



ADVANCES IN ADDITIVE MANUFACTURING PROCESSES IN ACHIEVING PRODUCTIVITY

Oppon, C.E.¹, Hackney, P.², and Shyha, I.³

¹*Department of Mechanical Engineering, Cape Coast Technical University, Ghana.*

^{2&3}*Mechanical and Construction Engineering Department, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, United Kingdom.*

¹pceoppon@yahoo.com

ABSTRACT

Additive Manufacturing which is also referred as three dimensional printing. Even though the technique has had remarkable improvements since its emergence over 25 years ago, still faces several technical challenges related to material characterization and availability compared with other conventional techniques. This paper aims at investigating the impact of additive manufacturing in achieving productivity. The objectives are to identify the strengths and weaknesses of the techniques. The methodology adopted was textual analysis of existing works. It provides a radically new method of production that enables new and better designs to be realised at lower cost with enhanced productivity and greater sustainability. It also transform supply chains and the way businesses operate that will result in completely new business models. The strengths identified are part complexity; material types and low volume production – advantage and the weaknesses are large parts; high accuracy and surface finish; high-volume production; and material properties.

Keywords: Additive manufacturing, cost, fabrication, prototyping, productivity.

INTRODUCTION

Additive Manufacturing (AM) which is the official industry standard term (ASTM 2792) for all applications of the technology encompasses many technologies including subsets such as: Additive Fabrication (AF), Rapid Prototyping (RP), 3-Dimensional Printing (3DP), Layer Manufacturing, and Solid Freeform Fabrication. Unlike conventional machining techniques, where material is removed successively until the desired shape or dimensions are achieved, AM is a layer-by-layer technique of producing three dimensional solids generated directly from 3D model data in which one layer is formed atop the previous one until the required geometry or shape is obtained. Whilst subtractive processes start from the top down, Additive processes start from the ground up (Nagel and Liou, 2012).



When Additive Manufacturing is fully understood and utilised correctly, an impressive niche and cost saving are possible. Parts and devices that are geometrically complex and have graded material compositions which otherwise are impossible to fabricate by conventional method as a whole can now be fabricated by AM technologies as a single customised component (Chu, Graf, and Rosen, 2008). The technology has tremendously helped trim weeks, even months of design, prototyping and manufacturing time whilst avoiding costly errors and improving product quality.

ADDITIVE MANUFACTURING TECHNOLOGY ADVANCEMENTS

Industry Growth

Figure 1 shows the percentage of cumulative industrial Additive Manufacturing systems installed in various countries from 1988 to 2012. Whereas the U.S. continued to lead by a large margin, Japan, Germany, and China followed as second, third, and fourth respectively as the largest installed bases (Vaezi, Seitz, and Yang, 2013).

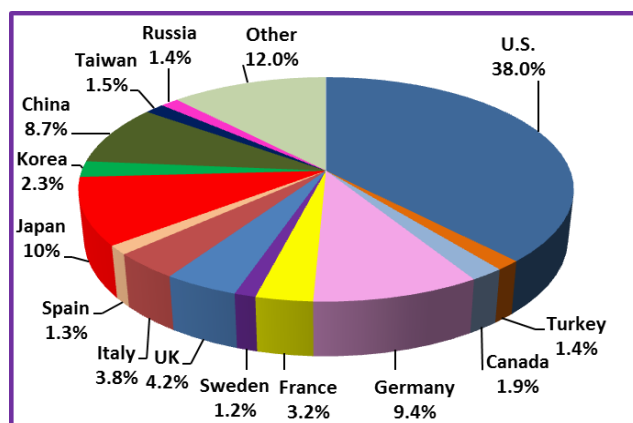


Figure 1: Countries Participation in Additive Manufacturing from 1988–2012 (Cumulative AM) (Vaezi, Seitz, and Yang, 2013)

Additive Systems Manufacturers

The demand for products and services from Additive Manufacturing technology keeps on increasing from time to time. Therefore, system manufacturers of AM are striving to meet the demand of users in various categories. Thirty five manufacturers from different parts of the world produced and sold AM systems in 2009 as against 34 in 2008. Figure 2 shows the 2009 unit sales market shares among manufacturers worldwide (Wohlers, 2010).

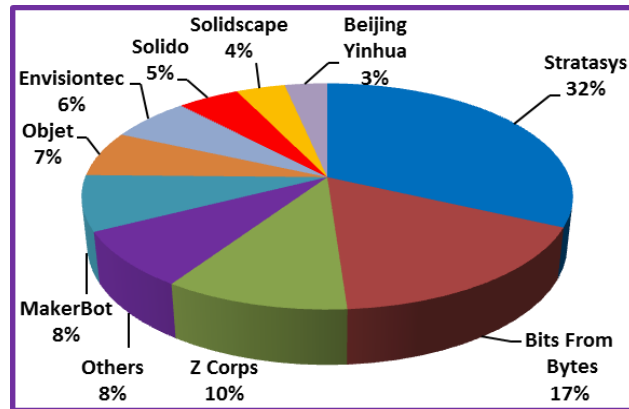


Figure 2: Additive Systems Manufacturers Worldwide (Vaezi, Seitz, and Yang (2013); Wohlers, 2010).

Characteristics of Additive Manufacturing

Strengths

In Additive Manufacturing, time used for traditional trial-and-error process is significantly reduced so a new product can enter the market quickly. With AM technology, because no custom tooling is needed, the lead time in completing parts is greatly reduced. Due to its short build time, the technology is normally described as “rapid”, therefore, companies can promptly create a unique part that can replace a worn or broken one which can avoid costly or untimely shutdowns. In Additive Manufacturing, irrespective of part complexity, once a part is created as a CAD model, it can be printed. Using AM, storage of bulky patterns and tooling is virtually eliminated (Pratt & Whitney, 2014).

Part Complexity

Since there is no tooling required in AM, internal features and surfaces which are complex are created directly when building the part. Also, any geometrical complexity of a part has little effect on build times, as opposed to the conventional manufacturing processes (Giannatsis, 2009). In conventional processes such as moulding and casting, complexity of part may not affect the cycle times, but can require several weeks in making the master pattern depending on the extent of part complexity. In machining, complex features directly affect the cycle time and may even require more expensive equipment, tooling and fixtures (Rosen, 2007).

Material Types

Additive Manufacturing technologies produce 3D parts by directing materials spatially in several possible ways: thermal, chemical, mechanical and/or optical. In thermal processes, the material is formed into an object after which it undergoes a thermal transition to maintain the shape (Gibson et al., 2010). In chemical-based processes, the manufactured shape is maintained by a chemical reaction (often polymerization). Mechanical processes rely on the physical deposition of cells or materials, and in optical processes, cells or polymers are manipulated using light (Gibson et al., 2010).

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Specifically, AM processes are able to produce parts in a variety of materials such as: plastics, metals, ceramics, composites, and even paper with properties similar to wood. Furthermore, some processes can build parts from multiple materials and distribute the material based on its location in the part (Gibson et al., 2010).

Low Volume Production - Advantage

Due to high initial costs on custom tooling and lengthy setup times for most conventional manufacturing processes, they are not very cost effective for low-volume productions. Additive Manufacturing supports low per-part costs for low volume productions in that it requires minimal setup time since it builds a part directly from the CAD model (Guo and Leu, 2013).

Weaknesses

Large Parts

Additive Manufacturing requires more time for a larger part in the X-Y plane and will require more layers to be built in the Z-direction for parts which are relatively tall (i.e. high in the Z direction). Hence, in AM, built times are largely dependent upon the part size, thereby making the processes best suited for relatively small parts. For casting and moulding processes, cycle times are typically controlled by part thickness and also for machining, cycle times are dependent upon the material and part complexity. Manufacturing large parts with additive processes is also not ideal due to the current high costs of material for these processes (Guo and Leu, 2013; Chua et al., 2010).

High Accuracy and Surface Finish

Additive Manufacturing cannot match the precision and finishes offered by machining, hence, parts produced by AM may require secondary operations depending on its intended use (Chua et al., 2010).

High-volume Production

Also, because per part cost of tooling at very large quantities becomes insignificant and cycle times remain shorter for moulding and casting, they (moulding and casting) are therefore preferred to Additive Manufacturing for high volume production (Chua et al, 2010; Hague et al., 2004).

Material Properties

Additive Manufacturing is limited to some individual material types and as a result, materials that offer certain desirable properties may not be available. The properties of the final part made by Additive Manufacturing methods may not also meet certain design requirements. Also, the current prices for materials used in additive processes are far greater than more commonly used materials for other processes (Chua et al., 2010; Hague et al., 2004).



Process Cycle of Additive Manufacturing Modeling

The AM process starts with a digital three dimensional representation of the object to be manufactured. Object representation (figure 3–stage 1) which has been generated by conventional CAD software or obtained from Laser Scanning, Computer Tomography (CT), Magnetic Resonance Imaging (MRI), or Mathematical Modeling software is stored in a Standard Tessellation Language (STL) file (figure 4–stage 2) (Sreenivasan et al., 2010).

The STL file is then imported into slicing software (figure 4-stage 3) in which the three dimensional digital object is sliced into layers (figure 4–stage 4) and oriented appropriately in order to define the best possible tool path for the printer (figure 4–stage 5) which then creates the object (figure 4- stage 6) via selective placement of material (Campbell et al., 2011).

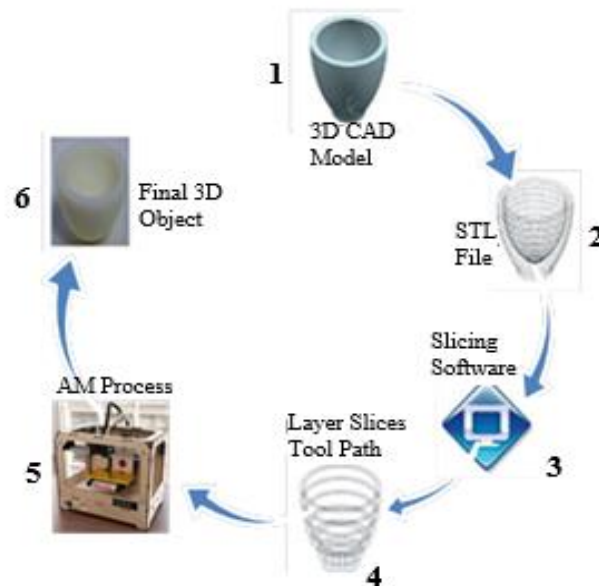


Figure 3: Additive Manufacturing Process Cycle

Additive Manufacturing takes information directly from Computer Aided Design (CAD) or animation modeling software and then slices them into digital cross-sections for the machine to successively use as a guideline for printing. Depending on the machine used, material or a binding material is deposited on the build bed or platform until material/binder layering is complete and the final 3D model has been "printed." It is a "What You See Is What You Get" (WYSIWYG) process where the virtual model and the physical model are identical (Guo and Leu, 2013).

Furthermore, it is important to select the appropriate building direction as this can determine specifications of the object such as cost, quality, and lead time. A direction chosen other than the optimum would lead to more layers required which will result in an increased lead time required to manufacture the product (Reeves, 2008).



Printing

When printing, the Additive Manufacturing machine first reads the design and then lays down layers of liquid, powder, or sheets of metal successively depending on the type of process by which way the model is built from series of cross sections. The final shape is created by joining together or automatically fusing together layers which corresponds to virtual cross section from CAD model. Most AM printers print a layer thickness of around 100 micrometres (0.1 mm), but some machines such as the *Objet Connex* series can print layers as thin as 16 micrometres with the X-Y resolution comparable to that of laser printers. The particles (3D dots) are around 50 to 100 micrometres (0.05–0.1 mm) in diameter (Wohlers, 2005).

If a model is to be constructed with contemporary method, several hours sometimes leading to several days depending on the method used and size and complexity would be needed. Additive systems can typically produce models in few hours, although it can vary widely depending on the type of machine used as well as the size and number of models being produced simultaneously. Conventional process such as injection molding can be less expensive for the manufacture of polymer products in high quantities, but Additive Manufacturing can be faster, more flexible and less expensive when producing relatively small quantities of parts. 3D printers give designers and concept development teams the ability to produce parts and concept models using a desktop size printer (Todd et al., 2005).

Finishing

The native resolution of a printer may be sufficient for some applications; if not, dimensional accuracy and surface finish can be enhanced by printing an object slightly oversized and then removing material with a higher-resolution subtractive process.

Some additive manufacturing techniques use two materials while constructing parts. The first material is the part material and the second is the support material (which supports overhang features during construction). The support material is later removed by heat or dissolved away with a solvent or water (Gibson et al., 2010).

Classification of Materials used in Additive Manufacturing

Additive Manufacturing Technologies are broadly classified in terms of material as: polymers, metals, ceramics, and composites. Some materials are applicable in more than one process whilst some processes also find themselves in many applications as shown in table 1 which summarizes the material groups, process(es) and specific material(s) applications.



Table 1: Classification of Materials Versus Corresponding AM Technologies/Techniques.

Material Group		AM Process(es)	Material(s)
Polymers	Thermo-setting	SLA, MJM	Photo-curable polymers
		MJM	Wax
	Thermo-plastic	SLS	Polyamide 12, GF polyamide, polystyrene
		FDM	ABS, PC-ABS, PC, ULTEM
		3DP	Acrylic plastics, wax
Metals	SLM	Stainless steel GP1, PH1 and 17-4, cobalt chrome MP1, Ti6Al4V, Ti6Al4V ELI and TiCP, IN718, maraging steel MSI, AlSi20Mg	
	LDM/LENS	Steel H13, 17-4 PH, PH 13-8 Mo, 304, 316 and 420, aluminium 4047, titanium TiCP, Ti-6-4, Ti-6-2-4-2 and Ti6-2-4-6, IN625, IN617, Cu-Ni alloy, cobalt satellite 21	
	EBM	Ti6Al4V, Ti6Al4V ELI, cobalt chrome	
Ceramics	SLA	Suspension of Zirconia, silica, alumina, or other ceramic particles in liquid resin	
	FDM	Alumina, PZT, Si ₃ N ₄ , zirconia, silica, bioceramic,	
	SLS	Alumina, zirconia, silica, ZrB ₂ , bioceramic, graphite, bioglass, and various sands	
	3DP	Zirconia, alumina silica, Ti ₃ SiC ₂ , bioceramic, and various sands	
Composites	Uniform composites	FDM	Polymer-metal, polymer-ceramic, short fibre-reinforced composites
		3DP	Polymer-matrix, metal-ceramic, short fibre-reinforced composites
		LOM	Polymer-matrix, ceramic-matrix, fibre and particulate-reinforced composites
		SLS, SLM	Metal-metal, metal-ceramic, ceramic-ceramic, polymer-matrix, short fibre-reinforced composites
	Functionally graded material (FGM)	LMD/LENS	CoCrMo/Ti6Al4V, TiC/Ti, Ti/TiO ₂ , Ti6Al4V/IN718
		FDM	PZT
	FEF	Al ₂ O ₃ /ZrO ₂	

(Guo & Lee, 2013)

Development of Additive Manufacturing

AM was initially used in similar applications of Rapid Prototyping and continuous research has resulted in a significant improvement in materials to be used from polymers to ceramics and metals and it is expected to be fully applied in full body organs by 2030 (Lee, An, and Chua, 2017). Figure 4 shows the development in AM where it was known as Rapid Prototyping together with future applications potential.

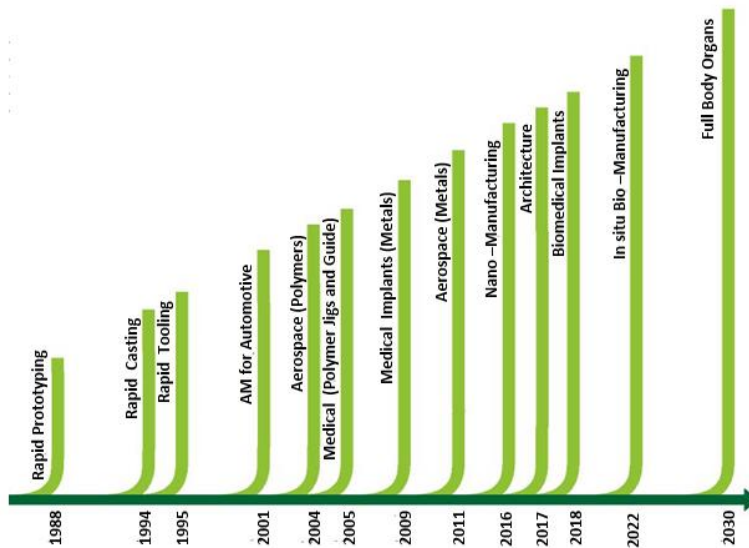


Figure 4: Development in AM with focus on Rapid Prototyping

Medical Applications

Additive Manufacturing has gained grounds in the medical field even though there is more room for improvements. One opportunity is its use for medical devices for planning and conducting surgery and custom surgical implants (Christensen, 2013). Custom prosthetics and orthotics are other potential applications for AM which were relatively early uses of AM due to the ability to produce custom-fit parts for highly variable joints, amputated limbs, and cavities (for example, ears for hearing aids) (Melchels, 2012). What makes AM technologies even more appealing in medical applications is that they utilize medical imaging data obtained by Computer Tomography (CT) or Magnetic Resonance Imaging (MRI), almost directly for the production of customized patient specific parts (Giannatsis, 2009).

Using Additive Manufacturing for a custom implant offers several advantages such as making operation less complex, reducing operating time and the associated risk to the patient involved with being in surgery for so long. It also reduces the possibility of repeating a surgery that is needed because it cannot be done right the first time (Salmi et al., 2012; Giannatsis, 2002).

Figure 5 shows a model of 14-month's old child heart built in three pieces using a flexible filament printed at the School of Engineering at the University of Louisville. This took around 20 hours and cost US\$600. This allowed the doctors to better prepare for a successful operation.

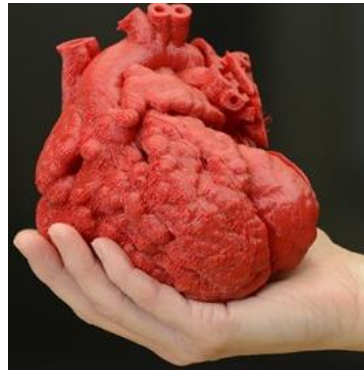


Figure 5: Additive Manufacturing Child Heart Model
(www.additivemanufacturing.com, 2014)

Aerospace and Aeronautic Applications

Additive Manufacturing is used for making non machinable complex parts for direct use preferably in the aerospace and the medical industry because of its mostly dense parts and very good mechanical properties (Gebhardt et al, 2010).

Aerospace and aeronautic components are critical parts which should be produced within very close tolerances to fulfil the high dimensional accuracy and surface finish. Also, when designing aerospace parts, producing of corners is avoided as much as possible to reduce stress concentration to the barest minimum and for this reason, critically chosen process should be used thereby making AM application more suitable (www.hk3dprinting.co.uk, 2013).

Additive Manufacturing technologies have proven to be a solution to parts complexities and therefore become the obvious choice for aerospace design as other forms of machining simply cannot meet the required standards. Also, often the case that the material required cannot be processed by conventional means and is too expensive in regards to buy-to-fly ratio are not relevant when it comes to Additive Manufacturing as the ratio is greatly reduced to minimize cost. Figures 6– 8 show examples of AM model aerospace parts.



Figure 6: Windform Tunnel Final Model (1:8 scale) for the Prototype of the Tilt Rotor
(www.additivemanufacturing.com, 2014).



Figure 7: AM Modelled Jet Engine
(www.additivemanufacturing.com, 2014)



Figure 8: AM Modelled Bladed Disk (Narine, 2007).

Tooling Applications

Figures 9 and 10 show samples of Additive Manufacturing or 3D printing used for the process of casting patterns for investment casting which is used to create a mold for use in metal casting.



Figure 9: Investment Casting Pattern
(Pratt & Whitney, 2013).



Figure 10: 3D Systems CastForm PS Material
Pattern (Pratt & Whitney, 2013).

Automotive Applications

Additive Manufacturing of automobile parts is a proven technology used by automobile engineers and designers to produce physical, tangible prototypes to work within design and testing. AM has been used to create a wide variety of parts in many materials, small and large automobile parts. Some examples of automobile parts produced by AM are Engine castings, engine parts, brakes, dashboards, handles, and knobs (www.protocam.com, 2014). Figures 11–14 show some automobile parts produced by AM technology.



Figure 11: AM Printed Turbocharger
(www.protocam.com, 2014).



Figure 12: AM Printed Vehicle Brake
(www.protocam.com, 2014).



Figure 13: Planetary Gearbox
(www.grabcad.com, 2014).



Figure 14: Engine Block
(www.grabcad.com, 2014)

Case Study at Northumbria University

Printed Skull

Figure 15 (1–3) shows a 3D printed skull at the Northumbria University 3D-Printing laboratory. The laboratory received the scanned data of the skull of the man in question who sustained a brain injury upon having a motor accident. The scanned data was saved in stl. file which was subsequently sent to the Objet 3D printing machine for printing. The figure 16 – stage 3 shows the printed model which took approximately 20 hours to complete the printing. The printed skull clearly shows the damaged part.

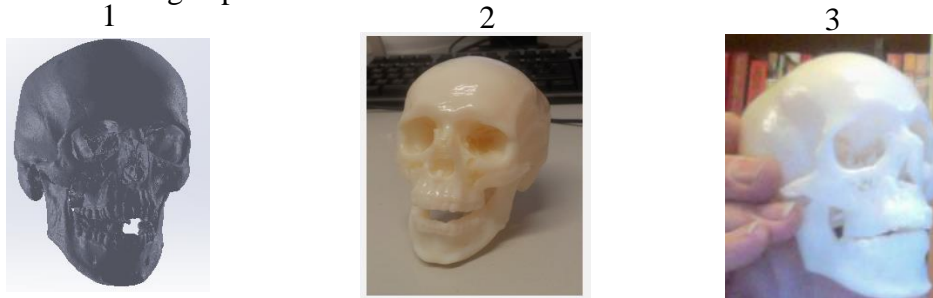
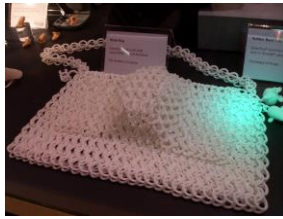


Figure 15: Printed Skull at Northumbria University

Stage	Activity
1	CT Scan Model (.stl file)
2	Printed Model Halfway Cleaned
3	Final Printed Model

Some Parts Printed at Northumbria University

Figure 16 shows models for several applications printed at Northumbria University, New Castle upon Tyne using various types of 3D facilities.



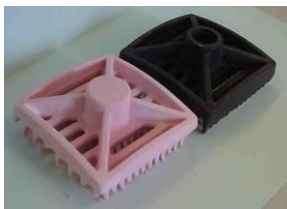
Nylon Bag (Z-Corps)



Mill (Z-Corps)



Duct (Z-Corps)



Square Hole Cutter (Z-Corps)



Millennium Bridge at
Newcastle upon Tyne



Auto Part
(Invasion Tech)



Human Brain
(Z-Corps)



Millennium Bridge at
Newcastle upon Tyne
(Z-Corps)



Northumbria University Logo
(3D Objet Printer)

Figure 16: Models Printed at Northumbria University

Conclusion and Future Work

Conclusion

Additive Manufacturing technology has a tremendous cost advantage when it is well understood and properly used. In Additive manufacturing, parts are precisely built by adding material layer by layer; hence, there is little or no waste of material as compared to traditional manufacturing where objects are created in a subtractive manner by trimming material (blank) and shaped to fit together properly. The problem of scrap disposal which is detrimental to the environment is eliminated and parts can be built on-site once the company can afford the machine and there is power supply. One of the major obstacles in Additive Manufacturing is surface finish which is critical to many engineering applications but not critical for most implants because coarse surfaces and porous structures are preferred as they favourably act as scaffolds for tissue growth (www.additivemanufacturing.com, 2013; Doubrovski et al., 2011; Karunakaran et al., 2013).

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Future Work

The research team intends to look at conducting several tests on Polyurethane (PU) material to determine its suitability for Additive manufacturing technology applications for further reduction of weight and cost. The problem of surface finish is another issue the research team hopes to tackle by incorporating a system with the existing AM technology to match with other machining processes such as CNC machining and grinding.

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