Revolutionary Additive Manufacturing: An Overview

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Abstract

Consumer demands are moving away from standardized to customized products, as such, the evolution of alternative manufacturing technique has become imperative. Additive Manufacturing (AM) is a process of building components layer by layer as against the traditional methods which are subtractive in nature. Though, AM offers lots of advantages over traditional manufacturing techniques, its wide application is still however at the infancy phase. Despite all the benefits derived from AM technology, there are still a lot of unresolved issues with the technology that has hindered its performances thereby limiting its application to high tolerant jobs. This paper takes a look at some important AM technologies, some problems currently facing additive manufacturing technology at large and proposes some solutions to these problems. A major known drawback in AM is poor dimensional accuracy and poor surface finish, only the layer height and melt pool temperature are controlled to solve this problem in the literature. The stair-stepping effect in adaptive manufacturing is rooted in a natural phenomenon of surface tension which is the cause of the poor surface finish and in combination with other factors is responsible for the poor dimensional accuracy. An adaptive controller is proposed for removing stair-stepping effect to improve the dimensional accuracy, the surface finish and the mechanical properties of the components. Successful implementation of these proposed controllers will greatly improve the performances of AM technologies and also aids its wide application for end use products. Further research works are also suggested to improve the overall AM performances.

Key words: Adaptive control, additive manufacturing, AM performance, AM technologies, poor dimensional accuracy, poor surface finish, rapid manufacturing, and stair-stepping effect.

INTRODUCTION

Shaping and forming processes are done through different stages, ranging from casting to cutting at various stages depending on the complexity of the component being manufactured. The traditional method of shaping is through material removal which is referred to as Subtractive Manufacturing (SM) (Baufeild et al., 2011). Examples of SM processes include: milling, drilling and grinding. Another traditional forming process is referred to as Formative Shaping (FS) also known as Compressive/consolidation process (Baufeild *et al*, 2011; Boboulos, 2011; Reeves, 2008). In FS processes, components are produced through application of pressure. Examples include: forging, pressing and bending. Subtractive and formative manufacturing processes are characterised as energy intensive, cumbersome, involving a number of steps and for components with complex geometry as there is need to split the components into various parts that are assembled at a later stage (Kruth, 1998; Fink, 2009). These traditional manufacturing processes waste a lot of materials, time and energy (Fink, 2009; Laeng *et al*., 2000; Ploude, 2003). A great deal of these energies are used for scrap disposal and making the overall cost of production to be very high.

Another major drawback of these traditional manufacturing processes is high lead time involved in the introduction of new product from concept, prototype, to final introduction to the market. Hence, there is need for an improved manufacturing process that can offset some, if not all of the drawbacks of the traditional manufacturing processes (Ippolito, 1995). Also, the recent trend in consumer demand is moving from standardised products to customised ones (Malhotra, 2010; Arabe, 2002). To remain competitive in this highly dynamic market, there is need for Flexible Manufacturing System (FMS) which will be able to cope with the constantly changing consumer demand. Also, there is need for a manufacturing process that will reduce the lead time required for introduction of new product that keeps material usage on a low side. Thus, Additive Manufacturing (AM) can be considered promising in this regard (Osakada and Shiomi, 2006; Yan *et al*., 2009).AM is the term used to describe a group of technologies such as energy, Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), printing technology, Powder Metallurgy and Control used in producing physical objects directly from the CAD files by incrementally adding material in layer-wise manner such that the object grows from scratch to completion (Beaman *et al*., 1997; Chua and Leong, 1997; Hopkinson, 2010; Kruth, 1991; Lu *et al*., 2001; Mazumder and Song, 2010;). AM is seen as the most exciting, emerging and enabling technology of the 21st century (Arabe, 2011). It offers high geometrical flexibility that is time and cost saving (Baufeild *et al*., 2011). It eliminates environmental polluting processes (through lubrication) and energy intensive processes (Sreenivasan *et al*., 2010). In addition, AM is a lean and agile technology (Reeves, 2008). It is a generic name that encompasses Layer Manufacturing Technology (LMT), constructive manufacturing, generative manufacturing, Direct Digital Manufacturing (DDM), Freeform Fabrication (FFF), Solid Freeform Fabrication (SFF), among others (Shellabear *et al*., 2004; Wohlers, 2002).

AM processes were initially used to make prototypes when it was referred to as Rapid Prototyping (RP) (Santosa *et al*., 2006). Rapid prototyping is used to produce prototypes that would have taken days, weeks or even months with a large number of steps or stages, in few hours and in one step. This exciting technology has seen lots of improvements making it to evolve into another technology called Rapid Tooling (RT) (Kruth *et al*., 2005; Louth *et al*., 2010). As against RP that was used to produce concept prototype, formfitting and assembly testing; RT technology is used to produce tools for other manufacturing processes (Ryan *et al*., 2008). Due to numerous improvement and confidence in performance of AM technologies, it has now being used in the creation of end use product. Using AM in the manufacturing of end use part started in the late 1990's and it is known as Rapid Manufacturing (RM) (Hopkinson *et al*., 2005). RM for making end use products is predicted to be the future technology (Rudgley, 2001). Various fields are reaping the fruit of AM especially in medicine (Chishti *et al*., 1999; Wohlers, 2009; Master and Mathey, 2002), automobile and aeronautics (Pham *et al*., 2004). Figure 1 shows these trends in AM processes and their applications.

<Insert Figure 1>

RM is a very interesting technology as functional end use products can be directly manufactured from CAD files, thereby eliminating many steps that would otherwise be required when using traditional manufacturing methods. Apart from this advantage, complex shapes can also be manufactured in one simple step which would have required splitting into various parts that are later assembled if traditional techniques were used. RM tends to be a promising future industrial revolution (Feenstra *et al*., 2003). With all these exciting features of RM technology, there are still a lot of works to be done to bring the technology to wide acceptance (Mahamood *et al* 2012).

This study takes a look at some important AM technologies and their applications. Current problems with AM technology such as poor dimensional accuracy and poor surface finish which has limited its use to high tolerant jobs. Some solutions to this and other problems have been proposed in this study in order to improve AM performances that will aid its wide acceptance. Further research suggestions are also highlighted.

The content of this paper is organised as follows: the brief background of Additive manufacturing is presented followed by classification, advantages and areas of application of AM. Some additive Manufacturing technologies are also discussed, followed by some current issues with AM technology.

The way forward and suggestion for future work are presented and the paper ended with concluding remarks.

Background of Additive Manufacturing

AM simply means forming of object by adding and bonding material in layer-wise fashion. Additive manufacturing is defined by American Society for Testing and Materials (ASTM) as the process of joining materials from 3D model data in layer by layer fashion to form objects (wikipedia, 2012). The demand for additive manufacturing products and services has been impressive over its twenty five years history though AM earliest root was traced to topography and photo sculpture dated back to the 1800s (Wang, 2009). The last two and a half decades has witnessed research activities in the area of various additive manufacturing processes which has been directed to tackle a number of problems in a different number of ways. Additive manufacturing technologies are used in a variety of industries, including the aerospace, automotive, biomedical, architectural, consumer customised product and military industries. Examples include: aerospace exhaust pipe, dental implants, etc.

Classification of Additive manufacturing

There are two major classifications of additive manufacturing namely: Laser Additive Manufacturing (LAM) and non-laser based additive manufacturing. These classifications are hereby discussed.

Laser Additive Manufacturing (LAM)

Light Amplification by Stimulated Emission of Radiation (Laser) provides a high intensity and a highly collimated beam of energy that can be quickly moved in a controlled manner with the help of directional mirrors or lenses. The use of laser in additive manufacturing is basically for curing or heating. In photopolymer resins application for example, the requirement from laser energy is to cause the liquid resin to solidify, or “cure” (e.g. stereolithography (SLA)). Heating is required for cutting through a solid material (e.g. Laminated Object Manufacturing (LOM)) or for melting powdered material (e.g. Selective Laser Melting (SLM)) or fusing powder (e.g. Selective Laser Sintering (SLS)) and sheet materials (e.g. LOM). Laser is required to carry sufficient thermal energy to be able to achieve the above mentioned applications. In powder processing application, the basic requirement from laser is to melt the material in a controlled manner without creating heat build-up. When the laser energy is removed, the molten material rapidly solidifies. Majority of the AM processes are laser based. They include: Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Laser Engineered Net Shaping (LENS). Laser AM is classified based on the state of the material used in the manufacturing process namely: solid, powder, molten and liquid states materials. A lot of laser AM applied to metals especially titanium and its alloys has been reported (Blackwell and Wisbey, 2005; Cai *et al*., 2007; Sexton *et al*., 2002; Wang *et al*., 2006; Xue, 2009; Zang *et al*., 2009; Zang *et al*., 2011). Ti–6Al–4V is one of the most common alloys used in the aerospace applications (Peters and Leyens, 2001). The laser additive manufacture of small and medium-sized Ti–6Al–4V parts for aerospace industry is an important research area. Classifications of AM and LAM are presented in Figures 2 and 3 respectively.

<Insert Figure 2>

<Insert Figure 3>

Additive Manufacturing technologies

There are over thirty AM technologies commercially available at present (Banerjee, 2009) with some still at developmental stages (Boboulos, 2011). There are five basic steps that are common to all additive manufacturing processes. They are explained briefly below:

- Receiving Data from a CAD model e.g. AutoCAD, Solid Edge, Unigraphics, Pro Engineer, Rhino, 3D Studio, CATIA, and Solid Works etc.

- Conversion of the CAD data into a Standard Triangulation Language (STL) format (Boboulos, 2011). STL format represents a three dimensional surface of an assembly of planar triangles containing the coordinate of their vertices. Conversion to STL file format has been adopted as a standard for consistency. Most of the CAD softwares have this file format in which the drawing can be saved.
- Preparation of the STL file for building process. The STL file is sliced into 2-dimentional cross-section profile according to the geometry of the CAD model and the required build orientation. Each AM machine has its own preparatory software i.e. slicing software. The program may also generate auxiliary support structure for the object (Boboulos, 2011).
- Building of 2-dimensional slice section layer by layer until the part is completed.
- Removal and finishing: the object is removed from the machine and cleaned, removing any auxiliary support structure, polishing, painting and heat treatment, depending on the service requirement of the part.

The steps involved in AM technologies are illustrated in Figure 4. Some of these commercially available AM technologies are discussed below:

<Insert Figure 4>

Laser additive manufacturing (LAM) technologies

Some of the commercially available LAM technologies are briefly given below:

Stereolithography (SLA)

Stereolithography is mostly referred to as Stereolithography Apparatus (SLA). It was the first commercially available Rapid prototyping machine developed and patented by Charles Hull of 3D systems Incorporations (Hull, 1986). It was presented at the AUTOFACT show in Detroit in November 19972. At that time, the process was inaccurate and choice of material was limited, so the part obtained were considered as prototypes (Boboulos, 2011). SLA uses laser to selectively scan and cures the liquid photo-sensitive polymer.

Selective laser sintering (SLS)

The selective laser sintering (SLS) process was first developed and patented by Dr. Carl Deckard for his master's thesis at the University of Texas (Deckard, 1989). SLS process was commercialized by DTM Corporation and subsequently bought out by 3D Systems incorporation (Banerjee, 2009). SLS uses the energy from laser to sinter the powder by fusing the powder particle to form a solid mass (Deckard, 1989; Greulich, 1997; Kruth *et al.,* 2003; Pham *et al.*, 2003). Other variant of SLS is known as Selective Laser Melting (SLM).

Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing (LOM) process was introduced in 1986 by Helisys of Torrance, California2, (Banerjee, 2009). Objects are formed by bonding together adhesive coated sheet material, the shape are then traced by laser optics system. The original material used was paper, but different materials are now being developed also by Helisys (Boboulos, 2011). The method is self-supporting for overhangs and undercuts. This basic laminating principle is also being used by several other processes, including Kira's Paper Lamination Technology (PLT) (Banerjee, 2009; Nakagawa, 1993; Nakagawa and Kunieda, 1984).

Solid Ground Curing (SGC)

Solid Ground Curing was developed by Cubital Inc. of Israel. It was patented by Scitex Corporation-Israel in 1990 (Pomerantz, 1990). SGC is a hybrid of SLA and laser printing technology (Boboulos, 2011). The machine forms the cross-section image of the object on a glass plate similar to laser printer (Kumar and Kruth, 2010). The surface of the liquid photo-polymer is solidified in a similar manner to SLA technique by exposing it to ultra violent lamp and cured the entire layer at once (Banerjee, 2009; Boboulos, 2011).

Laser Metal Deposition (LMD)

Laser Metal Deposition (LMD) also known as Direct Metal Laser Deposition (DMLD) or Direct Laser Deposition (DLD) or Direct Metal Deposition (DMD) or Laser Powder Deposition (LPD) is a solid freeform process and an additive manufacturing process based on Laser Cladding (LC) technique. This technique is unique in the sense that it can be applied to repair high valued component parts that in the past were prohibitive or difficult to repair (Bergan, 2011). The ability to use different materials simultaneously makes it possible for the production of functional graded material. This makes improvement of service life of engineering components possible using this process. Laser cladding produces better coating with minimum dilution. Parts produced using laser cladding technique exhibits minimum physical distortion, better surface quality, near net shape and fully dense. They have good grain structure which determines the mechanical properties of the component. Parts that were discarded in the past as a result of being non-wieldable can now be repaired using LMD technology (Gasser, *et al.,* 2010). It enhances thermal control through its well controlled heat affected zone. For repair of parts, LMD unlike the traditional repair methods (e.g. welding) which are destructive in nature is a safe repair technology especially on critical contacting surfaces. Laser Engineered Net Shaping (LENS) is an example of AM technology based on laser metal deposition.

Laser Engineered Net Shaping (LENS)

Laser engineered net shape, developed by Sandia National Laboratory in the mid 1990s uses high power laser (Paschotta, 2008; Kumar and Stucker, 2005) to melt metal powder by focusing the laser beam on small sport at a time through one or more lenses (Keicher, 1998; Hedges and Keicher, 2002; Singer, 1997,). Powdered material is fed through Direct Material Deposition (DMD) (Mazumder, *et al.,* 1999) process into the laser beam by nozzle. The molten material solidifies very quickly which results in fully dense component eliminating the need for heat-treatment after processing (Grylls, 2003). LENS is a very important technology that is used to produce a part with better control of property through the use of inert gas to shield the melt pool protecting it from atmospheric oxygen. Hence, better surface wetting is provided and better layer adhesion (Yan and Gu, 1996). It is also possible to dynamically change material composition leading to production of functionally graded parts (Liu and DuPont, 2003).

Advantage of flexibility offered by additive manufacturing and laser technology has been employed widely for production of functionally graded materials (Jiang *et al.,* 2005; Obielodan, 2010; Meng *et al.,* 2012).

Non-laser based AM technologies

There are few non-laser based additive manufacturing technologies. The common ones are briefly explained below:

Ink-jet printing

Ink-jet printing technology is also referred to as 3-dimensional printing (3-Dp) (Z Corp, 2010; Sachs *et al.,* 1990), it operates by squirting liquid build material that cools and hardened on impact to form the solid object (Feenstra, 2003). There are variants of 3D printing technology available amongst them is the revolutionary Objet Connex multi-material 3D printers, a precision tool for turning creative ideas and designs into models, parts and prototypes.

Fused Deposition Modelling (FDM)

FDM is the second most widely used AM technique and uses wire-like filament to build object layer by layer (Boboulos, 2011). This technique produces part from heated extruded filament that is deposited layer by layer onto the building platform. The platform is kept at lower temperature so that the thermoplastics hardened quickly (Kalpakjian and Schmid, 2000). A water soluble material can be used with this process for support structure and for over hangs (Koc and Lee, 2002).

Infra-red (IR) and masking systems

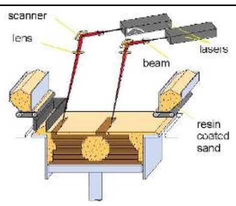
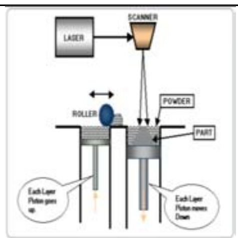
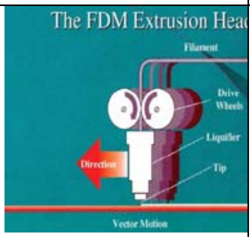
AM is considered slow for large production. In an attempt to speed up this process for the production of end use products, researchers have explored the use of new technologies using alternate faster source of heat to fuse the polymer powder (Banerjee, 2009). Infrared light has high processing speed and has low running cost compared to laser. Some of the processes that use IR heating as an alternative heat source include: Speed Part, Selective Inhibition Sintering (SIS) and High Speed Sintering (HSS) (Banerjee, 2009).

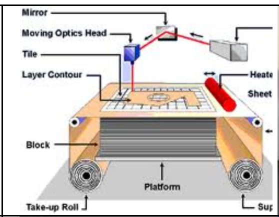
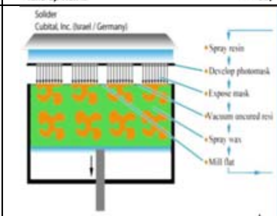
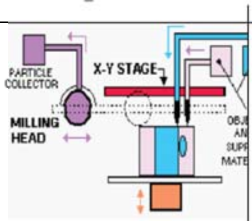
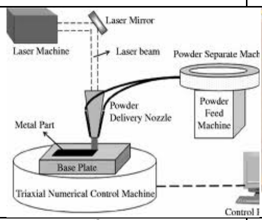
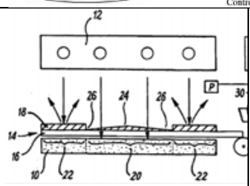
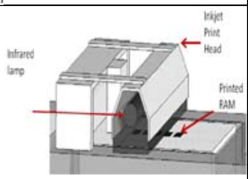
Advantages and areas of application of AM technology.

AM technology helps to reduce design error and production delay to the barest minimum. It is used to reduce cost, lead time and it has less environmental impact. Production of new type of product that would be impractical or difficult to manufacture through traditional method has been successfully produced using AM technology. Additive manufacturing provides opportunity for production of high value custom and limited edition products. It has the potential to reduce the carbon foot print through the elimination of energy intensive manufacturing processes. Components produced by AM technology are always lighter than the ones produced through traditional methods because part can be produced in a single piece thereby eliminating nuts, screws, rivets, among others for assembly. Figure 5 shows a part produced from traditional method (5a) and AM technology (5b). Automobile and Biomedical also have their market share of additive manufacturing. Most automobile parts and medical implants are now being produced using additive manufacturing technologies.

<Insert Figure 5 (a) and (b)>

Table 1 gives comprehensive information about the AM technologies explained above with the processes involved, machines used for these technologies, working principles, advantages, disadvantages and areas of application. This Table provides a better understanding of each of the processes mentioned above.

Technology	**process**	**Machine**	**Working principle**	**Materials**	**Advantages**	**Disadvantages**	**Application field**
Stereolitography (SLA)			laser is selectively scanned onto photo-sensitive polymer	photopolymer	Good surface finish, fully automated, high resolution, most widely used	Curling and wrapping problem, post curing required, limited material, high cost, highly toxic material.	Prototypes, Casting pattern, medicine. 
Selective Laser Sintering (SLS)			Heated laser is used to sinter particles together	Polycarbonate, Nylons, elastomers, ceramics, metals	Wide material range, requires no support structure during building processes, stronger part can be produced, requires no post curing, part can be built on top of an existing part.	Requires lots of time for heating below melting and subsequent part cooling, surface finish depend on powder size, high running cost because of the use of Nitrogen, generation of toxic gases(Knox) hence environmental issues.	Prototypes, injection moulds, Aeronautics, Automobile, Medicine. 
Fused Deposition modelling (FDM)			filament is extruded through heated nozzle	Thermoplastic, wax, ABS, elastomers	Use of different colours are possible, material can be changed quickly, fast, does not require clean-up	Accuracy depends on material size; require support, weak part, delamination problem resulting from poor temperature control.	Model, assembly testing, investment casting, injection moulding 

Laminated Object Manufacturing (LOM)			laser is used to cut cross-sections out of layers of material; layers are thermally fused together	Paper, plastic, ceramic and metal powder tape	Faster cheaper, good for building large part,	Cannot produce hollow part, strength depend on bonding strength	Prototype, models, pattern for injection moulding 
Solid Ground Curing (SGC)			used electro photography technique to print mask and cured the entire layer at once	photopoly mer	High throughput, require no support structure, no post curing required, build process can be interrupted and adjusted	Requires attention, requires skill, noisy operation, high equipment cost	Prototypes, casting pattern, Medicine. 
Ink-Jet Printing		 	Printer head is used to deposits molten Material	Plastic, wax, plaster, bronze	Fine resolution, good surface finish	Fragile part, noisy in operation, slow for large part	Prototypes, model, casting pattern 
Technology	**process**	**Machine**	**Working principle**	**Material s**	**Advantages**	**Disadvantages**	**Application field**
Laser Engineered Net Shape			High laser power is used to melt metal powder supplied coaxially to the focus of the laser beam.	metals	Material composition can be changed dynamically, can make fully dense part with good grain structure, requires no post processing firing	Requires finish machining.	Near net shape object can be produced 
Infra-Red & Masking Systems			Use infrared radiation to fuse the powder layer through the negative masks printed under glass plate.	Polymer, metal, ceramic	Faster, low running cost	Radiation absorption depends on colour of material, i.e. darker colour absorbs more than brighter colours	Prototypes, injection moulds, Aeronautics, Automobile, Medicine.

AM can be deemed to be a future technology that provides unprecedented level of flexibility which will redefine the much needed flexible manufacturing. The technology offers design freedom by allowing manufacturing for design as against design for manufacturing in the traditional manufacturing methods. It is now been used to produce environmental Control Ducting (ECD) for military and commercial jets by Boeing. As at mid-2010 Boeing has produced over 20,000 AM end-use parts (Wohlers, 2011). This shows that AM technology has come to stay. Laser material deposition technology and Direct Metal Deposition (DMD) allows the use of different materials making it possible to produce functionally graded parts. The list is endless for benefits of AM technology but one of the major advantages that cannot be overemphasised is the application of LMD process to repair of an existing part. Especially high valued part that were not repairable in the past can now be repaired by direct laser material deposition thereby reducing scrap and extending parts' service life (Landers, 2003).

Current unresolved issues with AM technology

Despite all the benefits offered by AM technologies, it is yet to be widely utilized for end used parts. This is because of a number of unresolved issues about this promising technology. Some of these issues are highlighted below:

Dimensional accuracy

Dimensional accuracy is still an issue that needs to be resolved before AM technology will be widely accepted. A lot of research efforts have been put on these issues over the years. Lots of work has been done to improve dimensional accuracy of AM technologies (Campanelli *et al.,* 2007; Sood *et al.,* 2009; Sood *et al.,* 2010; Raghunath and Pandey, 2007) of which some are through layer height control (Fathi *et al.,* 2006; Tang *et al.,* 2009), but up till now little has been achieved in this area.

Surface finish

The main contributing factor to poor surface finish in AM processes is stair-stepping effect. The stair-stepping effect is more pronounced in direct metal deposition and fused deposition modelling. Selective laser sintering/melting (SLS/SLM) has less stair stepping effect because the powder bed provide support for the selected fused or melted powder but they also suffer poor surface finish as a result of gluing unmelted powder (from powder bed) on the component surface. To reduce the stair-stepping effect in the literature, reducing layer thickness is proposed (Huang, 2009; Thrimurthulu *et al.,* 2004). Reducing the layer thickness will adversely affect the speed of the process as well as the property of part produced because of the heat affected zone. There are various attempts to improving surface finish of additive manufacturing (Daneshm and Aghanajafi, 2012; Pandey *et al., 2003*; Pradhan *et al., 2009*) in the literature but the surface finish achieved is not comparable with the one achievable in traditional manufacturing methods.

Productivity

Additive manufacturing is yet to be feasible for mass production because of all the underlying factors mentioned above. Productivity of AM process is still very low especially for simple large volume parts. Brajlih *et al.,* 2011, developed a method for measuring achievable speed and accuracy of additive manufacturing technology. This tool is very useful in comparing achievable speed and level of accuracy from any AM machine. Despite different research effort in improving speed of AM (Kruth and Leu, 1998), not much has been achieved. It is still below what is considered acceptable for mass production. There are a number of issues that need to be resolved before AM can compete with traditional method like casting in terms of mass production. All the associated technologies (Laser, materials, etc.) need improvement.

Repeatability and reliability

Repeatability is also a major concern which has made the technology not to be fully accepted. Repeatability is a major concern of AM technology as a result of highly sensitive nature of AM technologies to environmental variation. There is always a variation in part produced at constant process parameters (Berezowsky, 2012; Meyer, 2011; Hague, *et al.,* 2004).

The way forward and suggestion for future research

The cause of poor surface finish in additive manufacturing is attributed to the stair-stepping effect. Reducing the layer thickness which also comes with its attendant effect can only reduce the stair-stepping effect but cannot eradicate it. The stair-stepping effect is not as result of the layer-wise manner with which the component is built. The underlying physics is as a result of the cohesive force in the molten metal as s result of surface tension. The same principle is responsible for bead like shape in welding processes. Liquids tend to hold themselves together in free space when not supported, this is the reason for the spherical shape seen in liquid metal and the shape is retained after solidification. For further reading on surface tension in molten metal see (Skapski, *1948;* Lu and Jiang, 2005). Alloying can reduce the surface tension so also increase in temperature but there is limit to which temperature can be increased in additive manufacturing processes because of its attendant effect on the overall quality of the part being produced.

Stair-stepping effect also contributes to poor dimensional accuracy in AM technology. When a layer is deposited on the previous layer that is still very hot, though solidified, the weight of the new layer plus the temperature being transferred makes the previous layer to become softer and deformed under the combined effect of the weight of the upper layer or layers and temperature gradient. This effect, further results in increased width of the layers, hence poor dimensional accuracy. For a relatively simple structure, post processing can correct all these problems of poor accuracy and surface finish. For a complex structure with intricate parts, the cavity becomes in accessible after the build process and post processing will not work in this situation. The solution proposed in this study to put an end to the problem of poor dimensional accuracy in additive manufacturing technology is to design an adaptive controller, which works like an expert constantly monitoring the build process and giving corrective action as required. The controller should be adaptive because of the sensitive nature of AM to environmental variation. An adaptive controller will be able to adjust itself to any variation.

AM technology is very sensitive to variation in process parameters and environmental disturbances which is the major cause of poor repeatability. Most commercial AM machines use open-loop controls except the Arcam Electron Beam Melting (EBM) machines and the class of direct metal machines that are based on Laser Cladding (LC), which uses feedback control (Beaman, 2003). The problem with open loop control is that once the command is generated it can not account for any unforeseen uncertainties. The feedback control utilised in EBM and LC are for temperature control and as mentioned above, temperature control alone cannot stabilize the whole process. Most of the work in the literature that addressed poor dimensional accuracy is through the layer height control (Fathi *et al.,* 2006; Tang *et al.,* 2009). It is not only the height that determines the dimensional accuracy of parts produced but also the width of the layers. However, it should be noted that the width is produced by the laser spot diameter, which is determined by the focal length of the laser lens and the standoff distance. The effect of surface tension will also come into play which is an external disturbance on the system. This needs to be taken care off by a closed-loop control. So there is need for a separate controller that uses a real time measurement for width control. Such controller should be adaptive in order to take care of variations as a result of environmental disturbances in the system.

Adaptive feedback control

For AM technology to be fully accepted for in the industries there is need for separate real time sensing and adaptive feedback control for layer's width. The function of this controller will be to use the real time measurement of the layer's width; compare is with the required width and use laser to erode the error from both internal and external part of the layer. By so doing, the controller will remove stair-stepping effect and the surface finish will greatly improve. Stair-stepping impacts the service life of a part that is subjected to dynamic loading. The stair-stepping has a high stress concentration factor which is where most failures are initiated (Rodet and Colton, 2003; Widden *et al.,* 2011). This controller will not only improve surface finish, but also improve the mechanical property of the part. This controller will also eliminate the need for in-process inspection. The proposed adaptive controller can be incorporated with an existing system without affecting its performance.

The proposed controller will greatly influence the long standing problem of additive manufacturing and open a new capability for the system. Repeatability and reliability will be greatly improved and the use of AM technology for mass production will be economically and technologically feasible.

Suggestion for future work

The literature is still very scarce in the area of material characterisation of components from AM technology, some of work in this area include (Yu *et al.,* 2011; Brandl *et al.*,2012; Shah1 *et al.*,2010; Vega *et al.*, 2011; Masood *et al.*, 2010; Schick *et al.*, 2010; Dehoff and Babu, 2010; Baufelda *et al.*, 2011). To fully benefit from this technology, there is need for more research in the area of extensive material characterisation of component produced at various process parameters in order to optimise the process window for the expected service requirement from the part. This will enable the improvement and the ability to predict performance based on the operating parameters. Inability to guarantee material properties for any given process is one of the major drawbacks for the wide adoption of AM technologies in the industries (Wholers, 2009). Further understanding of the underlying physics of interlayer bonding will result in greater ability to control the bonding of the layers in order to produce high quality and more consistent parts. Also there is need for further understanding of process/material interface. This knowledge will help to generate a comprehensive database for AM technologies with different materials that will enable proper modeling and simulation that will lead to a better process control. These amongst others will ensure higher overall process performance.

Conclusions

AM technology is a promising future technology for manufacturing of end-use products. It reduces time and cost of production. Some key AM technologies are highlighted, poor dimensional accuracy; repeatability and reliability are some of the problems still confronting AM technologies. In order to solve these problems further study is recommended for extensive material characterisation of parts produced from AM at various process parameters. This will enable the development of predictive modelling of the system for proper process control in order to improve part properties. Also, a separate controller is proposed in this study which utilizes real time measurement to achieve both dimensional controls, removing stair-stepping effects, improving surface finish, promoting repeatability and reliability. Effect of stair-stepping on life of components cannot be over emphasized, as it produces high stress concentration factor and crack initiation site. These controllers will improve the mechanical properties of the component produced. Successful implementation of the proposed controller will not only improve dimensional accuracy and surface finish but will also increase the speed of production, as the layer thickness can be increased without the fear of stair-stepping.

Funding Acknowledgement

This work was supported by the Rental Pool Grant of the National Laser Centre - Council of Scientific and Industrial Research (NLC-CSIR), Pretoria, South Africa and The Schlumberger Foundation Faculty for the Future (FFTF).

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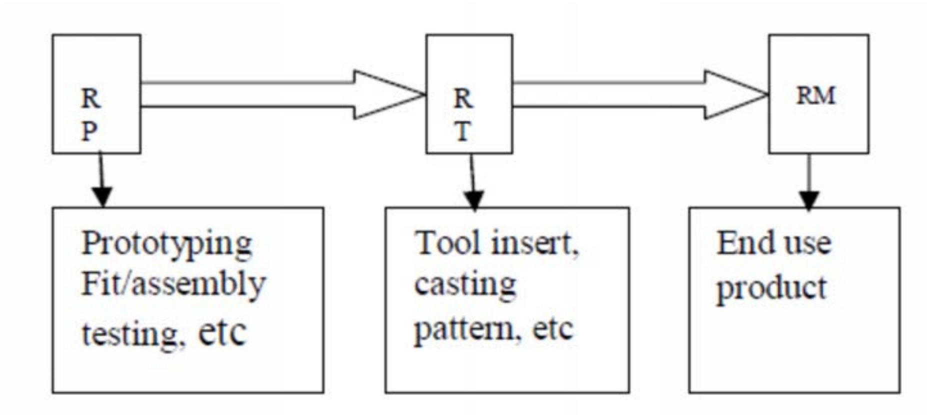


Figure 1: Trends in Additive Manufacturing processes

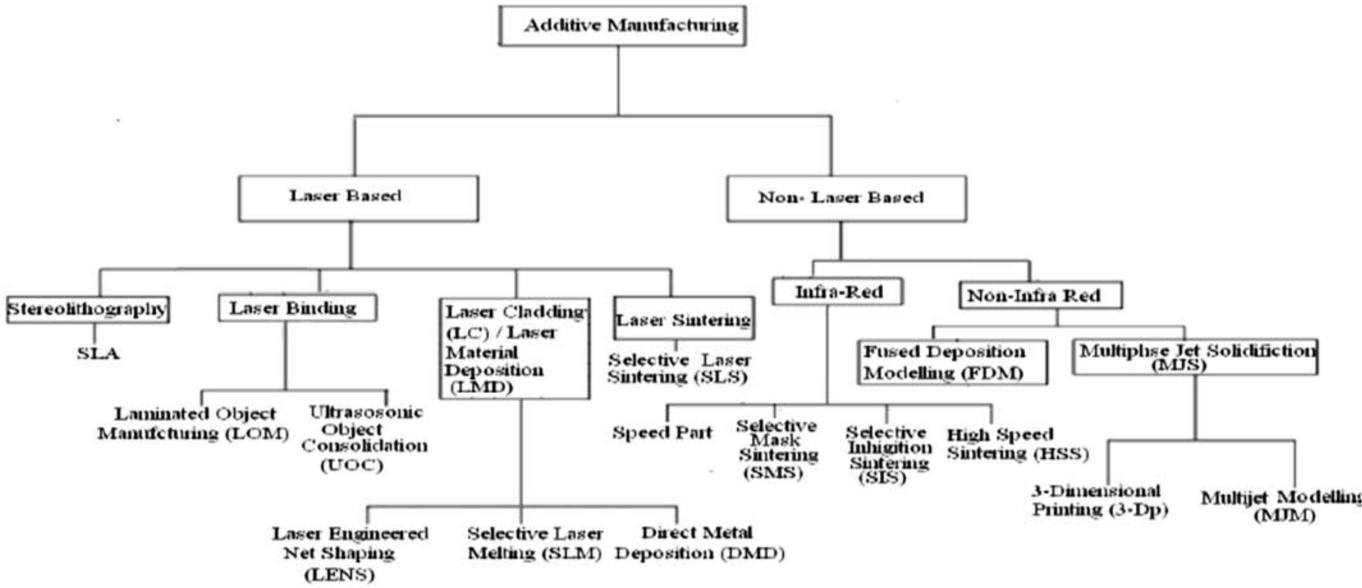


Figure 2: Classification of Additive Manufacturing (AM)

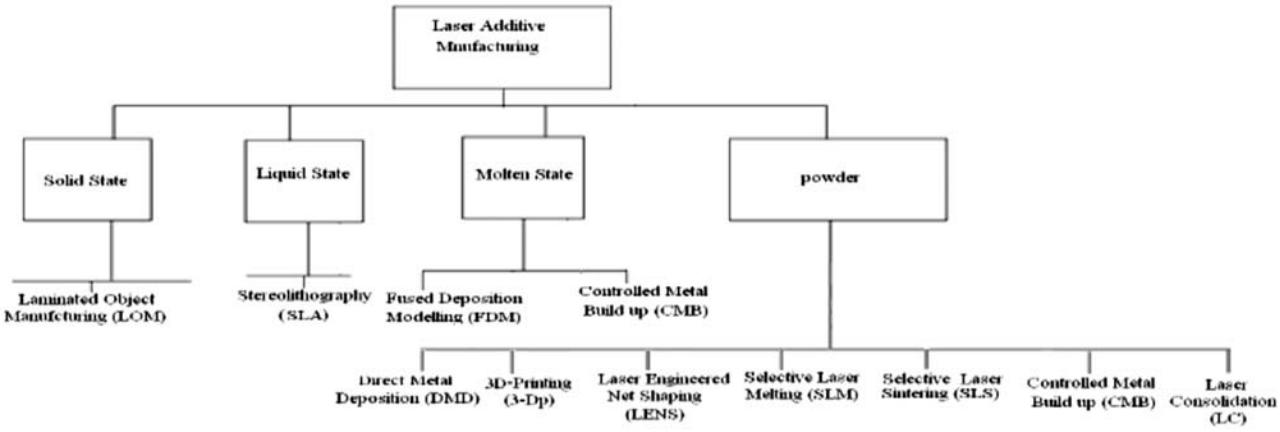


Figure 3: Classification of Laser Additive Manufacturing(LAM)

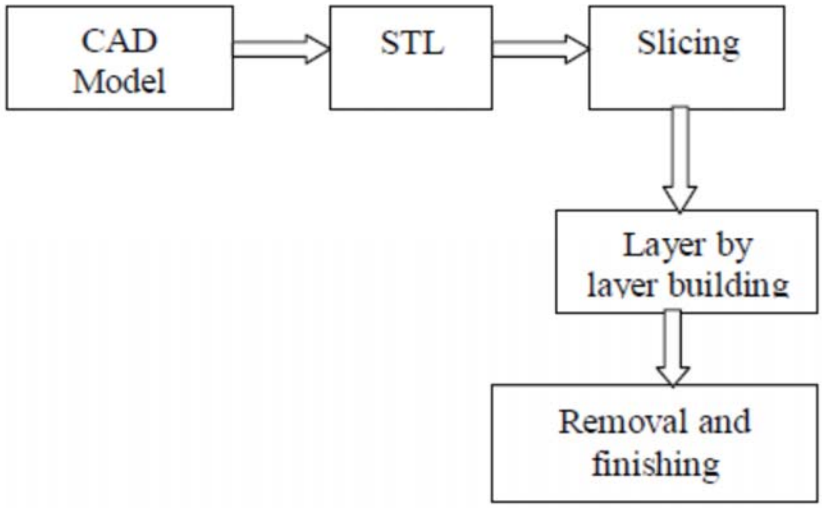
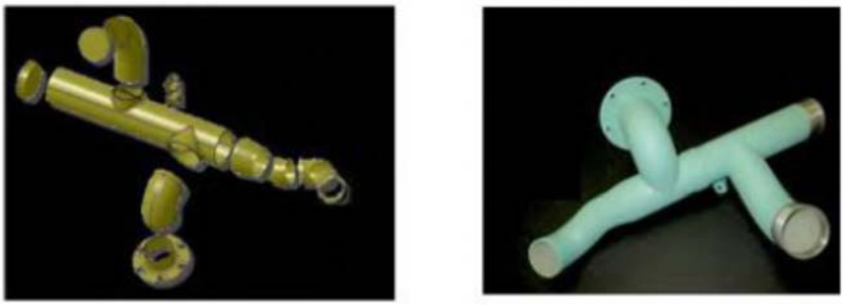


Figure 4: Basic Additive Manufacturing Processes



(a) (b)

Figure 5: Environmental control ducting (a) using traditional method (b) using additive manufacturing (Wohlers, 2011)