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Current advances in additive manufacturing

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Abstract

Additive manufacturing is a topic of high growth in recent years in both academic and industrial terms. Based on important advantages such as the possibility to manufacture complex geometries, the technology is being continuously developed and improved. So, additive manufacturing is rapidly overcoming some of its initial limitations and, thus, increasing its applications in a wide range of industrial sectors. In addition, additive manufacturing is of public interest due to the opportunities and applications that it offers, or it may provide. The article presents the basics of the technology, highlighting its main advantages and limitations. Moreover, it aims to collect the latest trends (e.g., 4D printing, bioprinting, hybrid processes and micromanufacturing), applications and developments that this technology currently has.

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1. Introduction

Additive manufacturing, also called 3D printing, has been around for more than 30 years and has gained public and commercial interest because it provides important advantages such as printing complex geometries in one piece without the need to assemble. The growth of additive manufacturing is due to a constant development of the technologies and the ability to work with a wide range of materials. The development of the technology is driven by the demand for customized products, shorter product development cycles, greater focus on sustainability, reduced manufacturing costs and lead times, as well as new business models [1]. Additive manufacturing has the three concepts of a revolutionary idea: universal, practical and efficient [2] and, thus, conventional manufacturing begins to give way to these new technologies [3].

The technology is rapidly expanding to a large number of industrial sectors such as aeronautics, automobile and biomedicine, with significant growth in the medical device and wearables markets [4]. However, it still has disadvantages such as low productivity, low quality and uncertainty of the mechanical properties obtained [5].

Within the context of Industry 4.0, additive manufacturing plays a very important role, being considered as one of the enabling technologies of the 4th Industrial [6]. For full deployment in industry, it is necessary to develop and test materials, to focus on establishing adequate processes and to solve design and software related problems to be able to manufacture personalized high quality products in smart factories of high efficiency with cyber-physical integration, as proposed by the Industry 4.0 philosophy [7].

Most of the industrial firms still do not consider additive manufacturing as a viable alternative to conventional manufacturing processes for reasons such as low precision and poor productivity. However, the technology is developing at a rapid pace and, it is expected, that if the main barriers to

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the adoption of additive manufacturing are addressed, it has a market niche with an enormous growth potential [8].

In the present paper, additive manufacturing is presented covering the main topics such as processes, materials, and advantages and limitations. After that, some of the latest trends in additive manufacturing are presented.

2. The basics of additive manufacturing

2.1. The process

The basic principle of additive manufacturing consists of building 3D geometries by material addition, generally layer by layer. Additive manufacturing processes have in common the following characteristics: a computer to store data, process geometric information and guide the user, and a deposition material that is processed by points, lines or areas to create parts [9].

In the ISO/ASTM 52900 standard [10], additive manufacturing is defined as: “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies”. Additive manufacturing can build complex geometry parts with minimal need for post-processing and almost zero material waste [5].

2.2. Main process categories

The ISO/ASTM 52900 [10] standard classifies additive manufacturing in seven process categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat polymerization (Figure 1).

Some of the most used technologies include fused deposition modeling (FDM), laminated object manufacturing (LOM), stereolithography (SLA), selective laser melting (SLM) and selective laser sintering (SLS) [11].

2.3. Materials

The type of material directly affects the shape, dimensions, durability and cost of a printed part and, thus, limits the potential applications. Currently, the number and types of materials to be used in additive manufacturing is still limited, but there are good expectations for the next generation of 3D printers that must have improved processing methods, allowing manufacturing with a greater range of materials. In general, there are three main categories of materials; these materials are based on liquids, solids and powder. Each of these three categories includes different types of materials, such as ceramics, composites, metals and polymers [12]. Depending on the additive manufacturing process that is going to be used, adequate materials should be selected for the process [13]. Recently, Bourell *et al.* [9] associated the main used materials for each of the seven categories identified by the ISO/ASTM 52900 (2015) standard.

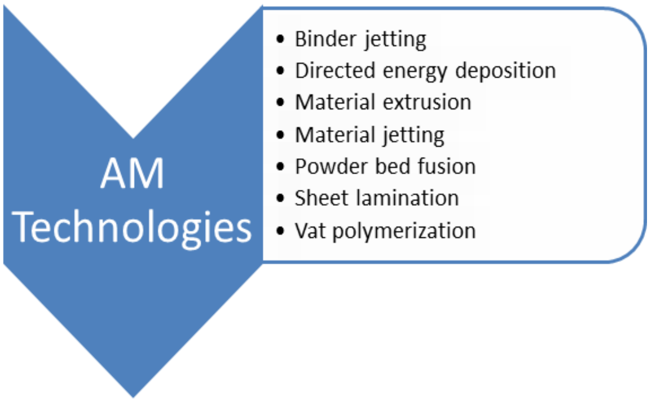

Fig. 1. Additive manufacturing process categories based on ISO/ASTM 52900 standard.

3. Advantages and limitations

One of the main advantages of additive manufacturing is that it allows to obtain pieces of geometric complexity that before could not be manufactured with traditional technologies without an elaborated configuration of the machine or a final assembly [14]. In addition, it can be said that it has already an adequate performance in the production of small batches [15]. Some advantages of additive manufacturing were reported by Noorani [12] as shown following:

- Consolidation of parts, complete set manufactured.
- Additive manufacturing can create thin walls.
- Unlimited length of small holes that make up the cooling channels.
- The machines work autonomously.
- The more complex the part is, the more cost saving is achieved.
- Automated pre-processing.

Some drawbacks are still associated to additive manufacturing and, thus, it is not considered as a completely viable process yet, because it involves a significant capital expenditure, it has not reached a similar performance to that of other conventional processes and the obtained pieces do not have great precision.

The pieces produced by additive manufacturing have limitations in the surface finish, which is relatively high when comparing to conventional manufacturing processes such as machining. These limitations are related to the thermal and mechanical aspects, since the material cools quickly leading to distortions and stresses, causing problems in the areas of the piece loaded cyclically or very stressed [14, 17]. The surface quality also depends on the orientation of the piece, the thickness of the layer and the orientation of the deposition of the material [14].

In biomedicine, additive manufacturing has demonstrated its ability to produce customized implants successfully. However, the limitation of almost all commercial techniques of this type of manufacturing is the choice of processing material. Therefore, subsequent treatments are required to improve the surface characteristics, especially in the case of biomedical applications [17].

Tofail *et al.* [8] define "materials" and "metrology" as key enabling technologies for additive manufacturing. They propose to address the challenges related to them to achieve the functionality of the objects manufactured by additive manufacturing. For this, they describe the scientific and technical challenges associated with the manufacture, materials and metrology of the products that will determine their acceptance in the market and the realization of their commercial opportunity. As an example, it is possible to highlight the problems of tolerance to control geometric variations, being an obstacle to achieve predictive models and realistic simulations.

4. Latest trends

In the present section, some of the latest trends in additive manufacturing are briefly presented. Some novel research topics are identified (Figure 2) in order to give a blueprint of the current state of the main research and development activities in additive manufacturing.

4.1. Hybrid processes

Hybrid machines that combine additive manufacturing with conventional technologies, such as machining are being developed in the last years [15]. The hybrid methods of additive and subtractive manufacturing processes use an additive process to build a near-net shape that will then be machined to its final shape obtaining the desired accuracy [18]. In this way, the problem of additive manufacturing on surface finish and precision is solved and, the potential of subtractive manufacturing is extended to parts of more complex geometry [19].

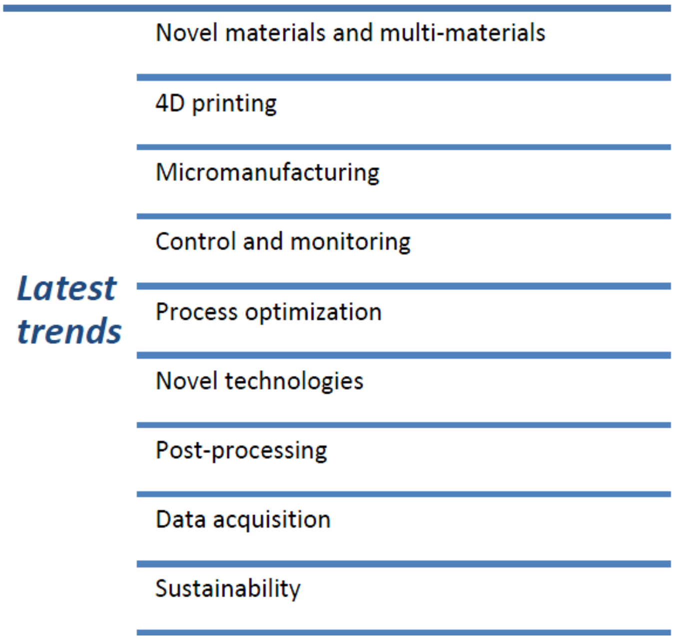

Fig. 2. Latest trends identified about additive manufacturing.

Often, for most traditional manufacturers, it is a challenge and an important investment to implement additive manufacturing. Strong *et al.* [20] investigate a system of strategically located additive manufacturing centers that can integrate hybrid additive manufacturing with capabilities and excess capacity in multiple traditional manufacturing facilities.

Thus, the increasing demand for complex metal parts could be realized by establishing additive manufacturing capabilities closer to the existing traditional manufacturing supply chains.

Elser *et al.* [21] present a combination of additive and subtractive manufacturing technologies to benefit from the advantages presented by both technologies. To decrease the planning efforts, an existing subtractive computer-aided manufacturing (CAM) system is used, expanded with modules to create additional additive manufacturing steps, obtaining a hybrid CAM system. A computer-aided hybrid manufacturing framework is presented, in which information flows and workflows are proposed to overcome existing problems.

4.2. Novel materials and multi-materials

3D printers now have the ability to create multi-materials systems. These processes allow the construction of parts benefited by properties of different materials. Although this technology is still in its infancy, Bandyopadhyay and Heer [2] have made a revision on the applications of multiple materials, in addition to analyzing their advantages and disadvantages.

The combination of additive manufacturing and biomaterials is promising for applications that concern human health and quality of life. Bose *et al.* [22] present a review of different additive manufacturing materials, followed by additive manufacturing applications in various treatment options.

The international Biomaterials and Additive Manufacturing: Osteochondral Scaffold (BAMOS) project addresses the challenges in the treatment of osteoarthritis. Among the objectives of the project is the development of new biomaterials to provide an appropriate environment for the formation of bone and cartilage. In addition, to developing innovative additive manufacturing techniques to produce patient-tailored osteochondral scaffold [23].

Bioprinting is currently an important research topic. Efforts by coming up with advanced solutions for biomedicine are being studied. An interesting example is the one presented by Campos *et al.* [24]. The authors are proposing a synchronized dual bioprinting approach for cartilage tissue engineering combining microextrusion printing and drop-on-demand (DoD) bioprinting.

Other interesting examples of novel materials include the recent developmentof meta-biomaterials with unprecedented mechanical properties. In this sense, Zadpoor [25] presented an exhaustive research into additive manufacturing metallic meta-biomaterials intended for bone substitution and orthopedic implants.

Li *et al.* [26] conduct a review on recent advances in different types of new materials for additive manufacturing. In addition, they also forecast the development trend for the future

4.3. 4D printing

The idea of 4D printing was first introduced in 2013. Gartner [4] predicts an important growth for the 4D printing market, up to 300 million dollars by 2023. 4D printing was initially defined as 3D printing + time, that is, the shape, property or functionality of a 3D printed structure can change as a function of time. It is also capable of achieving self-assembly, multifunctionality and self-repair. For structures to evolve over time, they require additional stimuli and intelligent materials sensitive to stimulation [27].

4.4. Micromanufacturing

Additive manufacturing takes place at macroscale levels, since most of the characteristics must be greater than 0.5 mm. Bhushan and Caspers [28] make a selection of several methods adequate for micro-additive manufacturing, among them, inkjet and SLA processes have presented the results with the smaller size. Samples were produced using microscale and, for instance, the thickness of the SLA printed samples was approximately 200 μm. In addition, the thickness of the samples by inkjet (ProJet 3510SD) was approximately 340 μm.

Shaw *et al.* [29] investigate microextrusion in additive manufacturing with high-aspect-ratio (HAR) nozzles. They found that the quality of the deposited plane was affected by different extrusion parameters, such as the nozzle moving speed, piston speed, extrusion rate, the distance between the nozzle and the substrate, the extrusion delay in response to the change of the ram speed and air pockets trapped inside the material reservoir.

4.5. Control and monitoring

Numerous researchers identify the quality assurance and control as the biggest challenge of the pieces produced by additive manufacturing. To overcome this challenge, it is necessary to implement inspection and monitoring systems to improve the quality of the parts and additive manufacturing processes. Chua *et al.* [30] review the current systems for control and monitoring additive manufacturing processes, reaching the conclusion that the size and temperature profile of the fusion assembly are critical issues in the monitoring and inspection processes. In addition, they propose an inspection method and a closed circuit monitoring system to address the quality control of additive manufacturing processes for metals.

4.6. Process optimization

There are numerous process parameters that influence the quality of the pieces obtained by additive manufacturing. Numerous studies have been carried out on the influence of different parameters on surface roughness. Several researchers studied these parameters and different post-processing techniques to improve the finish [31]. To obtain the required surfaces, the process parameters are optimized, generating different combinations in the initial stage in the standard triangle language (STL) file, referring to the orientation of the piece, construction orientation and layer thickness, in order to obtain good output requirements [32].

For example, Pérez *et al.* [33] study the influence of several printing parameters on the surface roughness in polylactic acid (PLA) samples produced by FDM. They concluded that, apart from the fact that layer height is the most critical factor on roughness as indicated by several studies; the wall thickness has also a significant influence on the surface roughness results.

Other outputs of the process are also being analysed. For instance, Alafaghani and Qattawi [34] study both the surface quality and the mechanical properties (tensile strength tests) for FDM samples. The authors found that both outputs cannot be optimized at the same time using a single configuration. Song *et al.* [35] also studied the mechanical properties comparing the 3D-printed material to that of homogeneous injection-moulded PLA, finding that 3D-printing improves toughness.

There are also studies on processing methods such as the one presented by Zhu *et al.* [36]. The authors propose a prescriptive deviation modelling method coupled with machine learning techniques to approach the modeling of shape deviations. In other study, Umaras *et al.* [37] present a research work on the main processes of additive manufacturing with respect to dimensional variations in the manufacture of parts.

4.7. Novel technologies

The mechanical properties of the 3D printed parts vary depending on the direction of printing due to the layer by layer approach. Digital Light Synthesis technology, patented by Carbon, uses digital light projection, oxygen permeable optics and programmable liquid resins to produce parts with consistent and predictable mechanical properties, creating solid parts in the interior, obtaining parts similar to injection molded parts [38].

Ultrasonic additive manufacturing (UAM) is a technology of 3D printing of metals that uses vibrations to weld metal sheets. Hehr *et al.* [39] use this technology to create a curved part by integrating neutron-absorbing materials. This process eliminates many steps, simplifying the production of control elements for Oak Ridge National Laboratory’s (ORNL) High Flow Isotope Reactor (HFIR) and, consequently, reducing costs.

Zawada *et al.* [40] present a new technology, multi-layer cryolithography, consisting of printing several individual 2D layers in parallel separately, in areas coated with hydrophilic materials to join water-based compounds. The individual layers are deposited one on top of the other and are linked by chemical crosslinking and freezing to generate a 3D structure. The applications involve tissue engineering and food engineering, as well as the ability to assemble a biological object.

Dilip *et al.* [41] perform a process of adding solid state material through a process called "friction deposition". They produced an AISI 304 stainless steel cylinder, the microstructural studies and traction tests gave satisfactory results, concluding that it is a viable process for additive manufacturing.

4.8. Data acquisition

Data acquisition plays an important role when reverse engineering comes to play but, more specifically, in biomedicine applications. In the later, data is scanned by methods such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) [42] and, then, the data should be transformed into CAD/STL files adequate to be printed. Manmadhachary [42] present a study on the additive manufacturing of an adult human dry mandible based on the results obtained from CT, which are optimized by using Taguchi and Gray relational analysis methods and 3D CAD models. When the optimized CT images are generated, it is possible to obtain the scaled STL model to finally print the dry mandible using FDM.

Xiao *et al.* [43] propose a 3D color image reproduction system for the automated and precise additive manufacturing of soft tissue facial prostheses. The results showed that the 3D manufacturing process was able to produce accurate skin colors with fine textures and 3D shapes, leading to significant savings in time and costs.

4.9. Sustainability

Currently, sustainability is one of the main topics in manufacturing. Administrations, researchers and companies are focusing their efforts in coming up with sustainable production processes with low harm to the environment. Efforts are also carried out to guarantee that the novel additive manufacturing processes are sustainable or, at least, to reduce their environmental impact. The main driver for the adoption of additive manufacturing technologies is still economical, while the influence of other factors such as social and sustainability are minimal [44].

Specific studies on some additive manufacturing technologies are being carried out as, for instance, the one by Kumar and Czekanski [45] in which they studied two processes, namely SLS and FDM that uses extensively plastics. The authors proposed the reuse of the non-used plastics in the production of powders for SLS (that will end as waste) to prepare feedstock for inexpensive high-value FDM products, resulting in important energy savings and, thus, reducing the environmental impact.

The use of recyclable materials is also being studied. In this sense, Fateri *et al.* [46] study a solvent-cast direct-write method using polyvinyl alcohol (PVA) as biodegradable material. Several process parameters were analyzed (solution viscosity, evaporation rate, print pressure and scan speed). The authors found the process viable for manufacturing complex geometries of adequate mechanical properties, and discussing the physical and chemical properties of the parts for space applications.

5. Conclusions

The present paper presents an updated review of the latest trends in additive manufacturing. Initially, a straightforward presentation of additive manufacturing and its advantages and limitations was introduced. And, finally, some of the newest advances and research topics in additive manufacturing were presented. Among them, it is possible to highlight the following:

- Hybrid machines that combine additive manufacturing with conventional manufacturing processes are being researched and developed. In this way, it is possible to benefit from the advantages of both processes and alleviate the disadvantages of each one.
- New materials are being studied and developed for different applications. Bioprinting in medicine drives the R&D of suitable biomaterials for implants.
- 4D printing is capable of self-assembly, and self-repair, and offers multifunctionality thanks to the fact that the printed parts can evolved over time due to the stimuli received by the intelligent materials used by this technology.
- Several studies on micro-additive manufacturing have been made, although, in general, additive manufacturing takes place at macroscale level.
- Quality and control of the pieces have to be guaranteed by additive manufacturing, being necessary to implement inspection systems and monitoring.
- Different results are being analyzed for the processes optimization, such as surface quality, mechanical properties, dimensional variations or shape deviations.
- Additive manufacturing covers a broad field of application, so novel technologies are being developed that adapt to the desired results.
- Reproductions can be made with additive manufacturing with the acquisition of data and the use of them by using advanced techniques such as computed tomography, specifically in applications such as biomedicine.
- New studies about sustainability in additive manufacturing are being carried out on the reuse of materials in manufacturing processes or the use of recyclable materials.

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