual stress was studied. The study found that the layer thickness plays an important role in the crack behaviour of the functionally graded material produced. The effect of the powder flow rate on the melt pool size was also studied; increasing the powder flow rate was found to increase the melt pool size. Lin *et al.* [60] used the laser-metal deposition process to produce functionally graded material of stainless steel-SS316L/super alloy-Rene88DT. They investigated the solidification behaviour and the microstructural evolution of the FGM. Epitaxial growth and columnar dendrites' microstructure were also observed. *Insitu* functionally graded material using the laser-metal deposition process was also studied in the literature. Qin *et al.* [61] produced *in situ* functionally graded TiC reinforced titanium matrix from Ti and Cr$_3$C$_2$ powder using laser metal deposition process. The functionally graded material was achieved by changing the powder flow rate of the Ti and the Cr$_3$C$_2$ powder. The microhardness and the wear-resistance properties were studied. The microhardness and the wear resistance were found to be greatly improved.

The problem with functionally graded material produced *in situ* is that the magnitude of the reinforcement achieved will largely depend on the reactions taking place during the deposition and cooling process. It would be very difficult to achieve a desired percentage ratio of the reinforcement and the matrix. Also, there is no doubt that different Ti6Al4V/TiC ratios would have different optimal process parameters; but these were not considered in the above studies. It has also been demonstrated that having powders placed in separate hoppers is an effective way of producing composite, with proper composition control, and without segregation due to difference in the densities of the powders [62]. Javaid and Haleem [63] presented research works on the application of additive manufacturing in orthopaedics. The study showed that research on additive manufacturing applications in the field of orthopaedics is on the increase, especially for patient-specific orthopedic applications, such as in lumbar discectomy, pelvic surgery and large scapular. It revealed that an orthopaedic surgeon can convert his or her need into a reality by using computer-aided design (CAD) model of the human part and then

produce the needed part using the AM technology. Also, AM are used to produce orthopaedic implantable medical devices. Additive manufacturing technologies can be used to fabricate on-demand production of customized surgical instruments, 3D printed bone, and biologic implants that are used in orthopaedics restoration of function and original structure.

Allevi *et al.* [44] investigated stress Analysis on a titanium based-alloy space bracket, produced using Electron Beam Melting (EBM) using a Non-Destructive Dimensional Measurement (triangulation system for reverse engineering). Araya-Calvo *et al.* [64] also studied mechanical behaviour of additively manufactured part of polyamide 6 (PA6) reinforced with carbon fiber. The influence of reinforcement pattern, reinforcement distribution, print orientation and percentage of fibre on mechanical properties was investigated. The study revealed that a maximized flexural response was achieved with 0.4893 Carbon Fibber volume ratio, concentric reinforcement and perpendicular to the applied force, producing a flexural modulus of 14.17 GPa and a proportional limit of 231.1 MPa.

Reddy *et al.* [65] conducted a research to identify the areas that are hindering the adaptability of Metal Additive Manufacturing to the industries. The constrains were identified as part identification, static strength analysis, design intent, materials properties, and process parameters. An aero structural part, Flap Lever, was developed as 3D model by using CATIA software, was selected for this study. Static strength checks were performed on the specimen, followed by optimization with respect to the design intent of weight optimization and savings on build to fly ratio, fuel costs, time to market, etc. The Flap lever component was successfully optimized based on the design intent. The result showed that the optimized part has a reduced weight of about 2/3rd of its initial volume and better margin of safety. The literature is very rich in terms of research on additive/3D printing that can further be consulted [66]-[72].

5. FUTURE RESEARCH DIRECTIONS

The advantages offered by additive manufacturing technologies have made them an important future manufacturing process, and continuous research effort are constantly being invested to improve the technology and properly position it for the 4th industrial revolution. AM technologies have lots of advantages that include their ability to fabricate very complex and smart structures with embedded components such as sensors, actuators or capillaries for temperature control and the short lead time offered by additive manufacturing. The ability to fabricate parts such as medical implants directly from 3D-data, has been obtained by using scanning devices as computerized tomography instruments, laser scanning devices or magnetic resonance imaging. Despite these exciting properties of AM technologies, there are still many challenges facing the use of AM technologies. These include the time consuming and costly post-fabrication processes such as polishing. Also, the need for high level of part accuracy and proper part material certification is still a big issue. There is a need to expand the limited range of materials used in AM processes that requires the researchers to start thinking outside the box because with AM technologies our orientation should change completely from the traditional ways of doing things. AM technologies have helped to remove many limitations of the traditional ways of designing and product manufacturing. There is a serious need in the area of process control and in sensor systems development which will help to reduce process variability across different AM devices. Researchers should continue to explore the benefits of heterogeneous material property for better design performance in AM technologies. This may result in an overwhelming benefit that we have never imagined. Also, future research should be directed towards how complex multimaterial objects can be generated simply by specifying design performance during the design process using efficient simulation algorithms. There is a need for other methods to develop geometric computation for 3D models for additive manufacturing. Researchers should look up to nature for inspiration and ideas such as self-assembly, biologically and ecologically inspired printing approaches. More research effort is needed in AM-based repair/remanufacturing. This will help to further improve existing product life and material life cycle. The future of manufacturing relies on AM technologies and this technology needs to live up to the expectations placed on it through active research that will further improve and position AM technology at the fore front. Four dimensional (4D) printing is a value added technology that helps to create reconfigurable AM or 3D printed parts. 4D Printing technology is achieved by using programmable and advanced materials to produce a 3D printed component that is capable of changing its shape and configuration in predetermined conditions such as temperature and humidity in order to perform different functionality. In 4D printing, through computational folding, objects larger than the AM machine envelope can be printed as a single part and then change shape, shrink, fold and unfold, into their required secondary shape. This capability brings about the flexibility that is not available with the AM produced part. There is a need for further research works into smart material development to further expand the benefit of additive manufacturing technology/3D printing and 4D printing. With further research work on 4D printing, a number of applications will evolve and the current application of 4D printing (such as architecture, and biomedical) will expand.

6. CONCLUSION

Additive manufacturing, also known as three dimensional (3D) manufacturing, was the main subject of this paper. Due to the flexibility offered by the additive manufacturing technologies, they are favoured in many industries, including automotive, aerospace and medical industries. The applications of 3D printing, especially in automotive and aerospace industries, are preferred to be used, due to the light weight of the components achieved. Light weight is important in moving and flying actions, because the lighter the moving parts are, the better the fuel efficiency.

Some of the research efforts made in this field, as well as several future research directions are emphasised, too. To enable the 3D printing to live up to its expectations in the next industrial revolution, there is a need for further research activities which are highlighted in this review.

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