Analysis and characterization of additive manufacturing processes

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Abstract: *Recently, additive manufacturing (AM) processes have expanded rapidly in various fields of the industry because they offer design freedom, involve layer-by-layer construction from a computerized 3D model (minimizing material consumption), and allow the manufacture of parts with complex geometry (thus offering the possibility of producing custom parts). Also, they provide the advantage of a short time to make the final parts, do not involve the need for auxiliary resources (cutting tools, lighting fixtures or coolants) and have a low impact on the environment. However, the aspects that make these technologies not yet widely used in industry are poor surface quality of parts, uncertainty about the mechanical properties of products and low productivity. Research on the physical phenomena associated with additive manufacturing processes is necessary for proper control of the phenomena of melting, solidification, vaporization and heat transfer. This paper addresses the relevant additive manufacturing processes and their applications and analyzes the advantages and disadvantages of AM processes compared to conventional production processes. For the aerospace industry, these technologies offer possibilities for manufacturing lighter structures to reduce weight, but improvements in precision must be sought to eliminate the need for finishing processes.*

Key Words: *additive manufacturing, fused deposition modelling, inkjet printing, laminated object manufacturing, laser engineered net shaping, stereolithography, selective laser sintering, three-dimensional printing*

1. INTRODUCTION

Additive manufacturing (AM) is a process that has developed over the last 30 years and involves the construction of parts by consecutive addition of material layers based on a solid computerized 3D model [1]. This process is also known as rapid fabrication [2] or rapid prototyping [3]. The advantages of this process include the possibility of optimizing the design stage and the production of customized parts, without using cutting tools, coolants or other auxiliary resources.

Additive manufacturing has been noted for its many benefits in the medical system by customizing products according to individual needs of consumers (improving the population health and quality of life), in industry through the sustainability of production achieved through reduced use of raw materials and energy consumption (thus minimizing the impact on the environment) and by the opportunity to reconfigure the supply chain in order to make products at low cost, time and resources (thus maximizing efficiency and ability to meet the parts manufacture on demand).

By traditional manufacturing methods, such as cutting and stamping, finished products are made by cutting material from a block with cutting tools or drawing sheets using presses, while additive manufacturing makes it possible to create the final shape of the part by adding material, having the capacity to use efficiently raw materials, considerably reducing waste production and having a satisfactory final geometric accuracy [1], [2], [3], [4].

2. ADDITIVE MANUFACTURING TECHNOLOGY

AM technology involves three basic steps:

a) developing the computerized solid 3D model and saving it as a file in standard AM format, such as STL (Standard Tessellation Language or Standard Triangle Language) [5] or Additive Manufacturing File Format (AMF) [6];
b) inserting the file into the AM equipment where it will be manipulated (the position and orientation of the part can be changed or the part can be scaled);
c) layer-by-layer construction of the part with the help of AM equipment.

The AM process only requires a solid computerized 3D model that will be used to make the finished product and offers the possibility of producing parts with complex geometry, which are difficult to obtain when using procedures that require material removal. Thus, it is found that additive manufacturing does not require the realization of the model for the manufacturing process (design for manufacturing - DFM) nor the design for assembly (DFA) in product design. In addition, 3D models can be improved through a process of topological optimization, which can increase the functionality of a product, thus reducing the amount of energy, fuel or natural resources required for its operation [7].

The first process of creating a layered three-dimensional object using computer-aided design (CAD) was rapid prototyping. The steps involved in product development using rapid prototyping are shown in Fig. 1, resulting in time savings through rapid production and the ability to test multiple models. Currently, this technology is called 3D printing, but it also has its origins in the process of rapid prototyping [8], [9], [10], [11], [12].

The rapid production process became possible through technologies such as computer-aided design (CAD), computer-aided manufacturing (CAM) and computer numerical control (CNC). These three combined technologies have made possible the three-dimensional objects printing [8], [11], [13].

Fig. 2 shows a classification of additive manufacturing processes that will be discussed in this research, and the criterion used in making this classification depends on the condition of the raw material used (liquid, solid and powder base). The processes considered are Stereolithography (SLA), Inkjet printing (IJP), Fused deposition modeling (FDM), Laminated object manufacturing (LOM), Selective laser sintering (SLS), Laser engineered net shaping (LENS) and Three-dimensional printing (3DP).

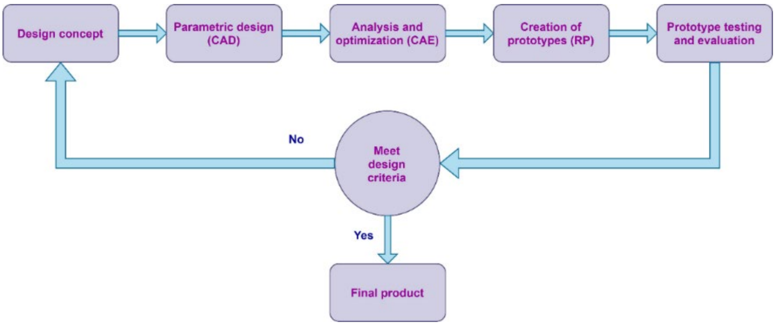

Fig. 1 – Steps in product development

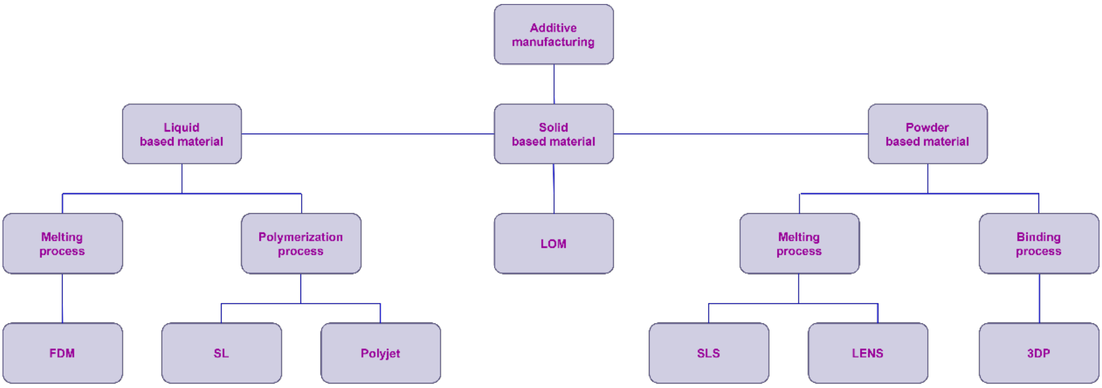

Fig. 2 – Classification of additive manufacturing processes according to the raw material condition used

These technologies were initially developed to produce laboratory models, later the service area expanded, and the increase in additive manufacturing of independent service providers shown graphically in Fig. 3 is the result of a survey conducted by Wohlers (report created with the support of 124 service providers, 113 manufacturers of additive manufacturing machines and 24 manufacturers of third-party materials, to which 88 co-authors and collaborators from 34 countries provided expert opinions and perspectives) [14].

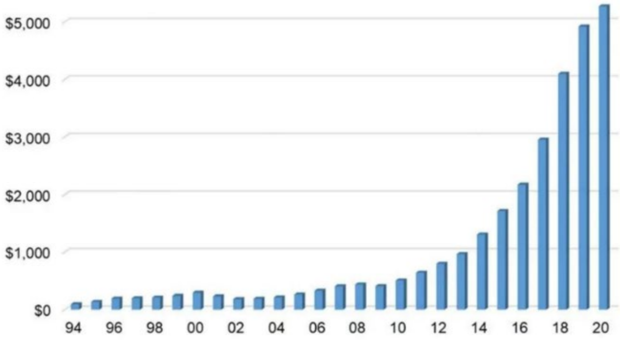

Fig. 3 – Market size for the production of components using AM by independent service providers (in millions of dollars) over the period 1994-2020 [14]

The STL file (Standard Tessellation Language or Standard Triangle Language) represents the standard for the additive manufacturing process. Creating the STL file involves converting the continuous geometry in the CAD file into small triangles or a list of x, y, and z coordinates with the normal vector to the triangles. For a proper geometric accuracy, the triangles must be created as small as possible, so that the piece model to be close to the real one [8], [15], [16]. The inner and outer surfaces are identified using the right-hand rule, and the vertices cannot share a point with a line. Additional edges are added following the slicing process, which introduces inaccuracy to the file by replacing the continuous contour with discrete steps [16]. Fig. 4 shows the moment of creating the STL file in the stages of the rapid prototyping process and the working steps in the software for creating the STL file.

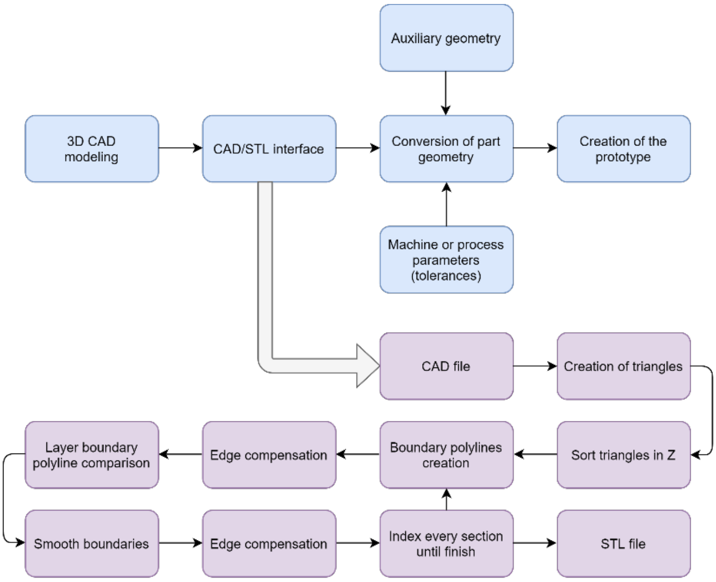

Fig. 4 – Process of making the STL file

3. CHARACTERISATION OF ADDITIVE MANUFACTURING PROCESSES

Additive production processes are of several types, and their categorization can be done depending on the method used in the layer construction and consolidation. Some processes use thermal energy from electron beams or from laser beams, energy that is optically directed in order to melt or sinter metals or plastic powders together. Other processes use extrusion heads to accurately spray the binder (hardener) or solvent on the ceramic in powder or polymer form.

The representative additive manufacturing processes are the following:

- **Fused deposition modelling (FDM)** - is an additive process in which a filament of thermoplastic material supplies the equipment whose printhead melts the filament and extrudes it with a diameter of about 0.25mm, depositing it in ultra-thin layers on a support layer using a mobile extrusion head (Fig. 5). The material is heated to 1°C above its melting point so that it solidifies almost immediately after extrusion and it adheres to the previous layers, making parts with an accuracy of up to ± 0,05 mm. The materials used by this equipment are polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyphenylsulfone (PPSF), PC-ABS and PC-ISO mixtures (which is a PC used in the medical industry). The main advantages of this process are: the costs of less expensive equipment and materials, the lack of chemical post-processing, the lack of resins that require curing time, thus resulting in a more cost-effective process [8], [11]. This type of process also has certain disadvantages, such as the visible presence of the edges between the layers of the part, the need for supports for the construction of the parts, the long lead time and the possibility of delamination caused by temperature fluctuations [17]. Also, the process itself is a slow one, taking several days to build large complex parts. To save time, some models allow two ways of filling the part: a completely dense mode and a low-density filling mode, but obviously reduces the mechanical properties [18].

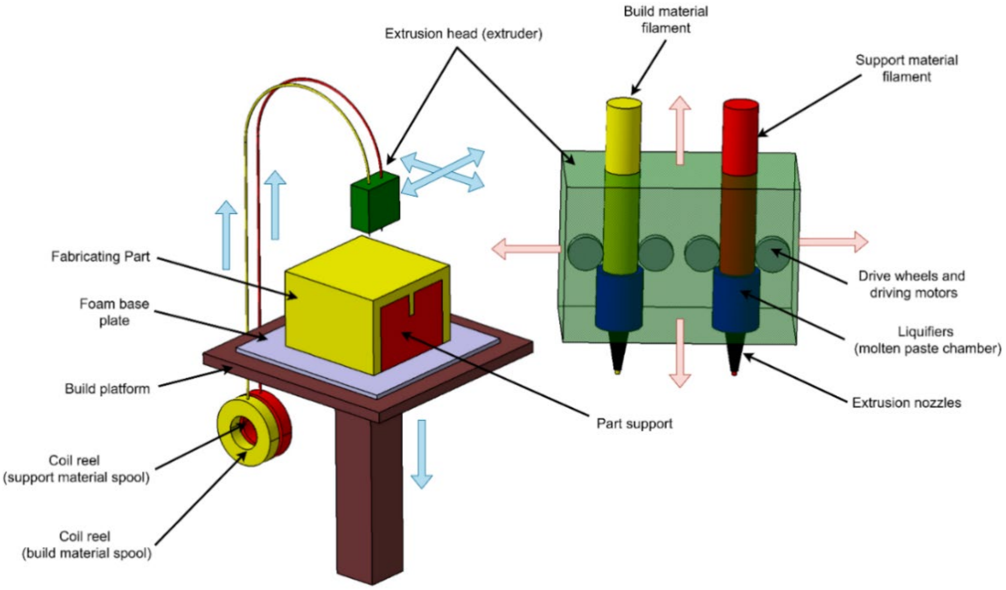

Fig. 5 – Fused deposition modelling process

- **Inkjet printing (IJP)** - is an impact-free dot matrix technology, originally developed for printing 2D images; it uses liquid materials or inks, which consist of a substance dissolved or dispersed in a solvent. By means of a piezoelectric drive, a quantity of liquid material is discharged through a nozzle, achieving a quasi-adiabatic decrease of the chamber volume (Fig. 6). The discharged marking fluid, under the action of gravity, forms the support layer, which dries after evaporation of the solvent. Disadvantages of this process include the use of expensive fluid cartridges and fragile printheads (which are prone to clogging).

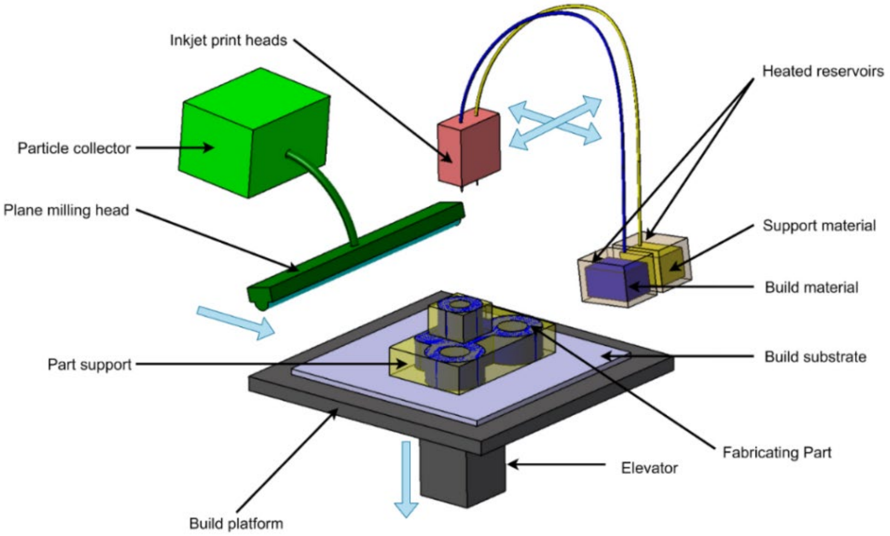

Fig. 6 – Inkjet printing process

A derivative process of IJP is Polyjet, a process that uses inkjet technology to manufacture parts. The printhead moves on the x and y axes to deposit a photopolymer, and after the completion of each layer uses ultraviolet lamps for curing the photopolymer (Fig. 7). The layer thickness can have 16 µm, thus obtaining high-resolution parts. A gel-type polymer is used to support the excess material, and after the process finishing it is removed by a water jet. Also, through this additive process, parts of different colours can be built [19], [20], [21].

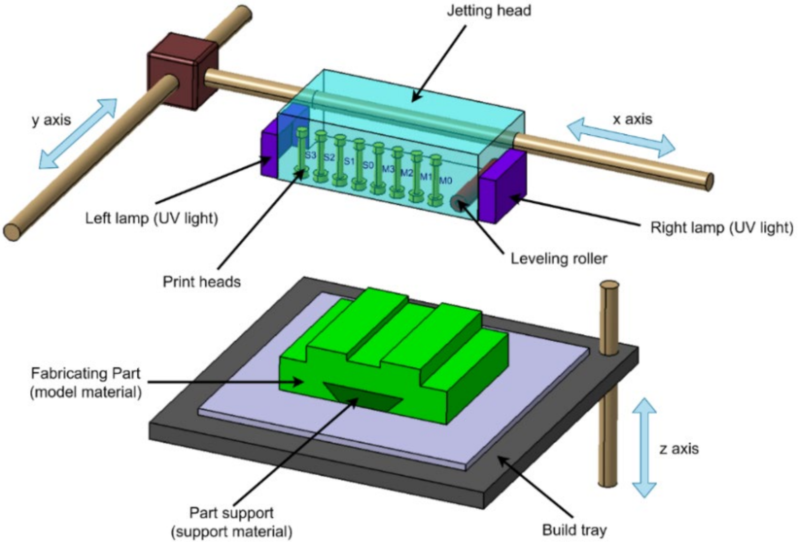

Fig. 7 – Polyjet process

- **Laminated object manufacturing (LOM)** - is a process that combines additive and subtractive techniques to build layer-by-layer parts from sheet materials. The sheets can be covered with adhesive. The adhesive (which can be in the form of pre-coating onto materials or deposited prior to bonding) makes possible the attachment of sheets to each other, and by sequential lamination, the 3D parts are made. The layers can also be joined together by methods that use variations in pressure, heat and thermal insulation layers. The 2D cross sections of the parts are cut using a laser beam (carbon dioxide laser, whose speed and focus are adjusted so that the depth of cut corresponds exactly to the thickness of the layer, thus avoiding damage to the lower layers). Materials used in LOM process include plastics, metals, synthetics and composites. The major advantages of this process are the low costs, the absence of toxic fumes release and post-processing processes, the possibility of automating the process, the lack of need for support parts and the possibility to build large parts. The disadvantages are that the parts are extracted from the manufacturing material, which means that the material residues are wasted, and the allocation of time after production for waste disposal is necessary, there is also inaccuracy on the z axis, which creates dimensional stability problems (generation of undesired internal cavities). Complex internal cavities are very difficult to make, and some additional processes are required to generate precision functional parts [22]. This process can be used for models in paper, composites and metals [8], [11], [23]. The manufacturing process of laminated objects is shown in Fig. 8.

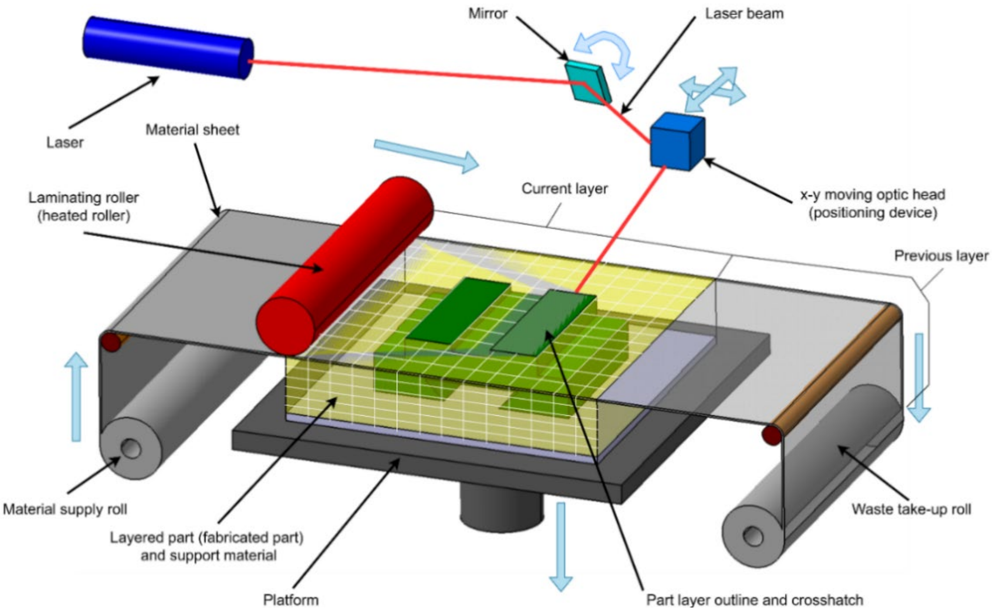

Fig. 8 – Laminated object manufacturing process

- **Laser engineered net shaping (LENS) -** involves manufacturing parts by focusing a high-power laser beam on a substrate to create a molten area where metal powder particles are injected at a defined location, the solidification of the material taking place following the cooling process. The whole process takes place in a closed chamber with an argon atmosphere. The substrate is moved under the laser beam to sediment the thin cross section, the consecutive layers being deposited sequentially to build the 3D part (Fig. 9).

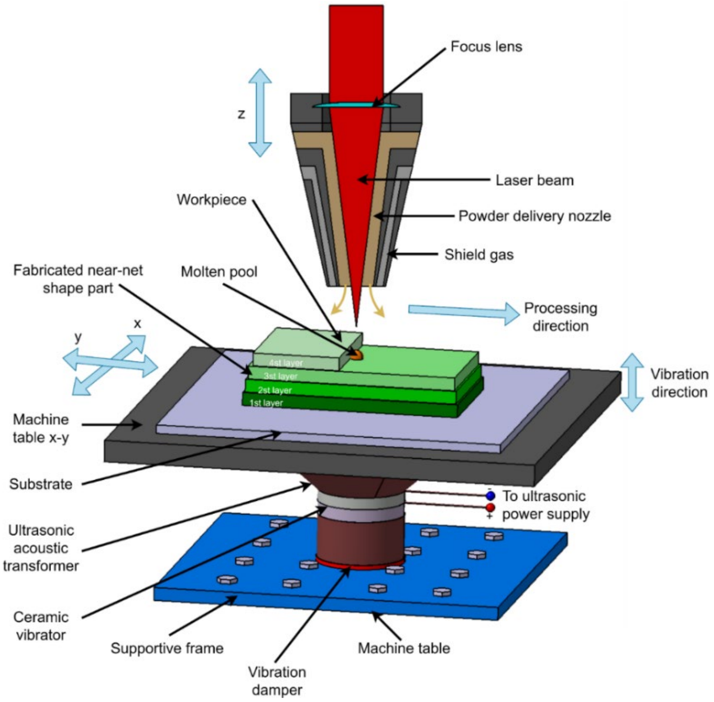

Fig. 9 – Laser engineered net shaping (LENS)

The geometric properties (precision of execution and surface finish) and the mechanical properties (strength and ductility) of the part material can be controlled by setting the fabrication parameters [24]. For this process are used metals and their combinations (stainless steel, copper alloys, titanium-6 aluminum-4 vanadium, tooling steel, nickel-based alloys, alumina). The LENS process can be used both to repair parts and to manufacture new ones, and does not require secondary calcination operations. The process has certain disadvantages, namely residual stresses resulting from uneven heating and cooling processes that can generate significant errors for high-precision processes [11], [15], [25], [26], [27], the need to cut the part from the substrate and to machine or polish the surfaces for a suitable finish.

- **Stereolithography (SLA)** - The basic principle of this process is photopolymerization, which consists in the hardening / solidification of a monomer or a photosensitive polymer when a laser comes in contact with the resin and by applying ultraviolet light from a UV laser acts as a catalyst for reactions [28]. This process requires support structures for the parts. On each layer, the laser beam moves along the part cross section on the liquid-resin surface to solidify the model, and when the process is finished, the monomeric or polymeric excess is drained to be reused [8], [11], [13] (Fig. 10).

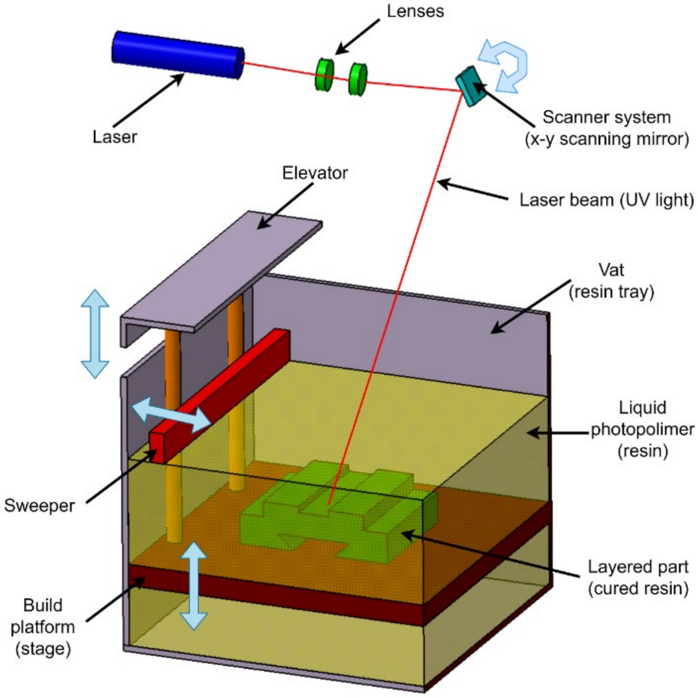

Fig. 10 – Stereolithography

The SLA process has the advantage of reducing the time required to manufacture a prototype part, and the surface finish is appropriate. The main disadvantages of SLA are the size limitations, the dimensions of the final product being relatively small (60cm x 60cm x 60cm), the costs are high (photopolymer is an expensive consumable) and the materials are relatively limited compared to other additive manufacturing processes [29]. Also, in this process there are errors of the final part due to the over-reinforcement that appears in the consolidation of the parts (no fusion with a lower layer), errors of shape due to the high viscosity of the resin (which generates a variable height of the layers, leading to deviations in edge position control) and surface finishing errors [30]. A derivative of this process is micro-stereolithography, which involves obtaining a final product of better resolution, the thickness of the layers reaching up to 10µm [15]. There is the possibility of making a piece from several types of material, the process being called multiple material stereolithography. This manufacturing technology requires that all the resin be drained when the new material layer is reached, and the vat to be filled with the latter one. These material interchange steps can be software programmed in the planning process [31].

- **Selective laser sintering (SLS)** - This additive process involves the use of a high-power carbon dioxide laser to sinter (fuse) small particles of the building material (spray materials such as polymers, glass, metals, ceramics). The working chamber is heated close to the melting point of the material to facilitate fusion with the previous layer, and the laser sinter the powder for each layer in a specified position from the design stage. The material particles are in a powder bed which is controlled by a piston performing a translational movement along the vertical axis, lowering the platform of the powder bed with the same unit length as the thickness of the layer when the layer is completed (Fig. 11), and the powder that is not sintered has the role of supporting the structure (later, it can be removed and recycled).

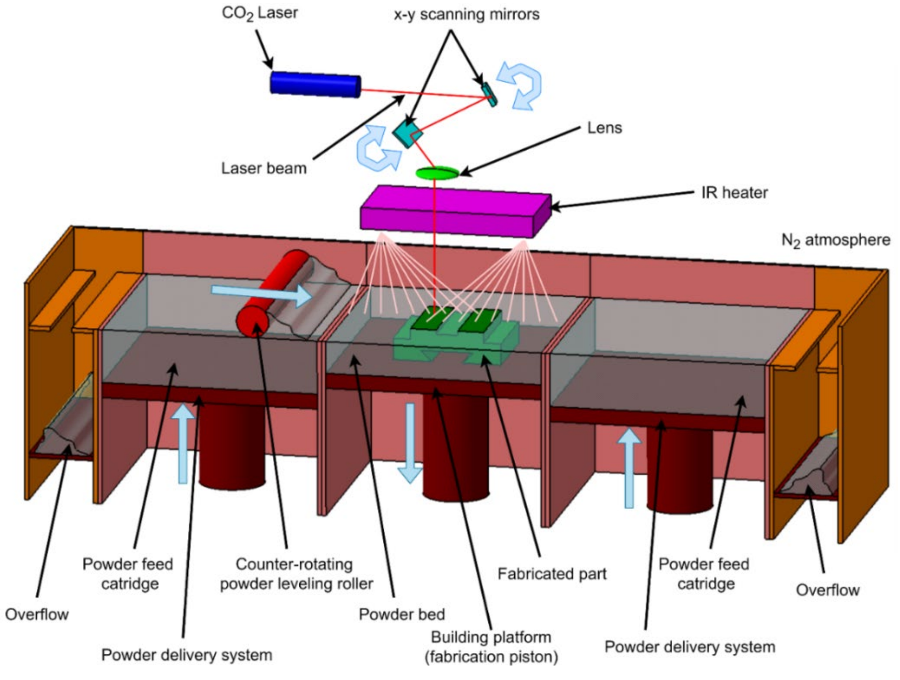

Fig. 11 – Selective laser sintering

A wide range of materials can be used for this process: plastics, metals, metal alloys, polymers (acrylic styrene and polyamide) [32], [33], combinations of metals and ceramics [15], [32], [34], composites or reinforced polymers (fiberglass polyamide). In the case of metals, a binder is required, and the binder may be polymeric (which is subsequently removed by heating) or it may be a mixture of metals with a different melting point [32], [33]. No additional curing time is required for this process, and parts manufacturing time is fast. Also, the existence of a wide range of materials suitable for this process and the possibility of recycling unused powder makes SLS a very attractive manufacturing method. The disadvantages of the process are the finishing of the surfaces (the accuracy being limited by the size of the particles in the material) which is not as good as that of the parts manufactured by the SLA process and the difficulty of changing the material [22]. Also, a major disadvantage of this process is the oxidation that must be avoided by performing the process in an inert gas atmosphere and maintaining a constant temperature during the process (near the melting point of the material).

- **Three-dimensional printing (3DP)** - This process involves depositing a material powder on a substrate, powder whose particles are then joined by a binder that is sprayed through a nozzle. After sequential application of the layers, the excess powder is removed and the part is further processed by high temperature firing. This process is used to manufacture ceramic parts, metal parts, metal composite or ceramic composites parts (Fig. 12). This process can use a wide variety of polymers [11], [15]. 3DP is among the fastest of all AM processes, offering the advantage of fast manufacturing and involving low material costs [35]. The limitations of the process consist in the rough surfaces finish and small dimensions of the final part.

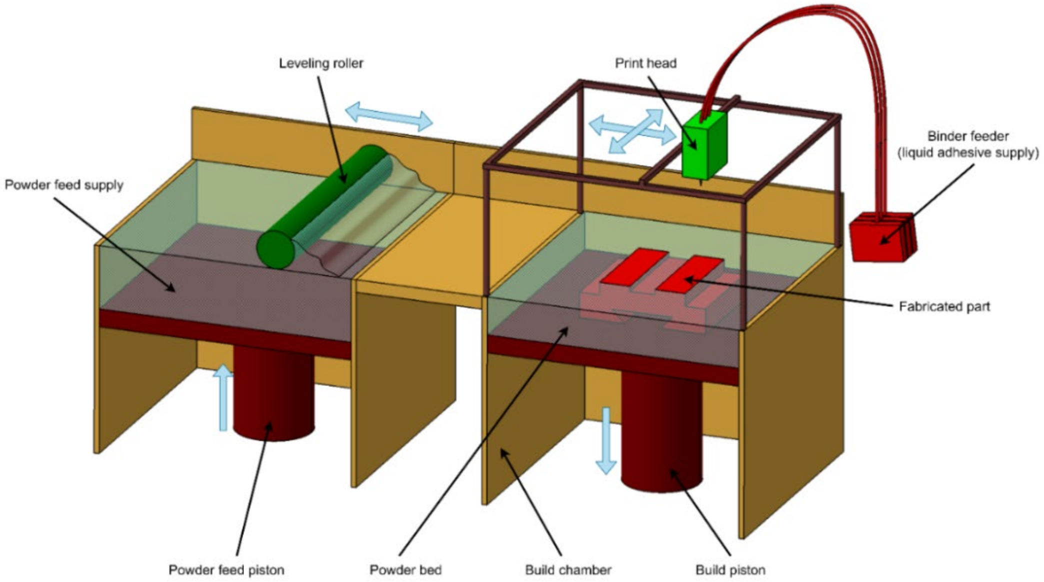

Fig. 12 – Three-dimensional printing

4. COMPARISON BETWEEN ADDITIVE AND CONVENTIONAL PROCESSES

Conventional manufacturing techniques involve the processes of forming and removing the material, such as turning, grinding, milling and stamping, in which a component is manufactured either by plastic deformation or by material removal. At the present, forging, cutting and other subtractive manufacturing processes are used for the parts manufacture, although it involves a waste of expensive materials. On the other hand, additive processes use the material to its full potential, have the ability to create crosslinked components and can be used for processing materials that are difficult to cast and process, requiring high temperatures (Ni alloys, Ti and W). AM also has the ability to manufacture parts and assemblies with complex geometries, composition and distinct properties [36]. The high potential of the AM is due to the ability to produce complex shapes, to reduce the total time (between giving the order and its fulfilment) by 30 to 50%, to reduce the weight of parts by up to 50% and the freedom in design that offers compared to conventional manufacturing techniques [36], [37], [38], [39]. The capabilities of these processes to have dimensional stability and the possibility of customizing the finished product have led to their intensive use in the manufacture of medical devices [40], [41], [42]. AM technology is considered to be economical for the production of small batches and has flexibility in design and production, aspects resulting from the fact that the machines do not need expensive arrangements. One of the disadvantages of AM is its high acquisition costs compared to conventional manufacturing equipment [43]. Having so many additive manufacturing methods with a wide variety of materials, there has also been a need to achieve new standards and requirements in terms of quality. Thus, conventional production continues to be the best option in terms of product reliability, quality and accuracy [44]. Batch testing (method of quality assurance / quality control for conventional techniques) has been found not applicable to AM due to the impact on the heat affected area, the inconsistency of the defects and the orientation of the layer [45].

Following the details presented above on the additive manufacturing processes, their advantages can be observed in relation to the conventional manufacturing processes:

- Material saving - AM efficiently uses raw materials by the fact that the parts are built layered by adding material, unlike conventional production where a quantity of material must be removed, so the remaining amount of material can often be reused with minimal processing.
- Production flexibility - additive manufacturing equipment does not require expensive installations, which creates a favourable environment for production in small batches, and the parts can be easily adapted to customer demands.
- Parts flexibility - complex parts can be made in one piece and can have variable mechanical properties (final product can have a flexible and a more rigid part).
- Resource efficiency - AM does not require additional resources as the conventional manufacturing processes for which, in addition to the machine tool, cutting tools, guides, coolants and clamps must be provided. This advantage also presents the opportunity for better supply chain dynamics.

Due to the following disadvantages, AM technology is unable to fully compete with conventional production, especially in the field of mass production [46]:

- High costs - AM equipment is considered an expensive investment, taking into account all the necessary accessories and operational materials.
- Size limitations - AM uses materials with poor mechanical properties compared to conventional production, which makes large parts production impossible to achieve.
- Imperfections at finishing - the produced parts often have a rough or ribbed surface finish created by the material overlapping layers.

5. CONCLUSIONS

In this research, an analysis of additive manufacturing techniques for rapid prototyping was performed. AM processes arose from the need for rapid model development, namely the time optimization between the product development and the market placement. Additive manufacturing is considered a very important technology especially in the aerospace industry due to the possibilities offered in the manufacture of lightweight structures, thus achieving the goal of designing aircraft by reducing weight. This paper also provides a starting point for future research on the development of UAV structure components that aims, for example, to reduce, the forced vibrations generated by the interaction of the air jet (produced by the brushless motors propellers) with drone structures [47], [48].

A classification of the additive manufacturing processes was made according to the raw material condition used, and a schematic of the rapid prototyping process stages and of the STL file creation was presented. For the different AM techniques, the operating principles were detailed and the types of materials used were specified. Also, the advantages and disadvantages of each process were presented, and with the help of Catia software the constituent equipment of each process was modelled for a visual exemplification of additive manufacturing techniques.

A comparison between the additive and the conventional processes was made to highlight the advantages of the former techniques, but also to make detectable disadvantages both in terms of high costs and dimensional limitations, which lead to the conclusion that AM processes play an essential role in production, but especially from the perspective of complementary technology. It was observed that the industry interest in developing AM processes is also due to the significant social impact they have, the positive effects being: the possibility of developing customized medical products (customized surgical implants), the provision of a simplified supply chain (increases efficiency and responsiveness, with the possibility of on-demand manufacturing) and reduced environmental impact compared to conventional manufacturing processes (low consumption of raw materials and non-use of coolants produce less pollution).

For future research, studies on the assessment of energy consumption in the AM processes, studies on the various materials effects used in AM on health, studies on the impact on the workforce and studies on the use of AM equipment in a home environment are needed. Research on the use of a wider range of materials must also be carried out before these additive manufacturing processes become standard in the manufacturing industry.

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