Review Paper

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The Current State, Outcome and Vision of Additive Manufacturing

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Abstract

Additive Manufacturing defines the fabrication of objects by successive consolidation of materials, layer by layer, according to a three-dimensional design. The numerous technologies available today were recently standardized into seven categories based on the general method. Each technology has its own set of advantages and limitations. Though it very much depends on the field of application, major assets of additive manufacturing compared to conventional processing routes are the ability to readily offer complexity (in terms of intricate shape and customization) and significant reduction of waste. On the other hand, additive manufacturing often suffers of relatively low production rates. Anyhow, additive manufacturing technologies is being given outstanding attention. In particular, metal additive manufacturing emerges as of great significance in industries like aerospace, automotive and tooling. The trend progresses toward full production of high value finished products.

Key Words : Additive manufacturing, Rapid manufacturing, Three-dimensional printing, 3D Printing, Free-form fabrication, Direct digital manufacturing

1. Introduction

Additive Manufacturing (AM) has been developed for over three decades. ASTM International, which created in 2009 the ASTM committee F42 on Additive Manufacturing Technologies, defines AM as[1] : “A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.” Over the past ten years, a worldwide enthusiasm arose for what have been commonly called nowadays 3D-printing technologies. Emergence of AM is largely due to progresses in development of both technologies and materials availability. In short, AM has the capability to produce any material, of any shape and for any industry. However, in spite of this outstanding potential, AM technologies struggle to find their rightful place in the industry. It is perceived by some as the ultimate breakthrough in process engineering promised to revolutionize the manufacturing world, by others as entertaining technologies with very limited industrial legitimacy.

It is rather difficult to give a clear, concise and exhaustive picture of AM processes as the amount and variety of both technologies and materials are important. Many agree the origin of AM can be attributed to the first commercialization of stereolithography in 1986 by 3D Systems[2]. Four key patents from the late 1980s and early 1990s can be considered the groundworks of AM [3]: vat polymerization[4], powder bed fusion[5], material extrusion[6] and binder jetting[7]. ASTM International, with the will to standardize the terminology related to AM, has recently classified the technologies based on their general method[1]. Seven categories were defined: binder jetting, direct energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat polymerization.

Many technologies are available today and differ essentially by the power source (light, heat, laser beam, electron beam), the base material nature (polymer, metal, ceramic, composite) and form (liquid/paste, fiber, powder, sheet). Each technology presents advantages, drawbacks and limitations. This short paper is an attempt to readily identify the current state of AM technologies, the challenges associated with AM and the future trends.

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Fig. 1 Additive manufacturing process chain

2. Additive manufacturing technologies

The generalized Additive Manufacturing Process Chain, which is common to all AM technologies, may be described by a sequence of eight key steps described in Fig. 1.

As it was suggested in introduction, it is difficult to promptly classify AM technologies. Whether the baseline technology is considered (lasers, jetting, extrusion, etc.), the type of raw material (polymer, metal, ceramic, etc.) or the form of the base material (powder, liquid, wire, etc.) for example, several AM technologies may belong to different categories. Many attempts have been made by various authors in scientific articles and text books using different criteria (the list is definitely not exhaustive)[2,3,8-11]. The scope of this paper is not to give a complete picture of the many AM systems available today. Nevertheless, Fig. 2 shows an example of significant AM systems organized according to the ASTM International nomenclature[1]. ASTM International provides several standards regarding Additive Manufacturing Technology. In addition to the terminology previously mentioned, standards regarding design, materials and processes and test methods are available[12]. For more details about the technologies, the reader is kindly invited to consult the excellent and abundant literature (for example[8]). A glossary is given at the end of the article listing the abbreviations commonly used and adopted in the present paper.

Of the many systems available, which some are mentioned in Fig. 2, each one has its own advantages, limitations and drawbacks. For example DLP, a photopolymerization process involving selective solidification of liquid curable resins by ultraviolet radiation, exhibits much high resolution and better surface finish when compared to FDM for the production of plastic parts. On the other hand, the cost of raw materials, e.g. the photocurable resin system is significantly higher than that of thermoplastic wires used in FDM. In another example, one may look at SLM and EBM (an example of production costs analysis can be found in[13]). Both technologies are acknowledged for their outstanding ability to produce metal parts with intricate shapes. Each system claims his share of advantages (and drawbacks) over the other. The two powder bed fusion processes have similar approach, selectively melting powders by means of a laser beam or an high-energy electron beam, respectively. EBM can boast to have significant higher building speed and lower energy consumption while SLM offers better resolution and surface finish. There are countless comparisons possible which brings to light one of the major dilemmas to consider AM in modern manufacturing. The

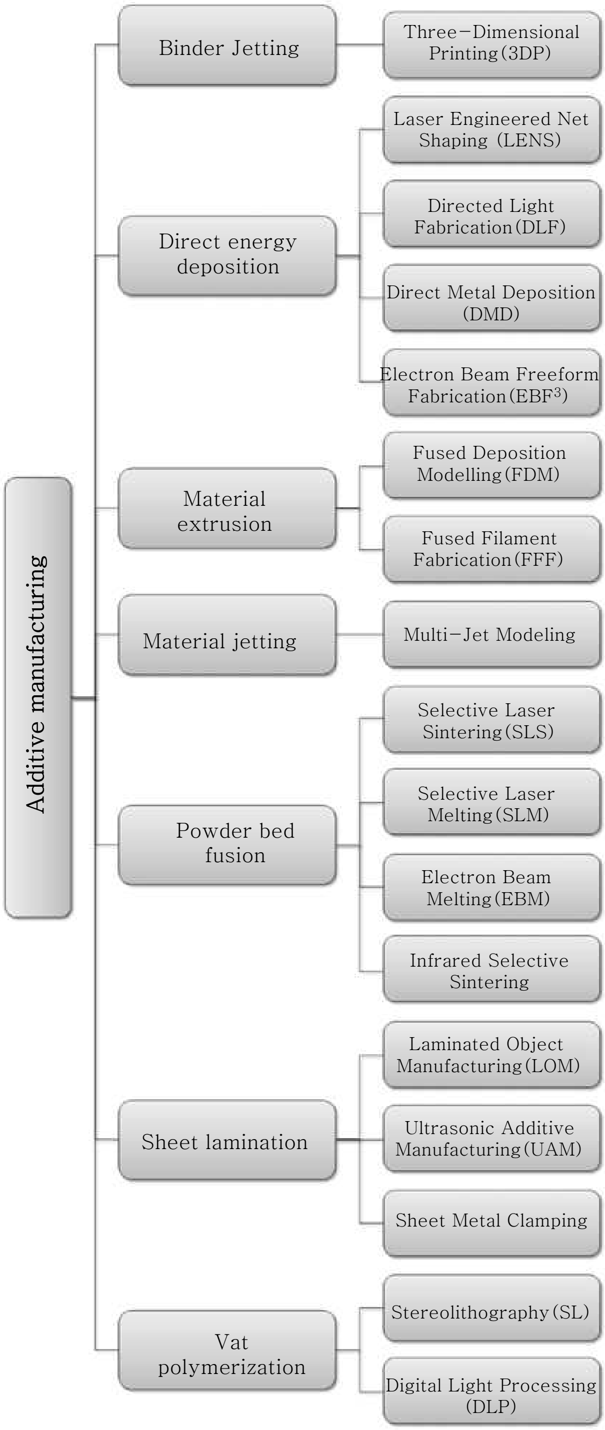

Fig. 2 Additive manufacturing technologies organized according to the ASTM nomenclature

suitable technology depends on the products, materials, costs and more. This is one of the reasons why AM processes have difficulties to find their place in modern manufacturing.

3. Current state of additive manufacturing

As a rather young approach, AM struggles to impose itself despite the general enthusiasm aforementioned. One thing which no one argues is the versatility and capability to produce virtually anything. However, the ability to produce something does not necessarily mean it is the way of choice. Accordingly, AM processes compete with the conventional manufacturing processes such as machining, casting, injection molding, and many more. For example, the AM cost study by Baumers et al.[13] concluded a relatively low processing rate for EBM and DMLS (essentially SLS for metal) when compared to injection molding or machining[14]. In addition, several AM technologies deal with additional limitations in terms of surface finish, dimensional accuracy or materials properties though it can also be found in conventional manufacturing routes. There are also limitations specific to AM in some case such as unprocessed material removal or the necessity of supporting structures[15].

As mentioned already, each technology has its proper set of advantages and drawbacks. Regardless of the actual AM process (such as the ones listed in Fig. 2), the main advantage of AM when compared to conventional processes is the simplicity to produce complex and/or customized products. The ability to build practically any geometrical feature has an outstanding engineering interest. It especially allows redesigning parts and products with obvious assets such as weight reduction, absence of assembly or better performances. This is particularly valuable in aerospace and automotive industries, continuously trying to increase the “buy-to-fly” ratio and lower fuel consumption and harmful emissions. It is also possible to manufacture parts with very complex geometry which may be difficult by conventional manufacturing. Moreover, the capability to readily manufacture highly customized products is rather unique to AM and very important to the medical field, other than pleasing customers with highly personalized products. These benefits proper to AM are often referred to as “complexity for free”. Another major benefit of AM over conventional manufacturing is the reduction of waste materials. When compared to traditional machining operations for example, which required an initial excess of material to be removed, AM is referred to as a “zero waste and efficient production”. The unprocessed material is completely reusable for most of the technologies. This is particularly significant when dealing with materials of high cost (such as expensive metals). The major limitation of AM, on the other hand, is the low degree of automation and processing rates with respect to conventional manufacturing routes. This is significantly detrimental to high volume production. Conner et al.[16] accordingly proposed a reference system for manufactured products based on the level of complexity, customization and production volume. It is concluded that AM in its current state is beneficial over conventional manufacturing routes for products with high level of complexity and/or customization and relatively low production volume. However, this study does not take into consideration the actual cost of production considering cost of raw materials and materials waste reduction, machine costs, labor costs, pre-processing and post-processing operations, effective volume of materials, etc. A valuable cost analysis realized by the NIST may be found in[17].

Several studies may be found in the literature focusing on the current market of AM. The total market for AM includes the systems (for example the machines themselves, software and related business), the services (such as contract manufacturing, training, consulting, maintenance operations, etc.) and the materials. One may consult for example the excellent reports from Wohlers Associates[2] or Roland Berger Strategy Consultants[18,19]. It can be mentioned that the AM market is in constant growth. It is reported in particular that since 2010 the CAGR for the AM industry, or the mean annual growth rate, has shown a growth of 30%. Moreover, the market is expected to quadruple over the next 10 years. Nevertheless, the AM market is still rather small with a value of 3.1 billion euros in 2014[19].

4. Evolution of additive manufacturing

Given the considerations stated in the previous section, it makes little doubt that AM technologies will increasingly settle in the processing field. The most optimistic even foresee a revolution. The economist titled in 2012 “a third industrial revolution”[20]. An enthusiasm shared by a number of companies, starting from the leaders in AM such as 3D Systems[21], Stratasys[22], EOS[23], Envisiontec[24], SLM Solutions[25], Arcam AB[26]. AM is nowadays all over the Internet. Several books and reports were published in the past few years as reference to AM (for example)[2,8,10,27-29]. Fig. 3 shows the number of results displayed by the website science direct (www.sciencedirect.com) when searching for the general term “Additive Manufacturing”. This is representative of the exponential enthusiasm about AM technologies. It should also be mentioned at this point the European AMAZE project[30]. This 20 million euros project aims at rapidly producing large defect-free additively-manu-

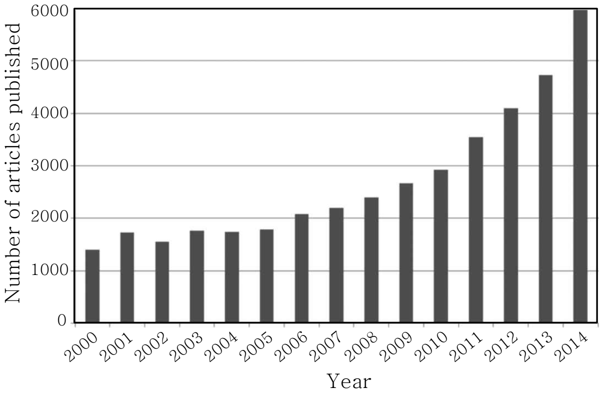

Fig. 3 Number of results in sciencedirect.com for "Additive Manufacturing" (www.sciencedirect.com)

factured (AM) metallic components for use in high-tech sectors such as aeronautics, space, nuclear fusion, automotive and tooling. This is only one of the many projects funded by the European Commission. For more information, one may consult the report from the EC Workshop on Additive Manufacturing[31)]. There are also strong investments in the field of AM all over the world, led by the United States (in particular through America Makes - The National Additive Manufacturing Innovation Institute)[32)] and China.

Despite the bright future envisaged for AM and the constant evolution of the related technologies, a number of issues should be addressed. First of all, the rather low production rate should be the major concern. This leads in particular to rather high cost per volume. Efforts are needed, and expected, to significantly increase the building rate in AM. For example, the multi-laser approach in powder bed processing is developed by SLM Solutions[33).] Another approach in powder bed processing consists in optimizing the powder deposition. Decreasing the layer deposition time, simultaneous deposition and sintering/melting of variable layer thickness may effectively increase the production rates. A second future prospect regards the price of raw materials whether powders or photopolymer resin is concerned. With the extensive democratization of AM technologies, the demand and thus the cost of raw materials is likely to decrease. For example, the gas atomized metal powders initially produced for Hot Isostatic Pressing (HIP) or Metal Injection Molding (MIM) may surely be used in AM of metals. Metal powders are supplied either by AM manufacturers themselves or companies such as Höganäs[34)], Sandvik Osprey[35)] ATI[36)] or TLS[37)] to name a few. Several reports regarding the global metal powders market announce a significant increase of the demand in the next ten years (for example [38)]). Finally, the last important concern involves the volume of AM parts which remains restricted by the rather low volume chambers of AM technologies. This is not perceived as an issue at the moment and reliability of the process for large chambers is critical (let's mention the vacuum environment of the EBM process for instance).

5. Conclusions

Additive manufacturing (AM) has raised a tremendous interest in recent years and will most probably continue to seduce. The different technologies have demonstrated significant advantages compared to conventional manufacturing routes. The greatest advantages of the layer manufacturing approach are the possibility to readily produce complex geometry and the ease to customize the products. Efforts are still necessary to increase the production rate in order to compete with conventional manufacturing of high volume productions. At the current stage, AM technologies are of great significance for the manufacturing of products with high degree of complexity and customization, and low volume production. It also offers important insight regarding materials waste and production efficiency. In short, while additive manufacturing is still in need of research and development, the envisaged benefits of such technologies and the amount of investment dedicated worldwide, especially towards metal additive manufacturing, suggest a bright future is awaited.

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[Glossary]

3DP: Three-Dimensional Printing
AM: Additive Manufacturing
ASTM: AmericanSociety for Testingand Materials
CAD: Computer Assisted Design
DDM: Direct Digital Manufacturing
DLF: Directed Light Fabrication
DLP: Digital Light Processing
DMD: Direct Metal Deposition
DMLS: Direct Metal Laser Sintering
EBF^3: Electron Beam Freeform Fabrication
EBM: Electron Beam Melting
FDM: Fused Deposition Modelling
FFF: Fused Filament Fabrication
HIP: Hot Isostatic Pressing
LENS: Laser Engineered Net Shaping
LOM: Laminated Object Manufacturing
MIM: Metal Injection Molding
NIST: National Institute of Standardsand Technology
PBF: Powder Bed Fusion
SL: Stereo Lithography
SLM: Selective Laser Melting
SLS: Selective Laser Sintering
UAM: Ultrasonic Additive Manufacturing

Mathieu Terner graduated in 2010 from Ecole des Mines d'Albi (France) in Process Engineering and Materials for Aerospace and received his Doctorate (Ph.D.) from Politecnico di Torino (Italy) in 2014 in Materials Science and Technology. His research focus on metal additive manufacturing, innovative materials for high temperature and processing.