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ADDITIVE MANUFACTURING TECHNOLOGIES

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ABSTRACT

Additive manufacturing (AM) is a latest technology that could improve manufacturing process by building up thin layers of materials from digitized three-dimensional (3D) designs virtually constructed using advanced CAD software. This technique affords the creation of new types of object with unique material properties. But while AM is widely billed as 'the next industrial revolution', in reality there are still significant hurdles for successful commercialisation of the technologies. This paper aims to provide a comprehensive review of literature, technologies and manufacturing practices on modern Additive Manufacturing.

KEYWORDS: Additive Manufacturing (AM), 3D-Printing, Rapid Prototyping (RP), Stereo Lithography (SL)

1. INTRODUCTION

Additive Manufacturing (AM) technology, which is referred as three dimensional printing technology which produces objects layer-by layer (additively), rather than subtracting similar to a two dimensional printer with the only difference that a third dimension (z-axis) is added, which is also called the building direction (Reeves, 2009)

Historically, AM technology was used to build conceptual prototypes referring to that process as Rapid Prototyping (RP), a term which is still often used as a synonym to AM. Those prototypes were meant only to accelerate the development phase of a product and under no circumstance are comparable to the end product with respect to material, durability and quality (Feenstra, 2002). Rapid Manufacturing (RM) has evolved through RP due to technological advancements defined by Rudgley (2001) as "the manufacture of end-use products using additive manufacturing techniques (solid imaging)".RM was responsible for approximately 20% of overall AM revenues in 2010, as per 2011Wohlers Report.

A sub-category of RM is Rapid Tooling (RT) whose aim is to create consistent tools which serve traditional manufacturing procedures (Dimov, 2001). RT has been mostly used to create injection molds but recent developments enable RT technology to be used for other tooling processes like casting and forging (Levy et al., 2003). RT further portioned into direct tooling and indirect tooling. In direct tooling moulds are layer manufactured for use, and indirect tooling, a master model is created and furthermore used to produce a casted mould. According to 2009 Wholers Report, 16% of AM processes were used for direct part production (RM), 21% for functional prototypes (RP) and 23% for tooling and metal casting patterns (RT) from which approximately 56% and 9% of process preferences were direct metal and direct polymer tooling respectively (Levy et al., 2003). In AM, object representation is stored in a STL file (stereo lithography), generated by conventional CAD software or obtained from Magnetic Resonance Imaging, laser scanning, Computer Tomography (CT) and mathematical modelling software (Reeves, 2009). Afterwards, the STL file is imported into slicing software in which the three dimensional digital object is sliced into layers and oriented appropriately in order to define the best possible tool path for the printer which then creates the object via selective placement of material (Campbell et al., 2011). Furthermore, it is essential to choose the appropriate building direction as it can change specifications of the object such as lead time, cost and quality. Choosing a direction other than the optimum would lead to more layers required resulting in increased lead time needed to manufacture the product (Reeves, 2009).

This paper aims to provide a comprehensive review of literature, technologies and manufacturing practices of Additive Manufacturing and its sub category Rapid Tooling. The paper is organized as follows. In section two the most widely applied and advanced technological processes of AM are presented. This section is also reviewed the technological limitations and design restrictions of AM. Section three focuses on the adoption of AM by various industries. Finally, in section four the possible outcome and the impact of AM technology adoption are discussed.

2. ADDITIVE MANUFACTURING (AM)

2.1 Definition

AM refers to a group of technologies that build physical objects directly from three dimensional CAD data. AM adds liquid, sheet, wire or powdered materials, layer-by layer, to form component parts with little or no subsequent processing requirements. This approach provides a number of advantages including near 100% material utilisation, short lead timesandun-rivalled geometric freedom of design.

The ASTM has defined ‘additive manufacturing’ as a (ASTM international, 2012) : “ process of joining materials to make objects from 3D models data, usually layer upon layer, as opposed to subtractive methodologies, such as traditional machining.”

Since the onset of layer based processing for creating 3D components, a number of terms have evolved and as such various terminology derivations have arisen. In more recent times, this has resulted in some misunderstanding or misuse of terminology contributing to a ‘weakness’ in its advancement. The innovative nature of the technology and lack of available standardisation have also contributed to this.

‘Rapid Prototyping’ seems to be the earliest describer and trends to be deemed ‘layer based processing for creating 3D components in its infancy’. However, considerable progress in the field has taken the technology far beyond that of ‘prototyping’. 3D printing, a term brought about in the 90s, has been widely used since and has become a wider spread term for creating layered 3D components, more generally known for low- cost 3D home printing and some of the larger commercial 3D printing systems. The term ‘Additive Manufacturing’ was later introduced and seems to have taken the position for describing the technology overall, and more specifically for industrial applications and professional high end equipment and applications. Figure 1 shows a number of terms for AM.

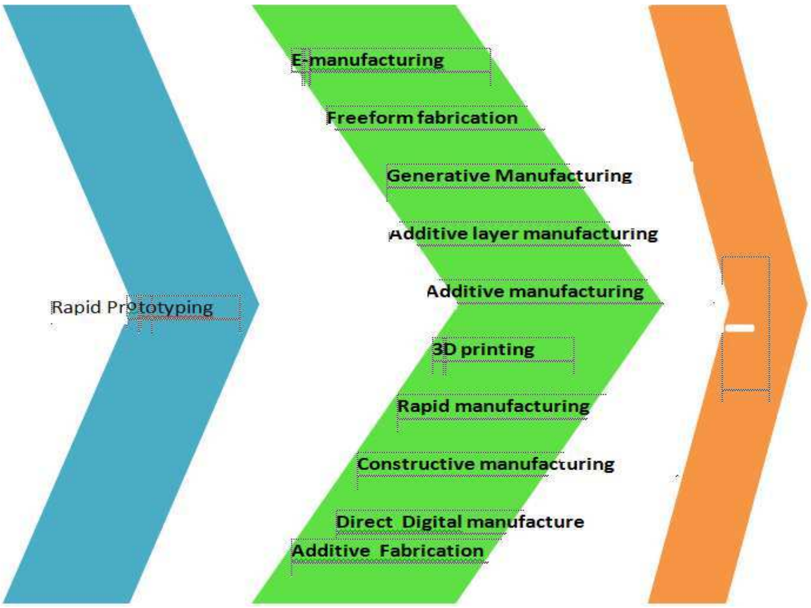


Figure 1: Schematic Outlining the Alternative Terms in the Field of AM

2.2 Basic Steps of Additive Manufacturing

Due to the layer based manufacturing, sometimes additive manufactured parts require post conditioning. As a result of these additional steps, AM can be divided into many categories. From the CAD model to the actual part, AM technology is separated to eight different steps (Gibson et al, 2010)

General Steps for Additive Manufacturing *Computer Aided Design*

AM starts with designing a model with any professional CAD software. The output model has to be a 3D or surface representation of the actual part. Scanning and reverse engineering equipment could be also be used to generate this model. (Gibson, Rosen, & Stucker, 2010, p. 4)

Conversion for AM Accepted File Type

STL is the standard file type for the AM machines. Once a CAD model is created it should be saved in STL format through the CAD software. STL file translates the surface in the CAD model to a mesh of triangles. The number of the triangles controls the precision of the rounded surfaces. The CAD software allows the user to control the number and the size of those triangles (Stratasys Ltd., 2015).

Transfer STL Files to AM Machine

The STL file should be transferred to the machine. The file should be verified for its right size and build orientation. Also if there are multiple parts they should be properly placed so they wouldn’t overlap with other parts.

AM Machine Setup

Machine setup is a crucial step in the process. The parameters should be properly set up to achieve the tolerances of the manufactured part. Layer thickness, orientation, energy provided, timing and roller speeds can be named as some of these parameters.

Build Phase

This is step is more of automated process done by the machine. Partial monitoring will be required to ensure there are no errors and the machine would not run out of material.

Removal

In this phase the machine is done producing the part and the user has to take it out. The user should follow the safety protocols and proper shut down procedures. This will ensure the safety of the user and the machine.

Post Processing of AM Parts

Once the parts are produced they might need some additional treatment such as curing, sintering and cleaning. At these stages parts may be weak and they should be handled with care.

3. ADDITIVE MANUFACTURING TECHNOLOGY PROCESS

Various AM processes have been introduced to the commercial market by industrial companies, including the Electro Optical Systems (EOS) in Germany, Arcam in Sweden, MCP Tooling Technologies in the UK, and Stratasys, 3D Systems, Optomec, and Z Corporation in the United States, among others [6]. There are several systems to classify the AM processes, e.g., the one proposed by the ASTM F42 Committee classifies the AM processes into seven areas [1].

Table 1: The Seven AM Process Categories by ASTM F42 [1]

Process types	Brief Description	Related Technology	Companies	Materials
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed	Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS)	EOS (Germany), 3D Systems(US), Arcam (Sweden)	Metals, Polymers
Directed Energy Deposition	Focused thermal energy is used to fuse materials by melting as the material is being deposited	Laser metal deposition (LMD)	Optomec (US), POM (US)	Metals
Material Extrusion	Material is selectively dispensed through a through Nozzle or orifice	Fused deposition modelling (FDM)	Stratasys (Israel), Bits from Bytes (UK)	Polymers
Vat Photo polymerization	Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Stereo lithography(SLA), digital light processing (DLP)		Photopolymers
Binder Jetting	A liquid bonding agent is selectively deposited to join powder materials	Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)	3D Systems (US), Ex One (US)	Polymers, Foundry Sand, Metals
Material Jetting	Droplets of build material are selectively deposited	Multi-jet modelling (MJM)	Objet (Israel), 3DSystems (US)	Polymers, Waxes
Sheet Lamination	Sheets of material are bonded to form an object	Laminated object manufacturing(LOM), ultrasonic consolidation (UC)	Fabrisonic (US), Mcor (Ireland)	Paper, Metals

3.1 Powder Bed Fusion (PBF)

Powder bed fusion (PBF) methods use either a electron beam or laser source to melt and fuse material powder together. Electron beam melting (EBM), methods require a vacuum but can be used with metals and alloys in the creation of parts. All PBF processes involve the spreading of the powder material over previous layers. There are different mechanisms to enable this, including a roller or a blade. A hopper or a reservoir provides fresh material supply. Direct metal laser sintering (DMLS) is the same as Selective Laser Sintering (SLS), but with the use of metals and not plastics. This process sinters the powder, layer by layer. Selective Heat Sintering differs from other processes by way of using a heated thermal print head to fuse powder material and, layers are added with a roller in between fusion of layers as before (Gibson et al., 2010). Figure 2 bellow shows Powder bed fusion methods

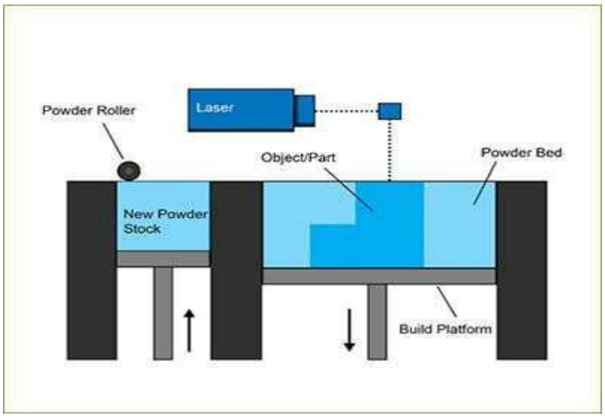


Figure 2: Powder Bed Fusion (PBF) Methods (CustomPart.Net, 2008)

Selective Laser Melting (SLM) Compared to SLS, SLM is often faster (Gibson et al., 2010), but requires the use of an inert gas, has higher energy costs and typically has a poor energy efficiency of 10 to 20 % (Gibson et al., 2010). The process uses either a roller or a blade to spread new layers of powder over previous layers. When a blade is sed, it is often vibrated to encourage a more even distribution of powder (Gibson et al., 2010). A hopper or a reservoir below or aside the bed provides a fresh material supply.

Selective Heat Sintering (SHS) uses a heated thermal print head to fuse powder material together. As before, layers are added with a roller in between fusion of layers. The process is used in creating concept prototypes and less so structural components. The use of a thermal print head and not a laser benefits the process by reducing significantly the heat and power levels required. Thermoplastics powders are used and as before act as support material. The 'Blue printer' is a desktop 3D printer that uses the SHS technology, with a build chamber of 200mm x 160mm x 140mm, print speed of 23mm/hour and a layer thickness of 0.1mm (Blue Printer SHS, 2014).

Direct Metal Laser Sintering (DMLS) uses the same process as SLS, but with the use of metals and not plastic powders. The process sinters the powder, layer by layer and a range of engineering metals are available.

Electron Beam Melting (EBM) Layers are fused using an electron beam to melt metal powders. Machine manufacturer Arcam used electromagnetic coils to control the beam and a vacuum pressure of 1×10-5 mba (EBM Arcam, 2014). EBM provides models with very good strength properties due to an even temperature distribution of during fusion (Chua et al., 2010). The high quality and finish that the process allows for makes it suited to the manufacture of high standard parts used in aeroplanes and medical applications. The process offers a number of benefits over traditional methods of implant creation, including hip stem prosthesis (Araguaia, 1995). Compared to CNC machining, using EBM with titanium and a layer thickness of 0.1mm, can achieve better results, in a faster time and can reduce the cost by up to 35%.

3.2 Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is a more complex printing process commonly used to repair or add additional material to existing components (Gibson et al., 2010), also called as Laser engineered net shaping, directed light fabrication, direct metal deposition, 3D laser cladding.

A typical DED machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, which can be deposited from any angle because of 4 and 5 axis machines, is melted upon deposition with electron or laser beam. The process can be used with polymers, ceramics but is typically used with metals, in the form of either powder or wire. Typical applications include repairing and maintaining structural parts.

The DED process uses material in wire or powder form. Wire is less accurate due to the nature of a pre-formed shape but is more material efficient when compared to powder (Gibson et al., 2010). The method of material melting varies between a laser, an electron beam, and laser beam or 201plasma arc, all within a controlled chamber where the atmosphere has reduced oxygen levels. With 4 or 5 axis machines, the movement of the feed head will not change the flow rate of material, compared to fixed, vertical deposition (Gibson et al., 2010).

Whilst in most cases, it is the arm that moves and the object remains in a fixed position, this can be reversed and a platform could be moved instead and the arm remain in a fixed position. The choice will depend on the exact application and object being printed. Material cooling times are very fast, typically between 1000 – 5000 degrees Celsius / second (Gibson et al., 2010). The cooling time will in turn affect the final grain structure of the deposited material, although the overlapping of material must also be considered, where the grain structure is changed as the overlapping can cause re-melting to occur, resulting in a uniform but alternating micro-structure. Typical layer thicknesses of 0.25 mm to 0.5 mm (Gibson et al., 2010)

3.3 Material Extrusion

Fused deposition modelling (FDM) is a common material extrusion process in which material is drawn through a nozzle, where it is heated and is then deposited layer by layer. The nozzle can move horizontally and platform moves up and down vertically after each new layer is deposited. FDM is a commonly used technique used by many inexpensive, domestic and hobby 3D printers.

The process has many factors that influence the quality of final model but has great potential and viability when these factors are properly controlled. Whilst FDM is similar to all other 3D printing processes, as it builds layer by layer, it varies in the fact that material is added through a nozzle under constant pressure and in a continuous stream. This pressure must be kept steady and at a constant speed to enable accurate results (Gibson et al., 2010). Material layers can be bonded by the use of chemical agents or temperature control. Material is often added to the machine in spool form as shown in figure 3.

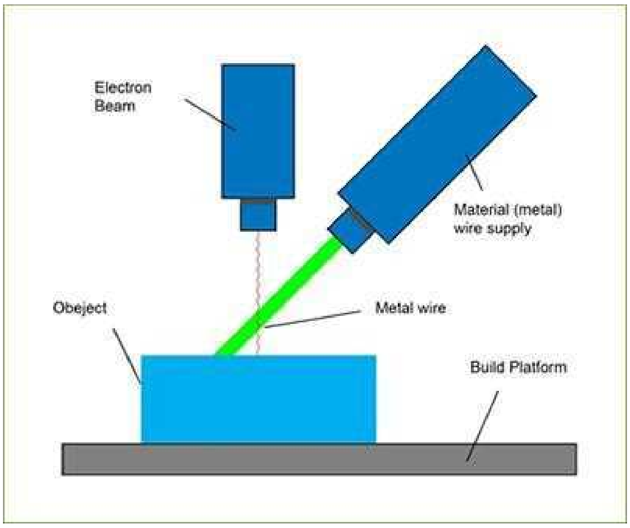


Figure 3: Metal Extrusion Process (CustomPart.Net, 2008)

Advantages of the material extrusion process include use of readily available ABS plastic, which can produce models with good structural properties, close to final production model. In low volume cases, this can be a more economical method than using injection moulding. However, the process requires many factors to control in order to achieve a high quality finish. The nozzle size and shape will affect the final quality of the printed object because nozzle which deposits material will always have a radius, as it is not possible to make a perfectly square nozzle and this (Chua et al., 2010). Accuracy and speed of FDM are low when compared to other processes and the quality of the final model is limited to material nozzle thickness (Krar et al., 2003).

One method of post processing to improve the visual appearance of models is through improving material transmissivity. Methods have been explored by Ahnet all; include increasing temperature and the use of resin. Experiments using cyamo acrylate resin, often used to improve the strength of parts, resulted in a 5% increase in transmissivity after 30 seconds and sanding (Ahn, 2004). As with most heat related post processing processes, shrink- age is likely to occur and must be taken into account if a high tolerance is required.

3.4 Vat Polymerisation

Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured.

As the process uses liquid to form objects, there is no structural support from the material during the build phase. Unlike powder based methods, where support is given from the unbound material. In this case, support structures will often need to be added. Resins are cured using a process of photo polymerisation (Gibson et al., 2010) or UV light, where the light is directed across the surface of the resin with the use of motor controlled mirrors (Grenda, 2009). Where the resin comes in contact with the light, it cures or hardens.

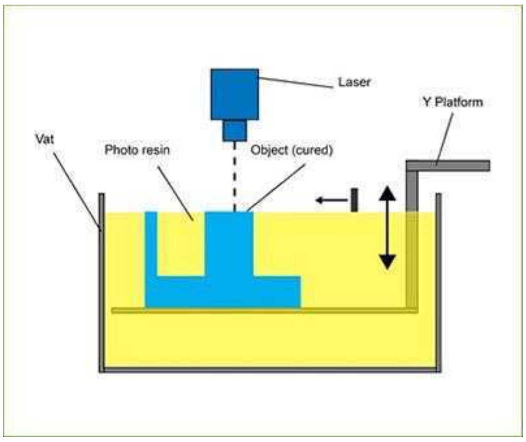
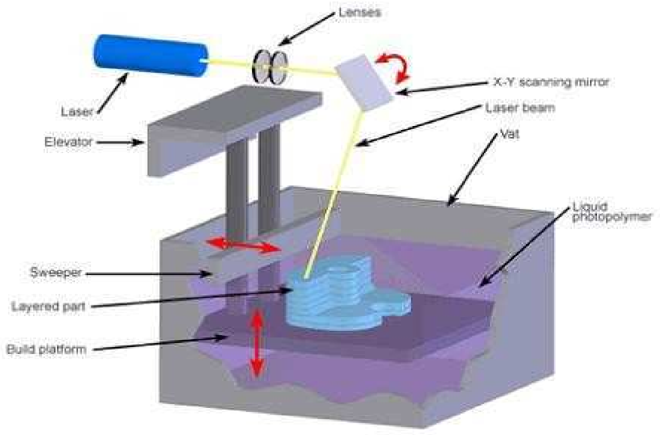


Figure 4: Vat Polymerisation Process (CustomPart.Net, 2008)

Stereo Lithography (SL) is the first commercialized AM technology using laser technology to achieve the photo-polymerization of liquid resin which becomes consistent when exposed to the laser (UV light) in order to create plastic objects (Figure 5). After each layer is completed the platform lowers itself by one layer usually allowing the blade to refill the liquid resin on the surface of the object (xpress3d, 2012). This technology is still used for RP to create conceptual polymeric products and for indirect RT to create master patterns for casting processes. Generally, the layer thickness achieved depends on the model of the machine and ranges between 0.05 mm and 0.15 mm with a roughness of approximately 35-40 µm Ra (Reeves, 2009). The main advantages of SL are temperature resistance and the creation of complex structures with very thin walls. The main disadvantage of SL is the necessary support structure to fabricate objects which consumes additional material and extended production time (Petrovic et al., 2011).

Post Processing: Parts must be removed from the resin and any excess resin fully drained from the vat. Supports can be removed using a knife or sharp implement. Care must be taken not to contaminate the resin and the appropriate safety precautions must be taken. Methods for removing resin and supports include the use of an alcohol rinse followed by a water rinse. The processing may be lengthy as parts may require additional scrubbing to remove material fully. Finally, parts can be dried naturally or by using an air hose. UV light is often used as well, for a final post cure process to ensure a high quality object.



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Source: http://www.custompartnet.com

Figure 5: Stereo Lithography Process

3.5 Binder Jetting

The binder jetting process uses two materials; a powder based material and a binder. The binder acts as an adhesive between powder layers. The binder is usually in liquid form and the build material in powder form. A print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform.

Due to the method of binding, the material characteristics are not always suitable for structural parts and despite the relative speed of printing, additional post processing (see below) can add significant time to the overall process.

As with other powder based manufacturing methods, the object being printed is self-supported within the powder bed and is removed from the unbound powder once completed. The technology is often referred to as 3DP technology and is copyrighted under this name.

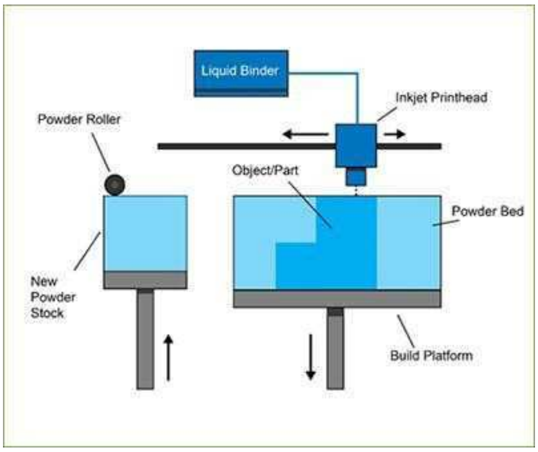

Figure 6: Binder jetting Process (CustomPart.Net, 2008)

The binder jetting process allows for colour printing and uses polymers and ceramics and metals. This process is faster than others and can be further speed up by increasing the number of print head holes that deposit material. The two material approaches allows for a large number of different binder-powder combinations and various mechanical properties of the final model to be achieved by changing the ratio and individual properties of the two materials. Therefore, the process is well suited when the internal material structure needs to be of a specific quality.

Layers of build material, often in granular and powder form, are held together using the adhesive binder. The print head deposits the binding material in micro amounts and the powder material is used in creating the majority of the overall object mass. A heated build chamber can help to speed up the printing process by increasing the viscosity of the materials (Chua et al., 2010).

Post Processing: The overall process time is extended as it requires the binder to set and the part is often allowed to cool in the machine to fully solidify to achieve a high quality finish (Gibson et al., 2010). Post processing is often required to make the part stronger and give the binder-material better mechanical and structural properties (Gibson et al., 2010).

3.6 Material Jetting

Material jetting creates objects in a similar method to a two dimensional ink jet printer. Material is jetted onto a build platform using either a continuous or Drop on Demand (DOD) approach.

Material is jetted onto the build surface or platform, where it solidifies and the model is built layer by layer. Material is deposited from a nozzle which moves horizontally across the build platform. Machines vary in complexity and in their methods of controlling the deposition of material. The material layers are then cured or hardened using ultraviolet (UV) light.

As material must be deposited in drops, the number of materials available to use is limited. Due to viscous nature and drop forming nature of polymers and waxes are commonly used materials.

Material Jetting builds objects in a similar method to a two dimensional ink jet printer. Multiple materials can be used in one process and the material can be changed during the build stage. Material is jetted onto the build platform surface in droplets, which are formed using an oscillating nozzle. Droplets are then charged and positioned onto the surface using charged deflection plates. This is a continuous system which allows for a high level of droplet control and positioning. Droplets which are not used are recycled back into the printing system.

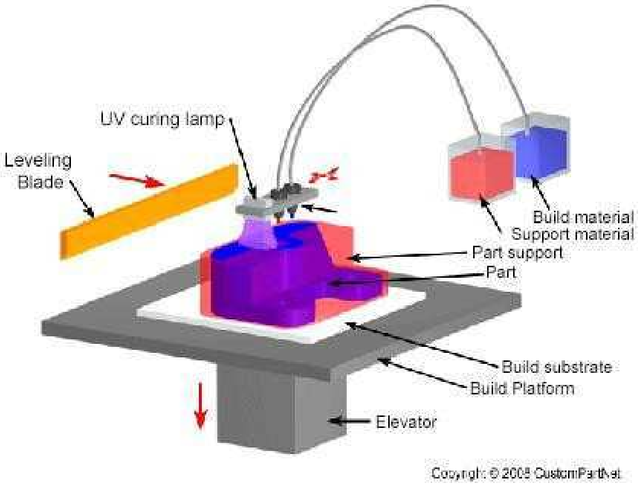

Figure 7: Material Jetting (CustomPart.Net, 2008)

Drop on Demand (DOD) is used to dispense material onto the required surface. Droplets are formed and positioned into the build surface, in order to build the object being printed, with further droplets added in new layers until the entire object has been made. The nature of using droplets, limits the number of materials available to use. Because of viscous nature and ability to form as drops, polymers and waxes are suitable and often used. Viscosity is the main determinant in the process; there is a need to re-fill the reservoir quickly and this in turn affects print speed. Unlike a continuous stream of material, droplets are dispensed only when needed, released by a pressure change in the nozzle from thermal or piezoelectric actuators. Droplets are deposited by thermal actuators at a very fast rate and use a thin film resistor to form the droplet. Piezoelectric method allows wide range of materials and often considered better option.

Post processing: Support material can be removed using a sodium hydroxide solution or water jet. Due to the high accuracy of the process technology, the level of post processing required to enhance the properties is limited and the functional and aesthetic qualities of a part are largely determined during the printing stage. Stratasys polyjet technology cures the material using UV light and therefore no post curing process is needed.

3.7 Sheet Lamination Process

Sheet lamination processes include ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). The Ultrasonic Additive Manufacturing process uses sheets or ribbons of metal, which are bound together using ultrasonic welding. This process does require additional CNC machining and removal of the unbound metal during the welding process. Laminated object manufacturing (LOM) uses a similar layer by layer approach but uses paper as material and adhesive instead of welding. Cross hatching method is used during the printing process to allow for easy removal of post build in LOM process. Laminated objects are often used for aesthetic and visual models and are not suitable for structural use. UAM uses metals like aluminium, copper, stainless steel and titanium (Ultrasonic Additive Manufacturing Overview, 2014). UAM uses low temperature and allows for internal geometries to be created. The process can bond different materials and requires relatively little energy, as the metal is not melted.

4. MATERIAL USED IN ADDITIVE MANUFACTURING

Polymers are the most widely used material in AM. Most notably, nylon is the most widely used polymer because it melts and bonds better than other polymers (Guo, N. & Leu, M.C, 2013)

Metal products can be formed in a “direct” way – by melting metal particles together or an “indirect” way – by bonding the metal with post-processing. There are many ways and AM methods to form metals through the indirect or direct way (Ibid)

Ceramics are used in AM processing because of their chemical structures and resistance to high temperatures. Unfortunately, these materials can be brittle making them difficult to manufacture especially if complex geometries are involved. Examples of ceramics include alumina, silica and zirconia. Ceramics can be produced through indirect or direct process (Guo, N. & Leu, M.C, 2013)

Composites are, as their name suggests, materials that are combinations of two or more materials, either naturally (in nature) or engineered. Composites can be mixed uniformly or no uniformly to make different compounds (Ibid).

Functionally graded materials can be created through AM processing. Guo & Leu (2013) show that, “One example is a pulley that contains more carbide near the hub and rim to make it harder and more wear resistant and less carbide in other areas to increase compliance.” (Ibid)

5. ADDITIVE MANUFACTURING INDUSTRIAL DEVELOPMENT

AM technologies started more than twenty years ago but public attention has only focused on it in the latest years, mainly owing to the publicity around developments in 3D printing (Hype Cycle for 3D Printing, 2014) This is illustrated by the Gartner Hype Cycle (Hype Cycle for 3D Printing, 2014) (Figure 8) which demonstrates what the expectations are for technologies to be close to adoption. For instance, up to 2009, AM is not even referenced. Only in 2010, AM appears for the first time with an estimation of 5-10 years to maturity (Figure 8). In 2013, nevertheless we already see that industrial applications appear, such as Enterprise 3D Printing already situated on the ‘slope of enlightenment’, almost near real production. There are also concepts emerging for 3D scanners and consumer 3D printing, estimated to reach in 5-10 year the ‘plateau of productivity’, close to mainstream adoption.

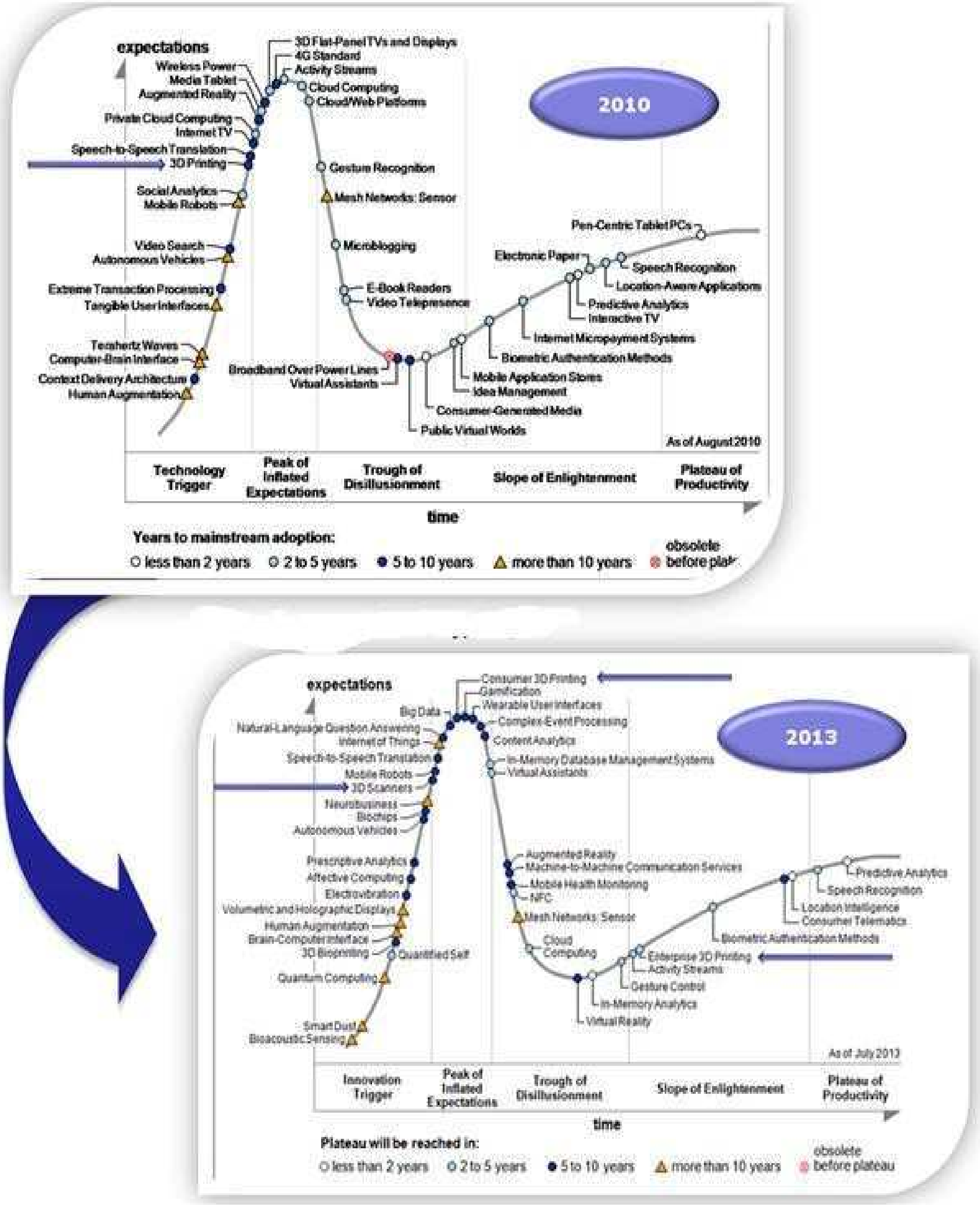

Figure 8: 2010 and 2013 Gartner Hype Cycles (Hype Cycle for 3D Printing, 2014)

Another information matrix that was released by Tuan Tranpham, from Objet Inc., helps to compare the various role-players in the AM industry (Materials KTN., 2012). The horizontal axis, from left to right follows the stages of development from obtaining 3D content to producing the physical part. The vertical axis, from the bottom up shows the different categories of user-groups for each of the various technologies presented

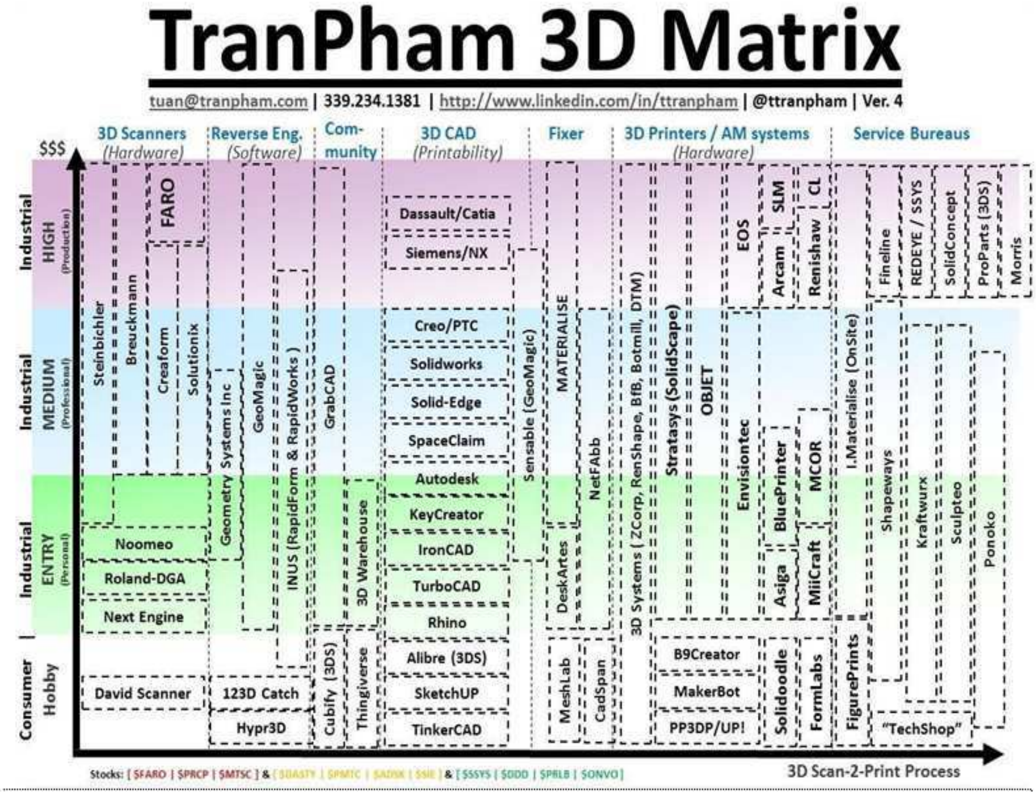

Figure 9: The TranPham 3D Matrix of Industry Role Players [6]

Applications of AM Technologies and Markets

Applications for parts made by additive manufacturing continue to grow. An industry that was once known for rapid prototyping has extended its reach to a broader, more diversified range of possibilities.

As applications grow, the users of the technology grow as well. Once relegated to high-tech laboratories at Fortune 100 companies, AM now is employed by the smallest organizations – and increasingly even by individuals. At every point along that spectrum are users with new ideas and unique applications. It seems that almost any problem involving three-dimensional objects can be solved faster and better with the use of AM technology (Neal de Beer, 2013)

The prerequisite for using AM was once a CAD model, but now input can be generated by medical scan data, entertainment software, as is the case with computer game avatars, and simple drawing and sketching programs. This frees the average individual from the need to learn complex, technical (and relatively costly) software in order to create 3D content for additive manufacturing. In addition, users can purchase 3D content online from companies like Shape ways or download them for free at other companies like Thing verse. Prototyping was among the earliest applications of AM technologies and remains one of the most powerful tools for product development. As material quality, surface finish, and dimensional accuracy have improved, AM models have been increasingly used for functional prototyping and for tooling and metal casting processes (Neal de Beer, 2013)

The Gartner Hype Cycle mainly represents trends to the adoption of a technology. However, AM technologies have already established themselves in some sectors at the level of real production. A survey conducted by Wohler's over 100 key AM system manufacturers and service providers (representing over 100,000 users and customers) showed that the industrial/business machines are the leading sectors using AM technologies (Figure 10). Immediately follows the consumer products/electronics and motor vehicles sectors. Medical/dental and aerospace sectors are also great users of AM technologies (Wholers Report, 2014).

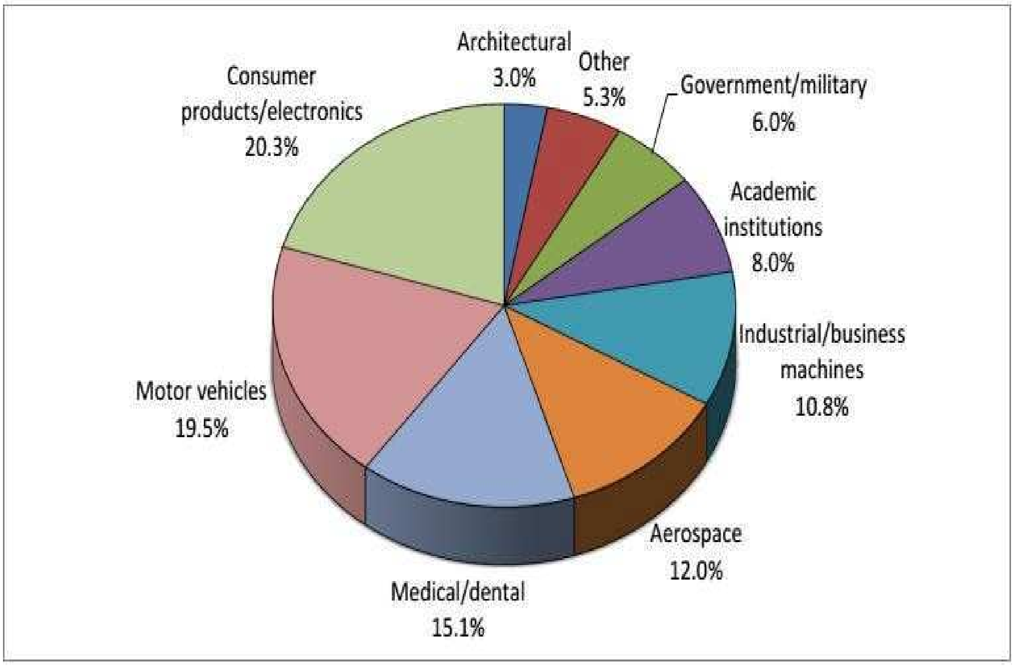

Figure 10: Industries Being Served and Their Revenues by Percentage

The main characteristics of the manufacturing sectors currently using AM technologies for real production conditions are the following:

a)Consumer Products

Within the consumer market there is a large array of products being manufactured by various AM technologies including toys, games, home furnishings, fashion items, sports equipment etc. Artists, jewellers and fashion designers are using AM in a range of ways including to produce one off bespoke pieces (figure 11)

Survey results from Wohlers 2012, showed consumer products/electronics as leading sector and reported that it had been for the last seven years (Hohlers, 2012). In UK, when combining the creative industries, consumer products and fashion/ home categories as one generic sector, SIG UK reported that this sector accessed some £2. 5 millions of industry contribution to lever around £ 7.5 million supports for sector (Materials KTN, 2012).

One of the principles of uses of AM parts in consumer goods industry is to produce prototypes and models. Although the main use of additive fabrication is making prototypes, technology is developing towards “rapid manufacturing” which is also called as “direct digital manufacturing” (DDM) by the Society of Manufacturing Engineers. Industry projection for the future would involve the use of a single machine for the design, prototype, and creation of finished parts.

Figure 11: Consumer Goods

b) Electronics

The electronics industry is using AM to print electronic devices and components. Similarities between AM and direct write technologies can also be made, particularly for the deposition of conductive materials onto conformal surfaces. Inkjet technology can be used to print passive circuit components such as resistors, capacitors and inductors, as well as diodes, and circuit interconnections (figure 12)

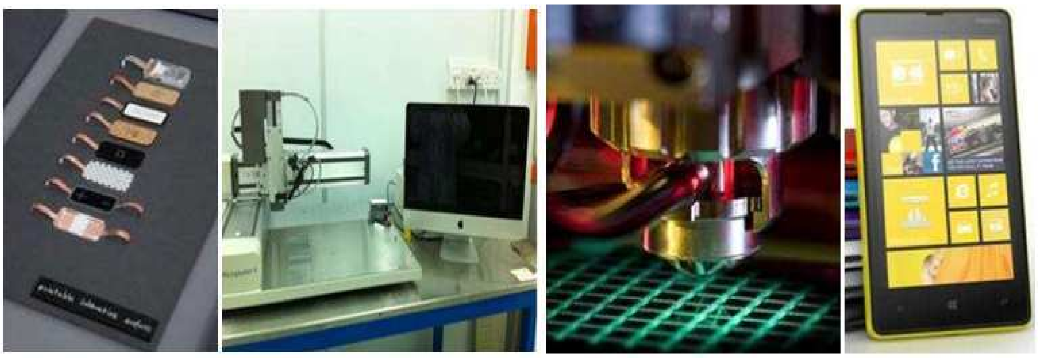

Figure 12: Electronics Equipment by AM Technologies

c) Motor Vehicles

More and more car manufacturers are using the benefits of AM in the production of concept cars. The process opens a new world of design freedom and allows concept cars to be built faster than with more traditional methods. 3D models are used for everything from concept creation to production planning, allowing design engineers to speed up and improve the development process. The automotive industry has historically used AM as an integral tool in the design process. The fast-paced design cycles in the automotive industry require a rapid prototyping solution that can produce almost any geometry with a variety of material properties, quickly and cost effectively.

Figure 13: Some of Motor Vehicle and its Component by AM

d) Medical and Dental

AM techniques have been applied within the medical and dental arena for the creation of assistive, surgical and prosthetic devices, surgical implants, and scaffolds for tissue engineering. For instance, AM allows complex parts to be created specifically for the patient direct from a 3D CAD model generated from a patient's CT or MRI scan. Accurate patient specific implants produced using the 3D scan data can reduce the removal of healthy bone, eliminate the need for bone grafting, promote effective planning of implantation/surgery and shorten the time of anaesthesia. There is also the possibility that the customisation enabled by AM will result in increased implant-life eliminating the need for further surgery. [ ]

Figure 14: Medical and Dental

e) Aerospace

AM is an attractive alternative manufacturing route for the aerospace industry, due primarily to its high material use efficiency and ability to process aerospace grade titanium and nickel alloys. AM is seen as an enabling technology for light-weighting or topology optimisation, because of its capability to create complex structures. This can have the additional benefits of improving performance and reducing waste. AM has also been used for testing of complex or difficult to implement designs, including extensive tests in 'full engine' rigs.

Figure 15: Aerospace

Although we can already see significant usage of AM in particular sectors, there is still a massive potential to further enhance its use and even enter new sectors. However, one of the present problems for AM is that many of the traditional manufacturing sectors are not aware of, or do not fully understand, how they can utilise AM. AM will replace certain manufacturing methods, but not all of them while it has the added potential to complement many of those it cannot substitute.

f) Architecture

In the field of architecture, AM is used to produce scaled replica models of buildings and constructions. A continued challenge in this field of application however exists in scaling down features such as window frames and guard railings. When scaling down a construction to a size that can be produced using AM, any such features virtually disappear and need to be reconstructed on the scaled CAD model – which is a time consuming exercise. Below is a selection of examples where 3D printing was used to construct architecture models.

Figure 16: 3D Printed Sport Stadiums

Figure 17: Architecture Model Printed in Colour

6. CHALLENGES AND OPPORTUNITIES

Additive manufacturing is disruptive in nature and has the potential scope to transform new ideas and methodologies outside of ‘conventional’ industry norms.

“As comparatively young technology, AM already today raises high expectations. Since AM is NOT just another

technology to replace conventional ones but requires a new thinking in entire business Models, Progress is needed in various elements of such a chain. Ignoring that and pushing AM too hard into traditional rules at this early stage may inflict damage on the technology and also ruin market reputation" (Lenz, 2013)

6.1 AM Challenges

The AM value chain can be described in five areas: 1) materials, 2) systems, 3) software, 4) application of design, and 5) production.[37] although all of these areas help in the creation and functioning of AM technologies, the market is fragmented with only a few key players in each area. Moreover, overall market penetration of AM is not very large (only about 1%) and the company's size limit investment in R&D indicates that one player cannot be active in all areas (Services, Licenses, Training and Seminars, Powder, Application Design, and Software).[39]

There are several challenges in widespread adoption of AM: (Energetic Inc. (2013), (Opens haw, E. & Cotteleer, M., 2014) and (Merissa Piazza, 2015)

- **Process Control**: Feedback control systems and metrics are needed to improve the precision and reliability of the manufacturing process and to increase throughput while maintaining consistent quality
- **Tolerances:** Some potential applications would require micron-scale accuracy in printing (Bullinger,2009)
- **Finish:** The surface finishes of products manufactured using additive technology require further refinement. With improved geometric accuracy, finishes may impart corrosion and wear resistance or unique sets of desired properties.
- **Bias toward conventional manufacturing** (Merissa Piazza, 2015)
  - AM has been used for prototyping for years, but the technology is now being used to directly manufacture products in small batches (Huang, Y et al, 2015).
  - PWC calls the road from using AM for prototyping to direct manufacturing the "long mile." Most manufacturers see AM as a tool for prototyping and small batch manufacturing, but not for large production runs(Price Waterhouse Cooper , 2014)
- **Economic/cost difficulties**(Merissa Piazza, 2015)**:**
  - High capital and material costs
  - Most parts are optimized for conventional manufacturing
  - How cost savings can be actualized through materials and assembly
  - Necessary improvements in AM product performance□ Supply chain geared toward traditional manufacturing
- **Intellectual Property**(Merissa Piazza, 2015)**:**
  - IP protection is important to recuperate investments made in the development of AM technologies
  - Estimates indicate that IP losses due to 3D printing will reach $100 billion by 2018. (*Gartner,2015)*

  - IP is considered a major issue since the marginal cost of 3D printing is significant (Price Waterhouse Cooper, 2013)
- **Educational challenges:**
  - AM is a multidisciplinary area, therefore it is difficult to train the workforce because technologies involve a variety of disciplines (modelling, physics, metallurgy, and statistics).
  - Difficult for one person to have adequate expertise in all areas to understand technology development
- **Materials capacity** (Merissa Piazza, 2015)**:**

One of the biggest challenges to widespread adoption of AM is the small amount of materials (e.g., polymers, metals, and ceramics) that can be used to fabricate items.46 Every year new materials are advanced in AM, resulting in better microstructures, and enhanced material tolerability.47 The types of materials used in AM (for more technical information (see Guo & Leu (2013):

Polymers are the most widely used material in AM. Most notably, nylon is the most widely used polymer because it melts and bonds better than other polymers (Guo, N. & Leu, M.C, 2013)

Metal products can be formed in a “direct” way – by melting metal particles together or an “indirect” way – by bonding the metal with post-processing. There are many ways and AM methods to form metals through the indirect or direct way (Ibid)

Ceramics are used in AM processing because of their chemical structures and resistance to high temperatures. Unfortunately, these materials can be brittle making them difficult to manufacture especially if complex geometries are involved. Examples of ceramics include alumina, silica and zirconia. Ceramics can be produced through indirect or direct process (Guo, N. & Leu, M.C, 2013)

Composites are, as their name suggests, materials that are combinations of two or more materials, either naturally (in nature) or engineered. Composites can be mixed uniformly or no uniformly to make different compounds (Ibid).

Functionally graded materials can be created through AM processing. Guo & Leu (2013) show that, “One example is a pulley that contains more carbide near the hub and rim to make it harder and more wear resistant and less carbide in other areas to increase compliance.” (Ibid)

To better understand and use advanced materials in AM processes, it is suggested that research in the following areas be conducted: 53

- Understand the basic physics and chemistry of AM processes
- Develop processes based on scalable material methods
- Develop machine modules that can be reconfigured
- Investigate why some materials can be used in AM and others cannot
- Develop better tools for micro- and nano- AM to build items atom by atom □ Develop sustainable materials

Other challenges in AM include understanding the fundamentals of materials, processes, and applications. For example, some scientists are grappling with the physics behind AM, while others question why certain materials can be used in AM and not others.

6.2 AM Opportunities

Overall, studies cite three major benefits and opportunities that AM can provide:

- Prototyping and reduced time to market
- Innovation
- Business case for widespread application

6.2.1 Prototyping & Reducing Time to Market

AM has been a game changer for rapid prototyping. AM allows companies to change design on the fly in a just a few hours, as opposed to the traditional method of creating a prototype from wood or metal from machine shops.

AM can contribute to entrepreneurial success because entrepreneurs can have a low cost mechanism to produce a prototype

Rapid prototyping is the vast majority of 3D printing users.

6.2.2 Innovation

- AM spurs innovation because it allows users to manufacture complex structures quickly and efficiently (Haung et al, 2015)
- There is conjecture that 4D printers are being built to incorporate “shape memory fibers” into inks to create different forms(Price Waterhouse Cooper (2014))
- Price Waterhouse Cooper (PWC) has conducted a survey of manufacturers that shows small firms are keeping pace with large firms in the adoption of 3D printing.
- Conversation has begun about how universities and industry can collaborate on this technology through technology transfer, but collaboration seems to be limited to federally funded programs (i.e. SBIR/STTR, NSF) (Haung et al, 2015)
- There is significant amount of funding in AM. Grants can be provided under:
  - SBIR/STTR
  - Federal Agencies: NSF, DoD, DOE
  - Centre for Aerospace Manufacturing Technologies (CAMT)
  - National Additive Manufacturing Innovation Institute (NAMII)

6.2.3 Business Case for Widespread Application

Costs Saving

There is a significant amount of academic literature of the cost savings attributed to AM. An excellent review of this literature can be found in Thomas and Gilbert (2014). According to Thomas and Gilbert (2014)

- It is more cost effective to use AM built aerospace parts.
- Additive of metal parts, compombined
- AM of metal parts, combined with part redesign, can show significant cost savings. The field is starting to consider the implication of electricity consumption in AM production as a component of the cost savings (Baumers et al ,2010 and Baumers et al 2011)

A 2013 article by Huang et al examined the societal impact of AM. The positive impacts of AM included: customizable healthcare products, reduced environmental impact (reduced energy use and reduced material use), simplified supply-chain. The authors call for more research on the cost savings due to energy reduction since this is a major cost for manufactures (Haung et al, 2013).

As manufactures can create products on demand with AM, the amount of inventory they need to keep on hand decreases. Inventory decreases come from the ability to manufacture needed parts on demand. Inventory costs are a significant portion of manufacturers' costs. Moreover, in traditional manufacturing if a manufacturer does not have a part in inventory, they have to order the part and this can delay production. AM can reduce these issues and costs (Walters et al, 2009 and Piazza, et al, 2014). According to Thomas et al Business cost savings can be achieved using AM because it can reduce the amount of transportation of parts with traditional manufacturing (Thomas et al, 2014). Dollar et al adds that, as the technology improves, the quality of AM machines will increase, while the cost will go down (Dollar et al, 2013). AM equipment has followed the digital technology progress model in which more capable and cheaper machines are introduced each year, following Moore's Law.

New Markets

There is significant discussion about technology advancements and innovation that takes place with AM, but little discussion on potential businesses and profits that can be made from this technology.

It is estimated that there are seven areas of revenue streams from this technology (Berger, L, 2013)

- System – creating standard and customized AM systems
- Services – maintaining AM systems, parts, and consumables
- Licenses – Licensing technology to other parties
- Training and Seminars – training and seminars on AM technology, design, and use
- Powder – sales of metal powder (some AM processes require material in powder form)
- Application Design – support in developing applications, and consulting on readiness
- Software – add-on and process software

Currently, metal powders, used in AM, are up to 30 times more expensive than their bulk counterparts; as the volume demand for metal powder increases, the price will decrease (Price Waterhouse Cooper, (2013) It is estimated that over the next few years the rate and speed of building products will increase while powder rates will decrease (Berger, 2013). Some researchers have suggested that examining how AM can fit into the lifecycle costs of components and create cost advantages is the best way to sell the technology (Lindeman, 2012). AM is also starting to be used in the consumer market. Products such as home electronics, entertainment components, computer and mobile device parts, shoes and fashion accessories, and customizable consumer products can use AM to create intricate designs or make it customizable.

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