



Additive Manufacturing: A New Industrial Revolution- A Review

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Abstract

Additive Manufacturing Technology has been developing rapidly in the last 30 years. Nowadays, it covers a large number of industries and applications. This technology indicates great potential for future development and an increasing number of industries benefit from the advantages of the additive manufacturing techniques. However, aerospace, automotive and medical industries have been leader in the use of this technology and will obviously drive it into the future. Currently, Stereolithography (SL), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), and 3D Printing represent the most important technologies for processing of plastics, whereas Selective Laser Melting (SLM or Laser Cusing) and Electron Beam Melting (EBM) are mostly used to create parts from a metal powder. The aim of this paper is to provide a brief overview of the most commercially important additive manufacturing technologies currently available for the manufacturing industry. It introduces the basic principles of the major common processes, highlights some of the key applications and challenges and finally, presents the recent developments and future trends in the additive manufacturing technology.

Keywords: Rapid Prototyping, Rapid Manufacturing, Additive Manufacturing

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1. INTRODUCTION

Additive Manufacturing (AM) technology is the latest approach for the manufacture of small quantities or complex individual end-use items directly from Computer Aided Design (CAD) data. In today's highly competitive global market, the manufacturing industry is looking for cost savings, improved product performance and reliability, failure prevention, longer product life and better environmental protection. Furthermore, the Global competition is forcing industries to not only look for new ways to improve their production processes but also to focus on important factors such as product features, quality, cost and time to market to remain competitive. In response, new manufacturing techniques and advanced materials have to be established for the production of robust, complex and accurate parts.

AM techniques are counted as established means of accelerating the product development cycle in numerous industries. They offer opportunities to make products faster and usually at lower costs. The success of these techniques marked a revolution in product development and manufacturing and in general, they may be the answer and a solution for numerous issues mentioned above.

The most important is that these technologies are not only fast and flexible in the whole forming process but also they provide the ability to fabricate parts with unbounded geometric freedom, which is their most important advantage and the main reason why they exist. The impact of AM is far-reaching and the opportunities and advantages are extensive (1, 2, 3 and 4).

2. BACKGROUND

Historically, Rapid Prototype (RP) technology is one of the earlier AM- processes and was originally employed for producing prototype models. Within the last 30 years, RP has evolved rapidly from simple 3D additive manufacturing to sophisticated Rapid Manufacturing (RM) (5). As the move towards RM continues, the term "Rapid Prototyping and Manufacturing (RP&M)" has become increasingly common in the literature (6). The term RM refers to those RP- technologies that have gained acceptance as viable for manufacturing and improved to the extent that they are increasingly used to deliver final or end- use products. As this happens, the term RP&M is more and more used interchangeably with the term additive manufacturing. The word "Rapid", however,

is a relative term, as most of AM processes are actually quite slow. It actually refers to the reduced time from initial design to the production of the final part (7).

By the early 2010s, the terms additive manufacturing and Three Dimensional Printing (3DP) developed senses in which they were synonymous umbrella terms for all AM technologies, since the available technologies in this field are often based on the same concept and share the common theme of sequential- layer material addition/joining throughout a 3D work envelope under automated control (8). This led to the appearance of the name: “AM technologies” as an appropriate name to describe the processes that build 3D objects by adding layer- upon- layer of material(s) (9).

According to ASTM F2792-10, AM is defined as: “The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies.” The term AM encompassing many technologies including subsets like Rapid Prototyping, Layered Manufacturing Technology (LMT), Solid Freeform Fabrication (SFF), Additive Fabrication (AF), 3D Printing (3DP), Direct CAD Manufacturing, Instant Manufacturing, E- Manufacturing and Direct Digital Manufacturing (DDM).

2.1. Creating a CAD model of the design

AM processes are based on cutting the 3D drawing into 2D slides and building those slides layer by layer to a solid 3D model. The process simply consists of two phases: virtual phase (modeling and simulating) and physical phase (fabrication) (10). Common to AM technologies is the use of a computer, 3D modeling software (CAD), machine equipment and layering material (polymeric, metallic, ceramic and organic materials). Once a CAD drawing is produced, the AM equipment reads in data from the CAD file and adds successive layers of liquid, powder or sheet material in a layer- upon- layer fashion to build a 3D object directly from the 3D CAD model without the aid of moulds, substrates or any hard tooling, Figure 1 shows the process of data transfer between CAD and the AM system (11, 12).

However, all AM techniques employ the same basic five step process (13), namely:

1. Creating a CAD model of the design
2. Converting the CAD model in to STL format

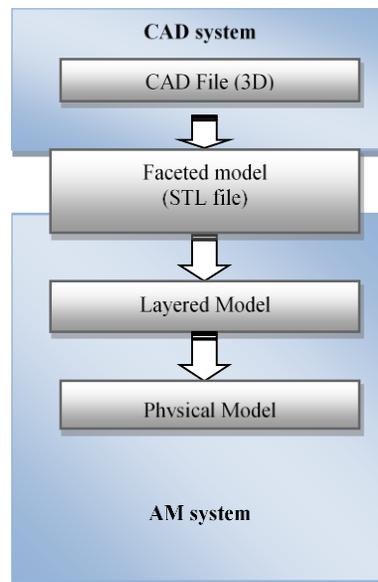


Figure 1. Data transfer between CAD and AM system (12)

3. Slicing the STL model in to thin cross sectional layers
4. Constructing the object one layer a top another
5. Cleaning and finishing the object

The Standard Triangle Language or Standard Tessellation Language (STL) file, is the standard for every AM process. The processes take the information from a computer- aided design (CAD) file that is later converted to an STL file. In this process, the drawing made in the CAD software is approximated by triangles and sliced containing the information of each layer that is going to be printed (14). Figure 2 illustrates a. STL file alongside its original CAD surface model (15).

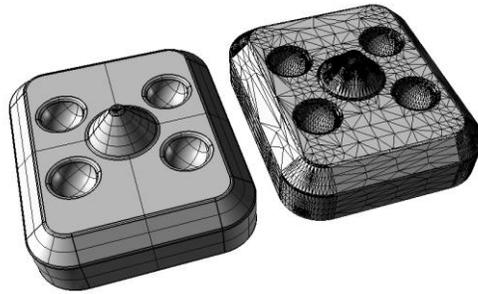


Figure 2. A. STL file alongside its original CAD surface model (15)

2.2. Classification of AM- processes

A wide range of technologies with varying benefits, disadvantages and potential are accommodated under the umbrella of AM. For the time being, there are about thirty AM techniques, but only few of them are widely used and dominant in the market. ISO/ASTM52900-15 defines seven categories of AM processes within its meaning: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination and Vat Photopolymerization (16).

The professional literature in AM field contains different ways of classifying AM processes, and as given in Figure 3, the classification of these processes is based on the state of the aggregation of their original material, mainly in: liquid, gaseous, powder or solid sheets (17, 18 and 19). Table 1 gives an overview of selected AM processes, whereas a comparison between them is presented in Table 2.

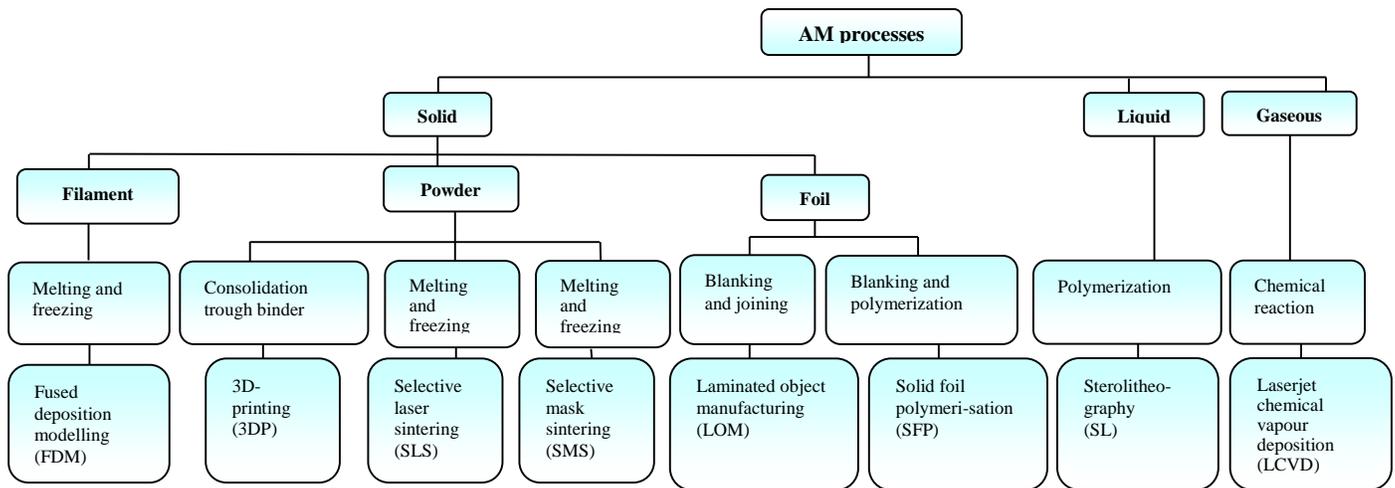


Figure 3. Overview of additive processing technologies (19)

Table 1. Material type and current most popular technologies for AM (10)

Material type	AM technology	Manufacturer	Materials
Photopolymer resin	SLA	3D Systems	Variety of epoxy resins and Nano- composite resin
	Envisiontec Perfactory (2D mask)	Envisiontec	Epoxy-acrylic resins, Nano-composite resin and acrylic resin (investment casting)
	PolyJet (3D printing)	Objet Geometries	Proprietary photopolymers and biocompatible resins
Plastic	SLS	3D Systems	Polyamide 12, GF polyamide, aluminum filled polyamide, composite plastics and Cast Form (polystyrene/wax system for investment casting)
	LS	EOS GmbH	Polyamide 12, GF polyamide, aluminum filled polyamide, flame retardant polyamide, carbon fiber filled polyamide and polystyrene (investment casting)
	FDM	Stratasys	ABS, PC-ABS, PC and biocompatible ABS
	Multi-jet modelling (3D printing)	3D Systems	Polymer (wax-like)
Metal	Multi jet Modelling	Solidshape	Polymer (wax-like)
	DMLS	EOS GmbH	Stainless steel GP1 and PH1, cobalt chrome SP1 and SP2, titanium Ti64, Ti64 ELI and Ti CP, maraging steel MS1, AlSi20Mg and EOS Inco718
	SLM Laser Cusing	MTT Concept Laser	Stainless steel and titanium Stainless steel, hot-work steel, titanium TiAl6V4, aluminum AlSi12, AlSi10Mg and nickel-based alloy (Inconel 718)
	EBM	Arcam	AB Pure titanium, Ti6Al4V, Ti6Al4V ELI and cobalt chrome

Table 2. Comparison of selected additive processing technologies (19)

	SLA	SLS	LOM	FDM	SMS	3DP
Materials	photopolymers (acrylic and epoxy resins)	metals, sand, thermoplastics (PA12, PC, PS)	foils (paper, polymers, metals, ceramics)	thermoplastics (ABS, PC, ABS-PC-blend, PPSU)	thermoplastics (PA12)	thermoplastics, cement, cast-sand
Part size (mm)	600x600x500	700x380x550	550x800x500	600x500x600	210x297x600	508x610x406
Accuracy	<0.05 mm	0.05–0.1 mm	0.15 mm	0.1 mm	0.05–0.12 mm	0.1/600x540 dpi ^{a)}
Cooling-off time/ curing time	no cooling-off or curing time up to 30 min	depending on geometry and bulk	depending on geometry	no cooling-off or curing time	depending on geometry and bulk	no cooling-off or curing time
Commercially available since	1987	1991	1990	1991	2005	1998
Costs (T €)^{b)}	from 130	from 150	from 150	from 50	from 150	from 25
Relative sample costs^{c)}	medium	medium–high	low–medium	low–medium	medium–high	low

^{a)} Dots per inch, ^{b)} Costs depend on the number, size and complexity of samples, ^{c)} Costs of machine and ancillary equipment (in thousand Euros)

The common AM methods included in this review article are considered to be the most relevant in the past and most promising for the future of the manufacturing industry; and these are:

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)
- Laminated Object Manufacturing (LOM)
- Three- dimensional printing (3DP).
- Electron Beam Melting (EBM)

However, none of the processes is excel in all respects; each process has restrictions imposed by costs, accuracy, materials, geometry and size. Each of these technologies has its varying strengths and weaknesses depending on the manufacturing details, type of material and post- processing (20, 21).

2.2.1. Stereolithography (SLA)

SLA was the first AM- technique developed and is still the most widely used process. It was developed by 3D systems of Valencia, California, USA, founded in 1986. This process is based on a photosensitive liquid resin which, when exposed to ultraviolet (UV) light, solidifies and forms a polymer. An SLA machine consists of: a build platform, resin bath, recoating blade, ultraviolet laser and a scanning device. A bath of photosensitive resin contains a vertically moving platform. A laser beam traces out the shape of each layer and solidifies the photosensitive resin. Figure 4 shows the SLA process (22).

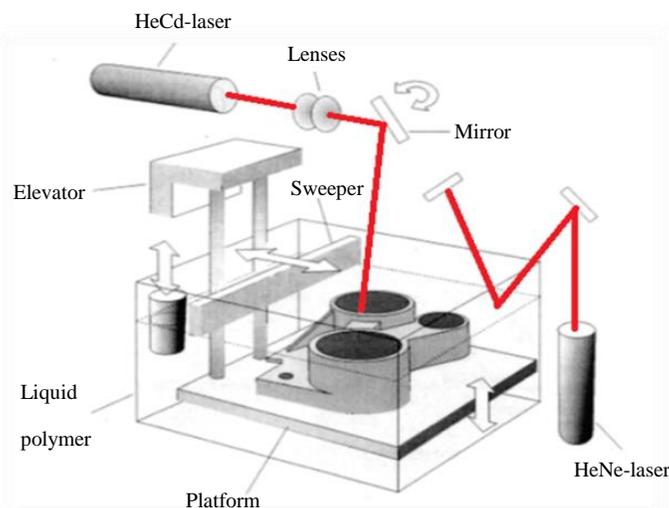


Figure 4. Principle of SLA system (22)

The surrounding resin gives no mechanical stability to the part; hence, a support structure is indispensable for the creation of overhanging layers. In a subsequent process, these structures are removed and the part is completely cured in a UV cabinet. In general, Stereolithography is considered to provide the greatest accuracy and best surface finish of any AM- technique. However, SLA is inexpensive compared to other AM processes; it exclusively uses a light- sensitive liquid polymer which has considerably poor mechanical properties, and so the fields of application are limited to the production of prototypes with reduced functionality (23).

2.2.2. Fused deposition modeling (FDM)

FDM is an additive manufacturing technology commonly used for modeling, prototyping and production applications. It was developed by Scott Crump in 1988 and was commercialized in the 1990's by Stratasys of Eden Prairie, MN, USA (24). The system is based on the heated nozzle process and consists of: a build platform, extrusion nozzle and control system. The overall arrangement of FDM is illustrated in Figure 5.

In this technique, filaments of heated thermoplastic are extruded from a tip that moves in the x-y plane. The extrusion head deposits very thin beads of material in a controlled fashion onto the build platform to form a layer. The material is heated just above its melting point so that it solidifies immediately after extrusion and cold-welds to the previous layers. The platform is kept at a lower temperature, so that the thermoplastic quickly becomes firm.

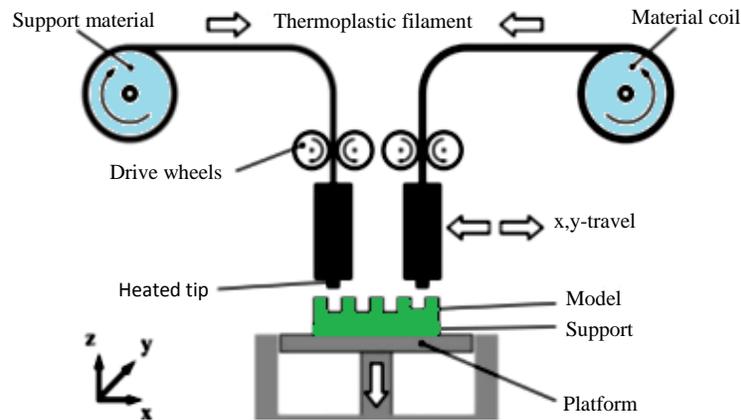


Figure 5. Fused Modeling System (19)

After deposition of a layer, the platform lowers and the extrusion head deposits the next layer onto the previous one. Supports are built alongside the deposition where required. These are fastened to the part either with a second, weaker material or with a perforated junction (25).

The FDM process creates functional prototypes, tooling and manufactured goods from commercially available engineering thermoplastics, such as ABS, sulfones, polycarbonate, elastomers, and investment casting wax as well as medical versions of these plastics. Unlike some additive fabrication processes, FDM requires no special facilities or ventilation and involves no harmful chemicals or by-products. FDM machines range from fast concept modelers to slower (high-precision) machines.

2.2.3. Laminated object manufacturing (LOM)

LOM is a process based on the principle of lamination. By definition, laminated object manufacturing [also known as laminated object modeling (LOM) or layer laminated modeling (LLM)], is a hybrid AM method, where an additive layer laminate process generates the part from paper, ceramic, polymer or metals followed by a subtractive step which cuts the outline with a CO₂ laser cutter. Figure 6a demonstrates the mechanism of a LOM machine.

In this technique, shapes are built with layers of paper or plastic. The binding together of the laminates is brought about by means of a thermally activated adhesive. A heated roller is used to glue the laminate to the previous layer. The outline of the part cross-section for each layer determined by the CAD file is then cut using a CO₂ laser beam. The laser also cuts the excess material in a cross-hatch pattern. The excess material provides support for subsequent layers. Finally, an overall rectangular outline is cut, freeing the cross-section from the paper roll. The platform moves down and the feed paper advances. The sequence repeats itself until the final layer is completed. The excess material, which is already sectioned into cross-hatched columns, is removed manually at the end of the process (26). Figure 6b shows the part building sequence of the LOM process.

LOM is used extensively for tooling and manufacturing by producing patterns and masters for sand casting, investment casting, cavity moulds for injection and tools for thermal forming and prototype stamping (26). At the present, the commercially available machines for LOM are LOM 1015, LOM 2030 and LOM 2030E.

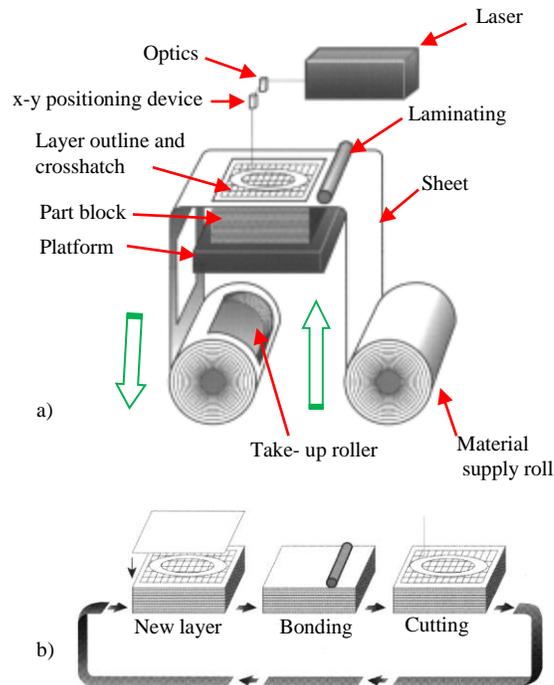


Figure 6. Mechanism of a LOM machine (a); and part building sequence of the LOM process (b), (source: Helisys Inc, CA, USA) (26)

2.2.4. Selective laser sintering (SLS)

SLS is a laser- powder- based AM method, which uses a laser as a heat source to fuse polymer powders into three dimensions' parts. It developed at the University of Texas and was initially commercially available from the DTM Corporation but was later bought out by 3D Systems in 2001. Needless to say, the SLS process, with a humble start in 1987, has grown to become one of the most well established additive manufacturing technologies (27).

In SLS, a fine powder is heated with a CO₂ laser which causes sintering of the powder particles and as a result they are mutually bound. The building of parts, as illustrated in Figure 7, is a repeatable two- step process: first; a roller is positioned beside one of the feed beds. This feed bed then raises a set amount and the roller pushes the raised powder across, covering the part bed with a powder layer. Second; with the layer of powder present, the laser starts to etch out the desired shape of the part in the powder, in effect melting the powder. Once this is done, the part bed drops down a set amount and the process continues from the opposite side with the other feed bed raising and the roller distributing another layer of powder over the part bed, followed by the laser etching out the shape. As the laser sinters the powder, each layer fuses together to give a full solid part.

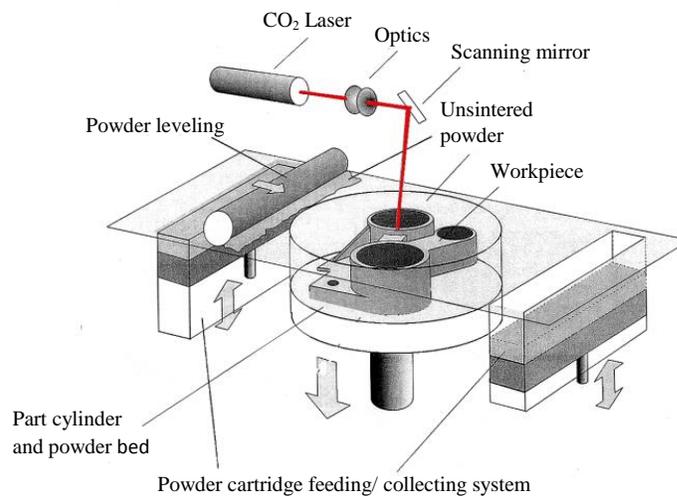


Figure 7. Principle of SLS process (22)

However, the process is self-supporting and parts can therefore be nested together. The selective nature of the laser process enables complex geometries to be achieved without compromising functionality. Finished parts are surrounded by, and often contain, unsintered powder; this loose powder is simply blasted away with an air gun and any post-processing work is then carried out (28, 29).

2.2.5. Three- Dimensional Printing (3DP).

The 3DP process is based on inkjet technology and was developed at the Massachusetts Institute of Technology for the rapid and flexible production of prototype parts, end-use parts, and tools directly from a CAD model (30, 8). From a computer (CAD) model of the desired part, a slicing algorithm draws detailed information for every layer. Each layer begins with a thin distribution of powder spread over the surface of a powder bed. Using a technology similar to ink-jet printing, a binder material selectively joins particles where the object is to be formed. A piston that supports the powder bed and the part-in-progress lowers so that the next powder layer can be spread and selectively joined. This layer-by-layer process repeats until the part is completed, Figure 8 demonstrates the mechanism of a 3DP equipment and Figure 9 illustrates the sequence of it (31, 32).

The process is self-supporting and has unprecedented flexibility. It can create parts of any geometry, and out of any material (including ceramics, metals, polymers and composites). Furthermore, it can exercise local control over the material composition, microstructure, surface texture and colors.

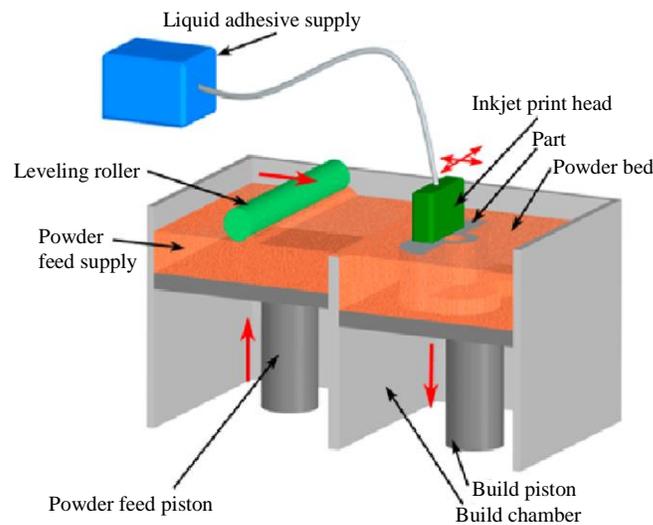


Figure 8. The mechanism of a 3DP equipment (31)

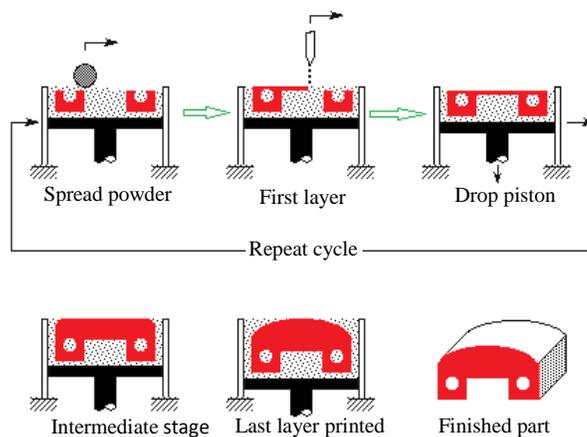


Figure 9. The sequence of 3DP process (32)

2.2.6. Electron beam melting (EBM)

EBM is a type of AM for production of metal parts, in which metal powders can be consolidated into a solid mass using electron beam energy. There is only one EBM based technology available (33, 34). Arcam Industries is a Sweden-based manufacturer of EBM. In the Arcam EBM[®] process fully dense metal components with excellent accuracy and good build speed are built up, layer-by-layer of metal powder, melted by a powerful electron beam. Figure 10 shows the Arcam EBM system (36).

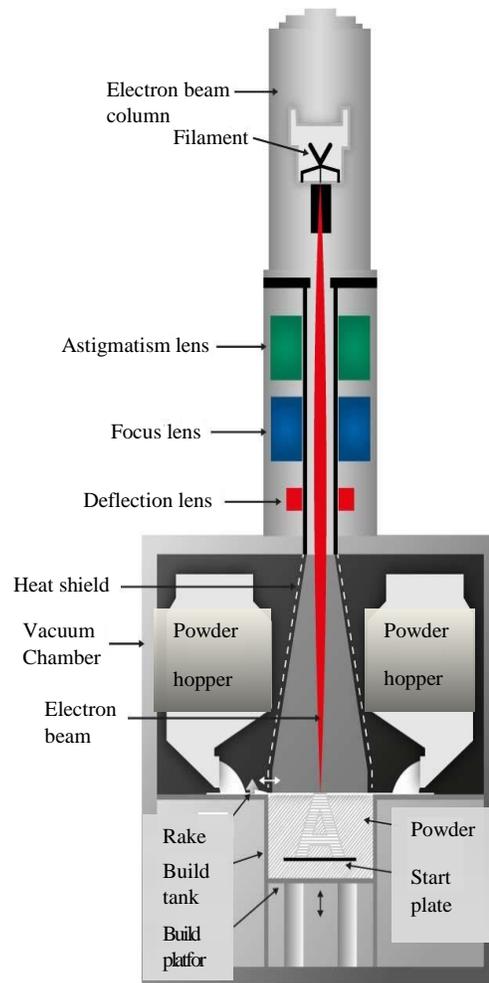


Figure 10. The Arcam EBM system (36)

The electron beam is managed by electromagnetic coils providing extremely fast and accurate beam control. The process takes place in vacuum and at high temperature, resulting in stress relieved components with superior material properties (strength, elasticity, fatigue, chemical composition, and microstructure) better than cast and comparable to wrought material. Common applications for EBM are the aerospace industry and medical devices (35). However, high power consumption, requirements of a vacuum chamber and high ongoing costs are among the disadvantages of EBM (34).

Currently, materials for EBM include commercially pure Titanium, Ti-6Al-4V, Ti6Al4V ELI, Titanium Grade 2, CoCr, Inconel 625 and ASTM F75. The Arcam EBM machines (Arcam Q10 plus and Arcam A2) are designed around the same concept; they utilize a high power electron beam that generates the energy needed for high melting capacity and high productivity.

3. APPLICATIONS

The applications of AM are virtually limitless. Early use of AM in the form of Rapid Prototyping primarily focused on preproduction visualisation models. As additive manufacturing methods advance, new application areas became possible (18, 37). Today, AM is already widely spread within known fields of application, such as aerospace, automotive and electronics industries. Progressively, AM technologies are being applied within the medical sector, and even consumer industries (the sports, the fashion, the furniture and the jewelry industry). AM applications timeline is given in Table 3.

Table 3. AM applications timeline: past, present and potential future of AM developments and applications (38)

1988–1994	rapid prototyping
1994	rapid casting
1995	rapid tooling
2001	AM for automotive
2004	aerospace (polymers)
2005	medical (polymer jigs and guides)
2009	medical implants (metals)
2011	aerospace (metals)
2013- 2016	nano-manufacturing
2013- 2017	architecture
2013- 2018	biomedical implants
2013- 2022	in situ bio-manufacturing
2013- 2032	full body organs

Three of the fastest- growing areas for AM applications include: automotive, aerospace and medical sectors. These industries have been leader in the use of AM and will drive it into the future. The growth in the automotive sector becomes part of the car industry in many industrialized counties, where AM for automotive parts (including engines and vehicle bodies) is showing increasing potential.

AM holds significant potential for the aerospace industry, which requires parts that are lightweight, strong, and geometrically complex- and typically produced in small quantities. The technology is already being used for a great variety of applications within the aerospace industry. For instance, the following parts have already been manufactured additively (9):

1. Aerospace landing gear components, (Figure 11)
2. Gas turbine combustion chamber
3. Gas turbine blades

**Figure 11.** Photo of an aircraft landing gear component (4)

The medical industry is another leading user of AM. It is being used to create customized medical devices that closely replicate the human form. The success of AM in the biomedical sector rests with its ability to create customized prosthetics, implants, replacement tissues and intricate body parts, including blood vessels (38).

Beyond these automotive, medical, aerospace uses, AM technology has applications in many other industries, ranging in size from miniature instrumentation to large structures. In fact, the applications of AM are so broad that they cannot be easily classified, but several are seen on a recurring basis, such as specialized manufacturing fixtures and tools, power generation equipment, robotics, heat exchangers, and thermal controls (39).

4. CHALLENGES

The field of AM is just over thirty years old. In spite of this, significant progress has been achieved in widening the use of this technology and in the development of new processes and materials. However, to achieve long- term growth in AM and realize its full potential, there are still many barriers and challenges that must be broken before wide spread adoption of the technology is economically viable. The high cost of AM machines and materials, the number of materials available, the size of the objects and build time are still significant hurdles for successful commercialization of the technologies (39). Other challenges include: the productivity, the mechanical properties and the accuracy of the final produced parts.

In order to accelerate the technology and overcome the above mentioned barriers, there must be focused attempts to improve the materials, software programs, product reliability, machine speed and size. However, to satisfy the specific requirements of a growing

number of new applications, research studies have been conducted to answer numerous questions and issues have been raised, such as (40):

- How can the build- up speed be improved?
- In what way can new machine concepts contribute to a higher productivity?
- Which automation measures keep the costs low?
- How can the dimensions of the components be increased?
- How can the components be configured and designed process- orientedly?
- Which measures improve accuracy and surface quality?
- How can process stability be improved by process monitoring?
- Which measures are necessary to certify the components?
- Which powder properties must be fulfilled so that it can be applied as a material?
- How can the material spectrum be expanded through standardized qualification measures?

5. RECENT DEVELOPMENTS AND FUTURE TRENDS

For the past three decades, researchers and engineers have focused on improving old and creating new AM techniques, as well as developing novel materials (41). In fact, AM technology has been developing rapidly in the last 30 years. The continuous and increasing growth it experienced since the early days and the successful results until the present time, allow for optimism that additive manufacturing has a significant place in the future of manufacturing and great potential for future development. AM is widely billed as ‘the next industrial revolution’ and will propel the fabrication modes forward, and bring in a new era for customized fabrication by realizing the five “any’s” namely: use of almost any material to fabricate any part, in any quantity and any location, for any industrial field (42).

As shown in Figure 12, Wohler’s Associates reports that, despite challenges, growth continued in many segments of the diverse industry, particularly in metal AM and the desktop 3D printer segments. In 2015, 62 manufacturers sold industrial- grade AM systems (valued at more than \$5,000), compared to 49 in 2014, and twice as many as the 31 companies that sold industrial systems in 2011. Furthermore, the AM industry (consisting of all AM products and services worldwide) grew 25.9% (CAGR) to \$5.165 billion in 2015. The Compound Annual Growth Rate (CAGR) for the previous three years was 33.8%. Over the past 27 years, the CAGR for the industry is an impressive 26.2% (43).

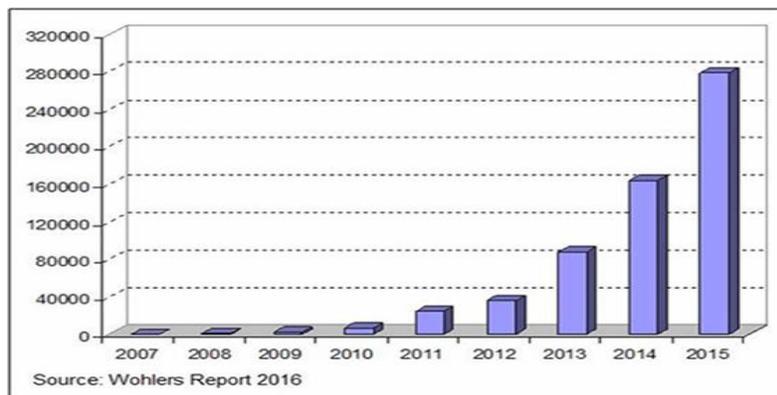


Figure 12. The growth of AM in terms of sold industrial- grade AM systems per annum (43)

The latest trends of research in AM area include (2):

- study of material properties and development of new/ advanced materials
- advancements in laser technologies, various software tools and advanced controls support to AM
- development of new methods of layer deposition and build techniques
- improvement of the mechanical properties of components as well as their surface quality and geometric accuracy
- exploring next- generation systems to overcome technology barriers for manufacturing (in terms of: bigger, faster, and cheaper)

6. CONCLUSION

The past three decades have witnessed the emergence and development of new manufacturing technology known as “Additive Manufacturing”. AM refers to various processes used to synthesize a three- dimensional object on a layer- by- layer basis.

With improvements in AM technology the equipment, processes and materials have all developed to the extent that AM techniques are used currently more and more in many industrial branches to manufacture functional parts and end- use products rather than prototypes.

Although AM technology has been significantly developed and improved, many challenges and issues remain to be addressed. The high cost of AM machines and materials, the number of materials available, the mechanical properties, the size and the accuracy of the final parts produced represent the major barriers in adoption of AM in industry. In spite, the AM technologies continue to develop and already there are plenty of applications where the benefits outweigh the limitations and risks of AM. The aerospace, automotive, medical industries and electronics were identified to be the most promising business opportunities for the application of AM in the future.

Finally, AM is growing at an impressive rate. The continuous and increasing growth experienced since the early days and the successful results up to date, additive manufacturing will obviously take a large share of manufacturing processes and have a significant place in the future of the industrial Manufacturing.

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