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Additive manufacturing technology, process parameters influencing product quality and its applications

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Abstract

Additive manufacturing (AM) technology is a new way of manufacturing components by depositing materials layer by layer according to a digital model. Since its birth in the 1980s, AM has offered new opportunities to manufacturers, and has given rise to new applications. Several three-dimensional (3D) processes exist, each having specific properties and different types of technology. While AM offers significant benefits, it also presents some challenges to designers that must be understood and addressed. This article reviews the advances in this field, the main processes studied or used, and their characteristics, including the main parameters influencing product quality. We summarize all the factors in fishbone diagrams for each AM family. Finally, some AF industrial applications were discussed with its use and contribution to the fight against COVID-19 during the pandemic.

Keywords

Additive manufacturing, Processes parameters, Fishbone, Applications, Covid19.

1.Introduction

Nascent technologies develop and mature over time. Research and development conducted throughout time led to innovation activity that can create new emerging technologies that disturb and upset the usual systems. AM is currently following this path. Invented in the 1980s, it is, nowadays, reaching its maturity, taking into account the changes it brings to the industrial field and the added value it is creating [1]. This technique can create radically new solutions or change the initial system architecture. The principle is to manufacture an object by printing according to a digital model, layer by layer, until obtaining a three-dimensional (3D) part involving different materials and processes. Developed first for rapid prototyping, it currently enables producing functional end-use parts. The expiration of specific patents, in addition to new materials developed, and innovative AM techniques have resulted in the emergence of new applications that have pushed the adoption of this technique by decision-makers [2].

Nowadays, amidst competitiveness and productivity, the demand for complex and customized products is increasing, driving many industries to explore and adopt 3D printing due to its ability to address many challenges [3]. The worldwide AM market is predicted to reach $54.96 billion by 2027, up from $10.41 billion in 2019, according to the Fortune Business Insights 2020 study. AM is applied in different industrial areas, including healthcare, defense, aerospace, and automotive [4]. During the corona virus pandemic, 3D printing provided solutions to specific needs at the time, such as personal protective equipment (PPE) and medical devices. This technology, with its short supply chain, was able to meet demands that could not be met due to lockdown [5].

This expansion has spawned a variety of additive techniques on the market, each with its unique characteristics. Despite the various advantages of those technologies, designers face many constraints that affect product quality that must be considered throughout the design process for defect-free production. However, 3D printed parts can have different properties due to the difference between 3D process, and materials used even for the same

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stereolithography file (STL). Problems like surface roughness, porosity, shrinkage defects, residual stress, dimensional accuracy, density, and surface quality, are some examples [6–8]. These issues represent a great challenge for industrialists and scientists, with a difference depending on the type of 3D technique used. Therefore, considerations must be taken when designing for each process to ensure flawless printing, in the drive to improve efficiency by optimizing process parameters and controlling the design parameters. Multiple studies have examined the AM research literature throughout the years [9]. However, since this new technology is continually being developed and improved, it is always worthwhile to analyse the trends and specifics of each process category. Nevertheless, there is no extensive review that summarizes the main issues and the effect of the different process variables on the quality of the 3D printed parts and its mechanical properties. It is essential to determine the parameters to be considered for each process family. This study explores the progress of AM technology through its advances. It aims to review the main applications of AM, as well as the key challenges designers face when designing for AM to ensure a good 3D printed part.

This document is structured into three main sections. The first describes the methodology followed. The second presents the analysis of the results, which is divided into three subsections. The first subsection presents the main phases of the evolution of this technology. In the second, we analyse the characteristics of each process and their impact on product quality. The third subsection highlights some industrial applications, emphasizing its contribution during the coronavirus pandemic. In the third and final section, we discuss the challenges and limitations.

2.Methods

2.1Research questions

The main objective of this work is to provide an understanding of the state of the art of AM. To achieve this, we formulate the following research questions:

RQ1. How has this technology evolved rapidly, and why?

RQ2. What are the characteristics of each process, and how do the process parameters impact product quality?

RQ3. What type of product has benefited from this technology's advantages through different applications?

RQ4. What are its contributions during the covid-19 period?

2.2Selection of relevant document

The methodology followed in this paper is based on a systematic review of formal academic sources (article, conference paper, Book…) and informal sources (internet and company reports). To carry out this work, we searched for sources, including patents, articles from Scopus and Google scholar database, Google Patents, books, conference papers, and reports containing information about the progress, applications, and major challenges in this field. The major challenges are researched from research works only, while the industrial applications are collected, in addition to scientific works, from reports and press articles of large companies. We first searched for keywords related to the technology and then each process separately, for example, stereolithography apparatus (SLA), fused deposition modeling (FDM), etc.

The documents included in this study are based on certain criteria, which are given in *Table 1.* A detailed preferred reporting items for systematic reviews and meta-analyses chart (PRISMA) of the methodology followed to identify documents is shown in *Figure 1*. We study all the selected papers to give an exhaustive study on most problems and challenges designers face regarding the effect of design parameters on quality and a review of its benefits in the industrial field. We summarize all the parameters in fishbone for easy understanding.

Table 1 Inclusion and exclusion criteria of the documents

S. No.	Inclusion criteria	Exclusion criteria
1	Patents of primary 3D techniques.	Patents of secondary 3D techniques, and invention papers.
2	Published in English language.	Documents which are not in English language.
3	Reports of companies specialized in 3D printing	Small companies report
4	Content directly related to AM, its applications and product properties from 2015	Content not related to AM, or focuses on AM environment or economic impact or before 2015
5	Studies related to machine, material, 3D process, and people.	Studies not related to machine, material, 3D process, and people.
5	Content related to Covid-19 and AM	Content which focuses on Covid-19 and not on AM.

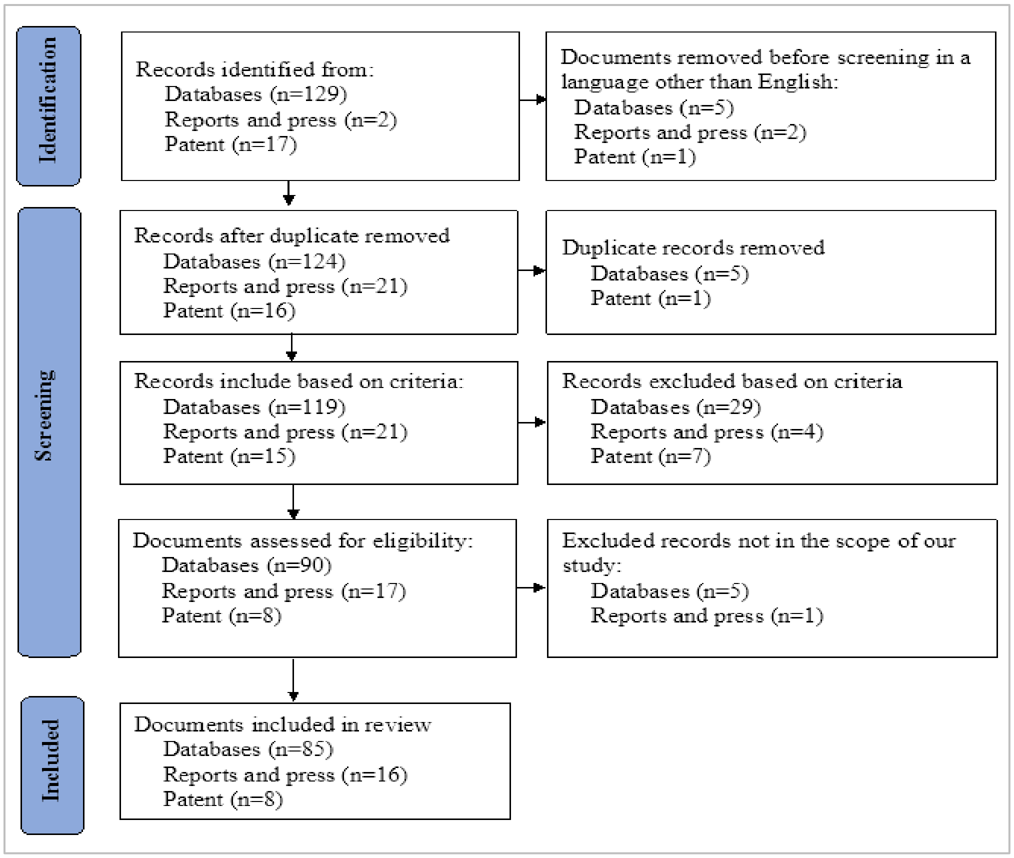


Figure 1 Detailed PRISMA chart for the manuscript identification

3.Results and analysis

3.1AM Evolution

Several terms such as additive fabrication, additive processes, additive layer manufacturing, layered manufacturing, free-form fabrication, rapid prototyping, and other expressions have been used since the 1980s. The finished part is built using this technique in successive layers where each one adhered to the previous one. The American society for testing and materials (ASTM) has defined it in the standard "ISO/ASTM 52900-15" as a process of assembling materials to make a part from 3D model data [10]. Before reaching the current level enabling important industrial applications, its emergence has taken three successive stages of development, the birth phase, a growth one, to reach its maturity phase, as summarized in *Figure 2.*

As the case of several inventions, different researchers developed AM simultaneously. Between 1967 and 1999, the birth of 3D printing occurred, as well as the filing and publication of several scientific publications and patents. In 1967, the patent of Wyn Kelly Swainson was filed detailing a process to manufacture three-dimensional figure product [11]. Scientific work has been published by the Japanese Kodama in 1981, which consists of constructing an object by solidifying a photopolymer [12]. In 1984, the American Charles W. Hull and the French Jean-Claude André each filed a patent in which they invented the technique "Stereolithography" [13]. However, the real breakthrough of AM is partly due to the development of the integrated STL file format by Charles W. Hull. Subsequently, in 1987, he founded the first company (3D systems), commercializing the stereolithography apparatus (SLA) process. In the late 1980s and in 1990s, the first patents for others 3D printing methods were filed, especially selective laser sintering (SLS) [14], and in 1986 laminated object manufacturing (LOM) [15], as well as binder jetting (BJT) [16] and FDM techniques in 1989 [17], laser engineered net shaping (LENS) in 1996, and inkjet processes in 1999 [18]. During this period, AM was used for rapid prototyping as a tool for visualizing concepts. The development of AM technology has positively influenced the sales of rapid prototyping units by a 10-fold increase in 9 years between 1989 and 1997 as reported in 1998 Wolhers' report [19]. However, the production speed remains slow and time-consuming during this period due to the printing time. Divers' technical improvements through research and development have allowed reducing printing time for the FDM process by 7.5 from 34 hours to 4.5 hours and 10 for SLA process [20].

The growth period of 3D printing technology from 2000 to 2009 registered when this technique gained media visibility. According to 2004 Wohlers report, 3D printing during this decade had challenged other applications like fabricating functional prototyping or rapid manufacturing of end-use parts [20]. The technical properties, particularly accuracy and speed printing, of primary processes SLS, FDM, and SLA techniques, have been upgraded. *Figure 2* shows other new processes introduced in the market like digital light processing (DLP), polyjet, as well as metallic processes. Despite the progress that this technology has made during this period, its use for industrial applications has been limited to functional prototyping with the beginning of rapid production [21]. The year 2009 is considered in the AM's history as the onset of democratization of 3D printing for the large consumer, thanks to the FDM patent's expiration. This led to reducing the price of FDM printers in the following years. In 2009, ASTM F2792 - 09 standardized the designation of 3D printing as AM. Since 2010, the pace of AM growth has increased dramatically. Furthermore, over the previous ten years, AM advances have witnessed the great rise in what this technology can provide to industrials and customers [22]. As illustrated in *Figure 2*, other new technologies have been invented, and several companies have ventured into this field and introduced new printers to the market with great features. New techniques for printing new materials have been developed. They allowed to widen the potential applications and to start rapid manufacturing. Part properties have been improved, allowing for widening industrial applications of 3D printing in highly challenging areas such as aerospace and medical fields. A new generation of printers, with various and powerful energy sources (laser, electron beam, plasma arc-based welding), printing volume up to 5m, and fine resolutions yielding high quality printed parts [23]. According to Wohlers report (2017), service providers have registered, in 2016, a revenue growth of 84% in their main AM activity. They have developed the service of producing final parts for manufacturers. The same report revealed a wide range of industrial applications of 3D printing. It is often used for consumer product, with increasing use in aerospace and vehicle motors between 2004 and 2015 [24].

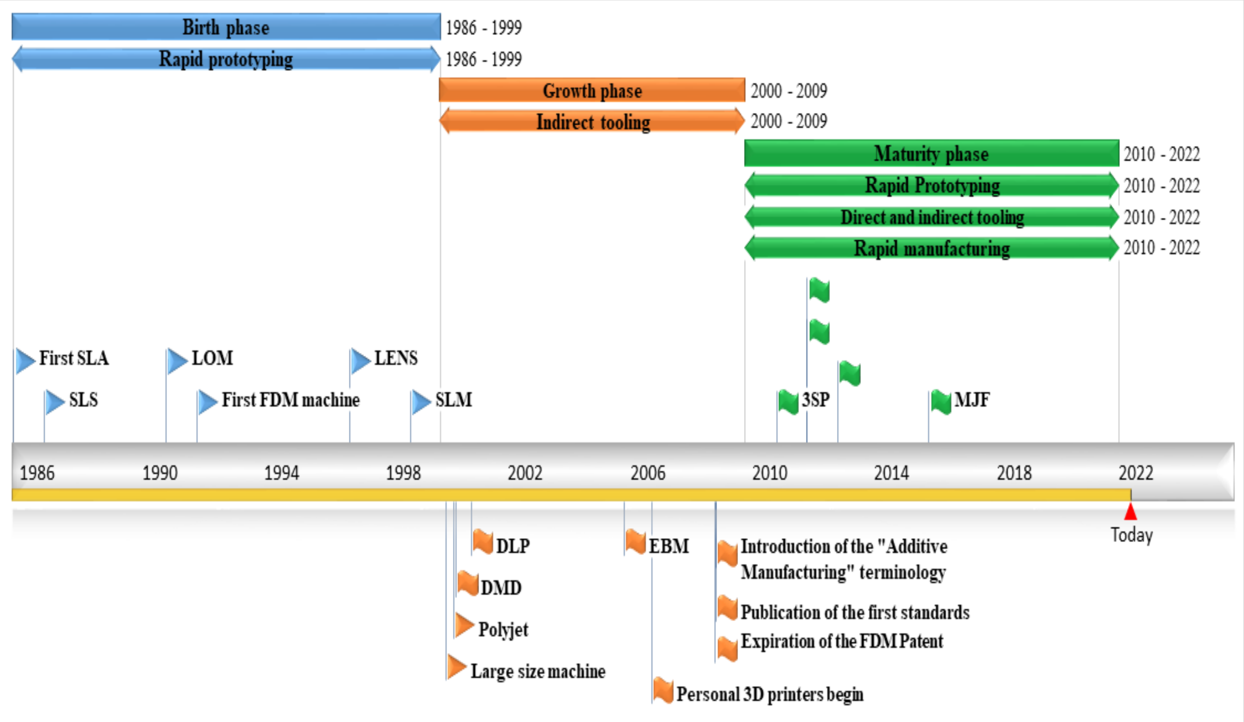


Figure 2 AM timeline process evolution

3.2AM processes categories and parameters

The fundamental principle of all AM processes is the same. The steps consist of: modelling the part in a computer aided design (CAD) file, generating the STL file, then converting it to a printable file such as g-code, and finally transferring the file to a 3D printer to build the part layer by layer and its support if necessary. Post-processing is performed after printing and according to the techniques of 3D printing technology used. The variety of technologies on the market has grown steadily since the early stages of this technology. From only three techniques in the 1980s to more than 30 processes on the market at present. All printing techniques follow the same principle explained above, however the respective technologies vary. For this reason, the world organization for standardization has classified in the "ASTM 52900-15" standard the AM processes into seven different families, depending on the process mechanics. This classification that the authors consider and present below [10].

3.2.1Vat-photopolymerization (VPP)

As specified earlier, the SLA process was first developed in the 1980s. It solidifies a photopolymer liquid by an energy source, usually an ultraviolet laser. Polymerization reaction happens when monomer molecules are linked to macromolecules under visible light. The liquid mixture of individual monomer molecules is spatially transformed into cross-linked plastic and cured, thus, producing complex components. This category includes many variants, and the most common is SLA. DLP technique is the second most used process; the projection is spread out on a digital micro-mirror device (DMD) consisting of many microscopic mirrors, which makes DLP faster than SLA. Two-photon polymerization (TPP) uses a non-linear two-photon absorption using a very powerful laser such as femtosecond that produces ultrafast implosions with a wavelength close to the infrared, allowing the production of nano-metric objects. Lithography-based ceramic manufacturing (LCM), derived from DLP process with a rotating tank, is specially designed for ceramic material, where a powder of the latter is suspended in a photosensitive resin. Projection micro-stereolithography (PμSL) uses a DMD device as a dynamic mask and lenses to reduce the images and digitally shape the light to cure an entire layer and produce high-resolution microstructures. 3D volumetric printing, also known as 3D holographic printing, can simultaneously solidify an entire three-dimensional object by irradiating a volume of liquid photopolymer from multiple angles. This category also includes other technologies such as scan spin and selectively photocure (3SP), mask projection stereolithography (MPSL), liquid crystal display (LCD), solid ground curing(SGC), and continuous liquid interface production (CLIP) [25–30]. This process family has several advantages, which boil down to high accuracy, fast printing in the case of MPSL the ability to print multiple parts at once, smooth surface, inexpensive and versatile material options, and very little material waste [29].

Two configurations exist, top-down (free surface) and bottom-up (constrained surface). We illustrate the two main configurations in *Figure 3.* The construction platform in a top-down design moves from the top to the bottom, opposite the manufacturing direction. In contrast, objects are produced from a tray situated underneath the liquid resin level in the other setup. The bottom-up approach has been widely used thus far. The first configuration does not need to separate the object from the bottom of the vat, as in the bottom-up case. However, the vat must be filled more than the necessary level in the z-direction. Also, contact with oxygen prevents curing the thin layer, and the need for a recoating system increases the production time [29]. The top-down configuration is adapted to the large scale, while the second one is more suitable for the small scale.

In the bottom-up method, the building part is situated between the platform and the vat bottom, causing an adhesive bond between the newly cured layer and the constrained surface. Hence, separating the part from the bottom at each construction is necessary, and refilling the vat with resin influences the construction time and part quality. Several studies have been carried out to make the separation process more effective. The most commonly used separation force is applied with a pulling-up mechanism, which can break the part. Tilting the vat to reduce the separation force is another method that, unfortunately, results in a considerable increase in printing time. A two-channel system for sliding the tray has also been tested. A vibration-assisted separation method combined with pulling up to reduce the separation force was investigated by Xu et al. [31], which significantly reduced the separation force. An inert film was used on the bottom surface of the tank as a coating to easily separate the part from the tank and reduce adhesion as the platform moves up (such as polydimethylsiloxane (PDMS), fluorinated ethylene-propylene (FEP), Teflon) [32]. Li et al. proposed a method to control the degree of resin curing during the continuous printing process by adjusting the ratio of photosensitive/thermosetting [33]. They found that increasing the thermosetting resin content up to 70% reduces the adhesion force. Dynamic acceleration instead of constant acceleration can reduce the separation force. A tenfold increase in acceleration resulted in a threefold decrease in separation force. Elevate the platform decelerated and then accelerate it [34]. In the CLIP process, the light is projected through an oxygen-permeable membrane that avoids polymerization on the surface to prevent the piece from bonding to the latter, thus preventing the platform from repeating the up and down movement [29]. Multi-material printing is a challenge for this category. Research has targeted to propose solutions, such as a rotating disk where several types of resins are distributed on vats in the form of a carousel. Change the tank and fill it with a second resin after its cleaning. Serving on demand is another process that only serves the necessary amount in the form of drops employing a pump and syringes. Other researchers have used two monomers with automatic exchange of resin chambers after printing layers of each material [35]. Like any AM process, VPP technology has some limitations that must be considered. Controlling the printing time depends on the right choice of scanning speed which depends on the complexity of the part, the type of resin, the energy source, platform velocity, and layer thickness. Therefore, the appropriate combination of machine type, resin type, curing process, and energy source must be selected to design the optimal object. The main issues of the VPP processes investigated are dimensional accuracy, mechanical proprieties, heat transfer, force separation, constrained surface, and deformation. Each of the mentioned techniques has specific properties that need to be considered in the design or production phase. *Table 2* presents some characteristics of the common VPP technologies. The VPP technologies have issues affecting the product's quality and mechanical properties, as illustrated in the fishbone diagram in *Figure 4*. In light of recent advances in VPP, we can conclude that the technology has significantly evolved and advanced from point-to-point scanning to full image projection, from continuous printing to 3D volumetric printing. Nevertheless, the force of separation due to adhesion must be decreased by developing new mechanisms or optimizing parameters. Note also that multi-material printing is extremely limited.

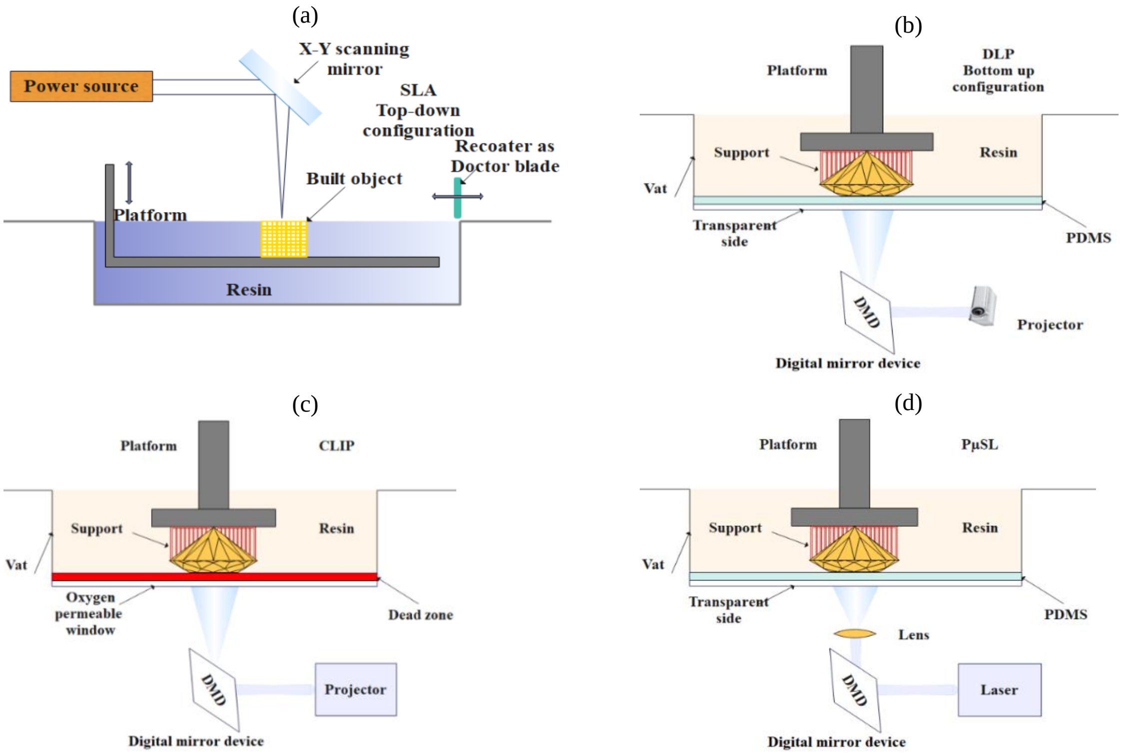


Figure 3 (a) Scheme of principle of SLA on top-down configuration. (b) Scheme of DLP principle. (c) Scheme of CLIP principle. (d) Scheme of PμSL principle

Table 2 Characteristics of the main 3D VPP process

VPP 3D	Specificities	Resolution	Maximum build size	Building speed	Light source	Ref.
SLA	Laser scanning process. Top-down. Times consuming. Curing point-by-point. Need recoating system. High resolution and accuracy. Microstructure scale.	50µm to 250µm	100 cm2 to 1m^2	100 à 1000mm/h	UV light	[36, 37]
MPSL	Curing entire one layer.	>1,2 µm	5040mm^2	>1.5mm/min	UV/Visible light	[29, 38]
DLP	Cure the whole layer at once. Faster than Sla. Printing by voxel. Limited monomer.	0.6 μm to 90 μm	-	30mm/s	UV/Visible light	[37]
LCD	High resolution and accuracy. Lower cost.	25 µm	10mm/min	55mm^3/s		[35]
3D Volumetric printing	Formation of 3D volume in one print. Irradiation simultaneous.	25 to 300 µm	>105 mm3	11mm^3/min	UV light	[29, 36]
TPP	Laser scanning process. Top-down, High resolution and accuracy. Smoother surfaces. Curing point-	<100 nm	100µm^2 to 4mm^2	20mm^3/h	femtosecond laser	[25, 36, 37]
LCM	Bottom-up vat photo-polymerization. Modified version of DLP. Rotating vat. Tilting the vat. Bottom-up system. Dental applications.	40µm	300mm^2	-	UV/Visible light	[39]
PµSL	Curing entire one layer.	0,6 µm to 30µm	2mm^2 to 4500 mm^2	4mm/min	UV/Visible light/Ar+ laser	[37]
3SP	Top-down system. Combine DLP and SLA technology. The laser can	25-100 µm	46550mm^2	-	UV/Visible light	
CLIP	100 times faster than any other 3D printing. High printing speed.	<100µm	>5000mm^{é}	1000 mm/h	UV/Visible light	[25, 37]

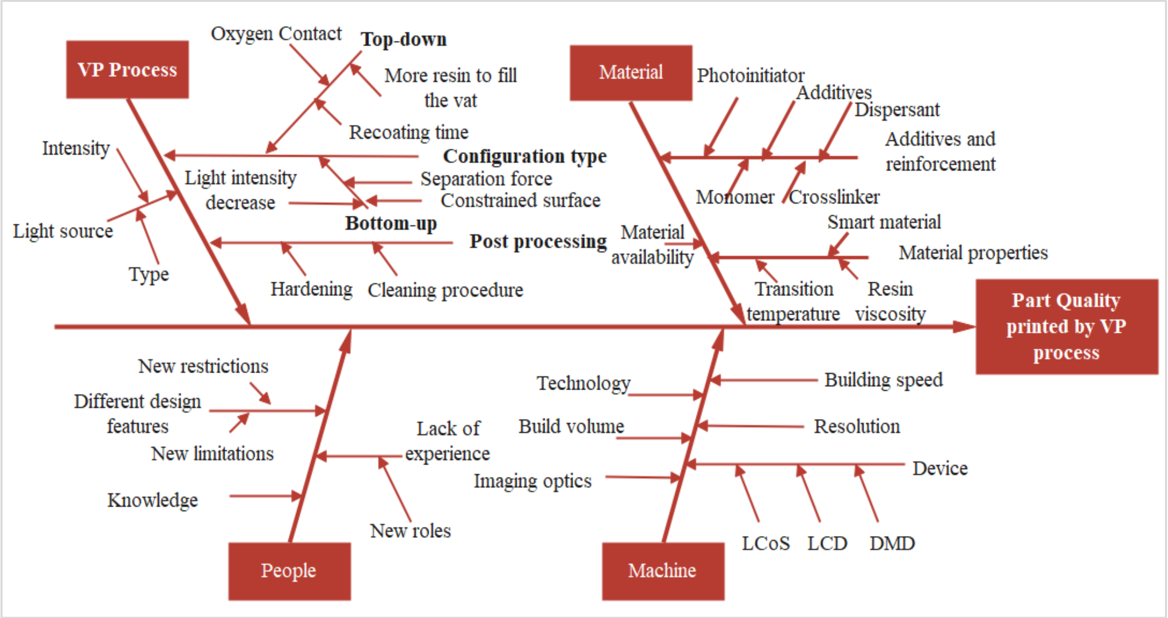
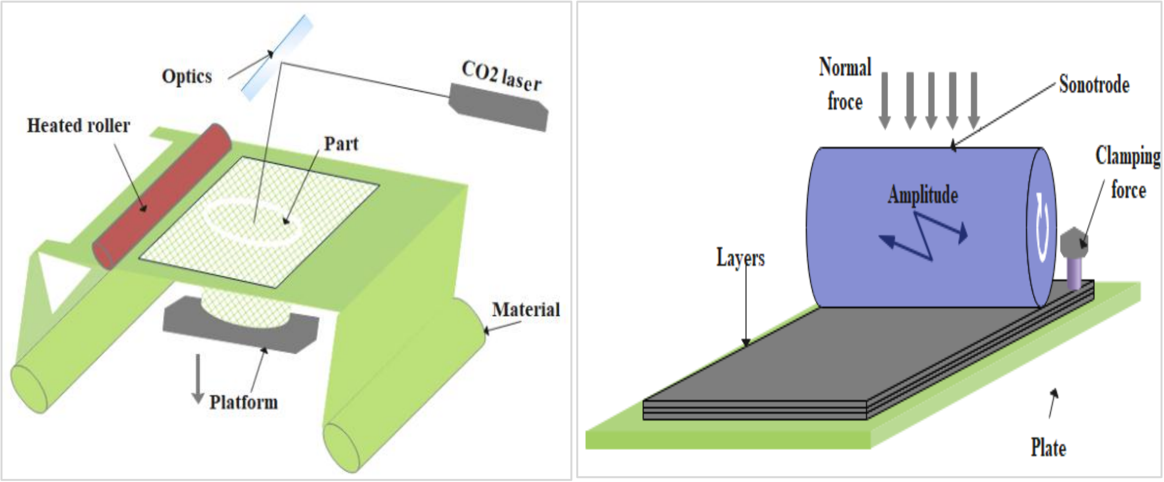


Figure 4 The fishbone diagram of the VPP process parameters affecting product quality

3.2.2Sheet lamination (SHL)

The CAD model is physically reconstructed by laminating and cutting thin sheets by a cutting method (CO_2 laser, tool cuts). The layers are bound together under pressure, by heating with a thermal adhesive coating, or by ultrasonic vibration. A cylinder moves the sheet, and the procedure is repeated until the component is produced. The principle is illustrated in *Figure 5 (a).* The 3D processes of this family differ in the way of adhering the layers by gluing, adhesive bonding, thermal, clamping, or ultrasonic welding [40]. This technique has the particularity of combining both subtractive and additive techniques. Rather, there is a waste of material, and building a complex geometry does not reach the level of other AM techniques. This category can be classified into two types: "Bond-then-Form" and "Form-then-Bond" [40]. With the first type, it is possible to manufacture large parts with less shrinkage and residual stress problems, and the material used is non-toxic and inexpensive. However, it has some limitations, namely the difficulty of controlling the Z-accuracy, constructing objects with complex geometry, and the inhomogeneity of mechanical and thermal properties. The second type is used mainly to manufacture metal and composite parts. Various materials can be fabricated, including paper, plastics, metals, and ceramics.

LOM is the first process of this category patented in 1988 by Michael Feygin, which is often confounded with the sheet lamination category [15]. Delamination, structural rigidity loss, and warping effect are the main manufacturing problems that can be encountered, thereby adversely influencing the product's quality. These can be overcome by a good combination of process parameters, especially roller temperature and speed, ambient air temperature, and plate speed [41]. Selective lamination composite object manufacturing (SLCOM) is a LOM process that produces only composite materials. Recently, two new solid-state promising techniques have emerged: friction stir additive manufacturing (FSAM) technology [42] and ultrasonic additive manufacturing (UAM) known as ultrasonic consolidation. UAM process is a hybrid metal technology that combines periodic ultrasonic welding and computer numerical control (CNC) machining to create a 3D part. This process involves pressing a metal foil (less than 150µm thick) with a normal force through a moving cylinder termed sonotrode, which creates a solid-state bond between the foils. *Figure 5 (b)* illustrate the 3D process. After welding, the CNC machining process shapes the part's contour [43]. The process operates at low temperatures compared to melting-based 3D processes. However, this process requires the microstructure to be controlled by the difference between the interfacial and non-interfacial characteristics. As shown in the fishbone diagram in *Figure 6* several parameters to be optimized control the product quality built by this technique, such as normal force and the sonotrode's amplitude. This combination of additive and subtractive processes has allowed the construction of complex parts, possibly integrating features during construction [44].



(a) (b)

Figure 5 (a) Scheme of principle of SHL process. (b) Scheme of UAM process principle

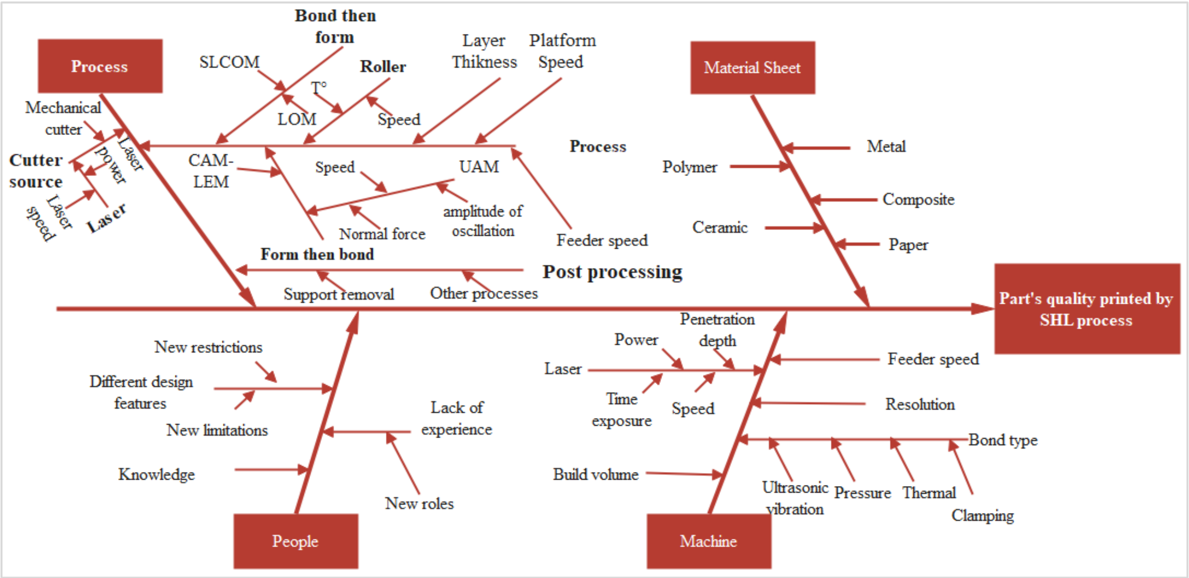


Figure 6 The fishbone diagram of the SHL process parameters affecting product quality

3.2.3Powder bed fusion (PBF)

In 1989, Carl R. Deckard filed a patent application for the process of SLS. Before that, in 1987, he built the first SLS machine called BETSY, a process in which thermal energy selectively fuses regions of a powder bed to build a 3D part [10]. In an inert gas chamber, powder layers are spread and compacted on a platform referred to as a powder bed. A powerful energy source melts or sinters a thin layer of material at a specific location, in a closed chamber filled with nitrogen gas to prevent powder oxidation and degradation, and an infrared heater to keep a high temperature around the part to avoid warping problems due to the non-uniform temperature. The rest of the powder acts as embedded support for the printed part. After each passage, a piston controls and moves the powder bed down by a distance equal to layer thickness. The powder is then spread over the previous layer with a roller, and the procedure is continued until the component is entirely built up and the unused powder may be recycled. The schematic of PBF process is shown in *Figure 7*. A laser or an electron beam can be used as the energy source. After manufacturing, it can be necessary to proceed to a post-treatment by sintering, coating, or other treatment [45].

The first PBF processes were targeted toward the manufacturing of plastic parts. Nowadays, with the emergence of new processes and their upgrades, the PBF family is very well adapted to metal parts manufacturing for the most challenging industries. PBF process category includes a variety of technologies; the most used are SLS, direct metal laser sintering (DMLS) which is used especially for metal, direct metal laser melting (DMLM), selective laser melting (SLM), electron beam melting (EBM) which works in a high vacuum chamber, selective heat sintering (SHS), and multi-jet fusion (MJF) [40]. PBF processes can be classified into four mechanisms: solid state sintering, liquid phase sintering, partial melting, and total melting.

SLS is a solid-state mechanism that fuses particles without melting. Several parameters influence product quality. Laser data and mechanical properties of the powder are the most widely examined. The most common problems in products made with SLS are surface roughness, porosity, and shrinkage defects. The sintering level is controlled by the energy density determined by four parameters as shown by Equation 1 [46]:

$$ED\left(\frac{J}{mm^3}\right)=\frac{LP}{(SS\times HS\times LT)} \qquad (1)$$

LP: Laser Power
SS: Scanning Speed
HS: Hatch Spacing
LT: Laser Thickness

The right energy density is the appropriate combination of the slow scan and short hatch spacing. In addition, the layer thickness and the build bed temperature impact the coalescence between the particles.

SLM is a full melting mechanism that fuses the powder completely and is commonly used for metal alloys. The melting process allows the construction of dense and well-bonded parts. The efficiency of the SLM process depends essentially on the power of the laser. New technologies lasers, like Nd:YAG fiber laser (1064 nm) and Yb:YAG fiber laser (1030 nm), are emerging and allow high power. Similar to the SLS process remain the same parameters to control for successful printing. The powder's composition and morphology also significantly influence the optimal process parameters, such as powder size, distribution, and energy absorption. Balling is another phenomena that occur in the SLM process that consists of forming rough and beaded surfaces that can be avoided by high laser power, low scanning, and keeping oxygen level at 0.1% [47]. Residual stress results from thermal fluctuation in the SLM process, which requires an additional heat treatment step between 600°C and 700°C. Some defects can be encountered depending on the type of material, as in the case of ceramics, where the problem of crack formation and delamination is very recurrent due to the need for a very high melting temperature, which can be avoided by adding an additional laser to preheat the surface of the powder bed.

DMLS is a liquid phase sintering mechanism, especially used for metal. In liquid phase sintering, a portion of the powder melts and acts as a binder for the rest of the particles that are still solid. The particles stick to each other by surface tension forces [48]. The process parameters that affect the part's microstructure are the same as those for SLS, plus the material properties, the hatch pattern, and laser spot size. Lower hatch spacing, between 100µm and 150µm, can provide a better coalescence [49]. It is recommended that the size of the laser spot should be controlled concerning the layer thickness.

EBM is a good 3D AM process that uses an electron beam as a thermal source and works in a high vacuum chamber. The particles melt when the powder absorbs the beam's photons, and the kinetic energy transfers from photons to powder. In order to avoid a negative charge in the powder creating a repulsion within the powder, the characteristics such as minimum powder size, layer thickness, and resolution are generally larger compared to the other PBF processes [40]. The only materials the EBM process can manufacture are conductive materials such as metal. The advantage of EBM is that it allows very high energy at a moderate cost. EBM is more cost-effective than laser processes at the same energy level [50]. The rapid cooling in the laser PBF processes causes the appearance of very distinct fine grains in the microstructures. In contrast, the higher powder bed temperature in the EBM process gives a microstructure with less porosity.

Multi jet fusion is a process for building polymer parts, introduced in 2014 by Hewlett-Packard (HP) Inc. The energy source is an array of infrared lamps. The principle differs slightly from the other PBF processes, which consist of two steps. First, a fusion agent can absorb infrared radiation with a detailing agent are sprayed through nozzles into the designed section. The detailing agent is used to protect the part's contour to prevent the powder's melting near the borders of the part. Then, infrared radiation is directed onto the section, while the fusing agent converts it into thermal energy that melts the powder. Some studies have compared the performance of both SLS and MJF processes in producing plastic parts, especially polyamide 12 as a material [51, 52]. The specimens printed by MJF provided better tensile strength and surface finish than those made by SLS. The dimensional accuracy of the parts produced by SLS is better due to the higher crystallinity.

In conclusion, in the PBF category, the selection of process parameters affects the quality of the product. Residual stress, dimensional accuracy, density, and surface quality are the most common defects. A correct combination of scanning strategy (speed and spacing), bed temperature, laser power, powder properties (material type, conductivity, absorbency, size, distribution, etc...), and layer thickness will provide the desired result. The fishbone diagram in *Figure 8* shows the main parameters to be considered in design and production using PBF processes.

3.2.4Material extrusion (MEX)

The MEX is also known as FDM or fused filament fabrication (FFF), invented and patented by Scott Crump in 1992 [17], and in the same year Stratasys company introduce the first machine called “3D modeler”. FDM is the most widely known technique for its accessible price and simplicity. As shown in *Figure 9*, a filament is extruded by a nozzle to a semiliquid state and deposited in a building plate in the desired place. If necessary, support is built from the same material or another less costly one, simultaneously with the part construction. Nowadays, machines with two or more nozzles exist, nozzles to build the part and the second to add the support. Fused granular fabrication (FGF) is a technique in this family that requires melting plastic particles and pushing them through the nozzle [53].

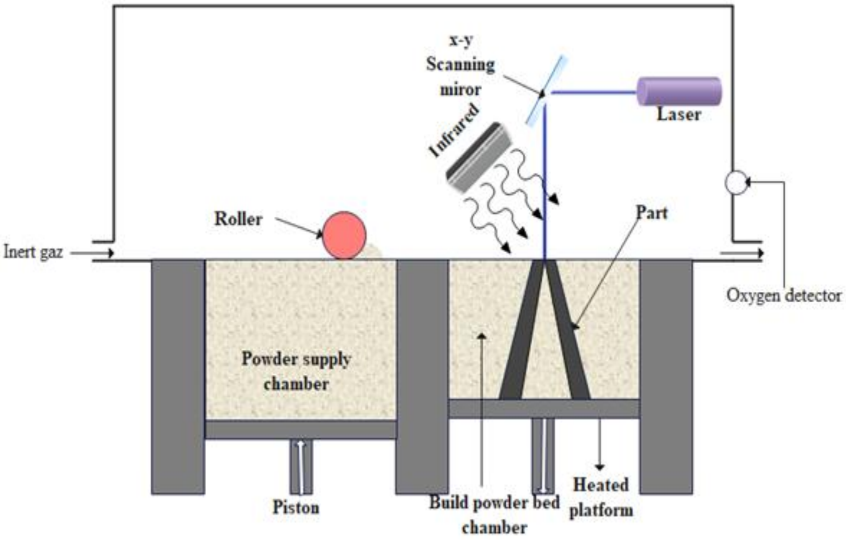


Figure 7 Scheme of principle of PBF process

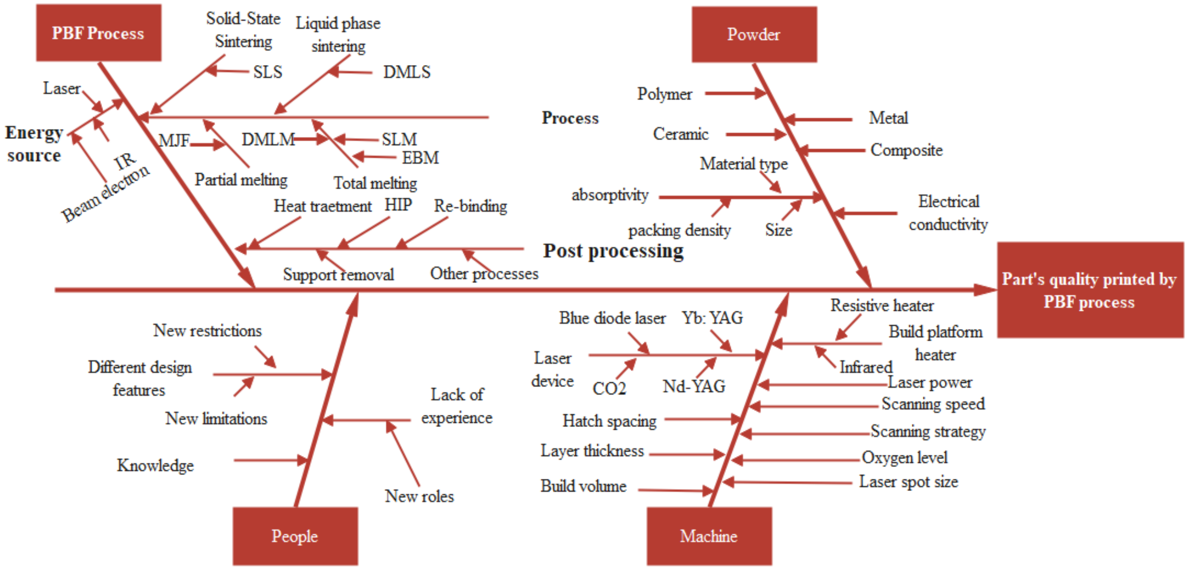


Figure 8 The fishbone diagram of the PBF process parameters affecting product quality

MEX processes are cost-effective for producing prototypes quickly, but it is not easy to obtain small and complex parts because of the nozzle size of only 0.2 mm. Objects printed by these processes have some defects, namely stair step effect, warpage, anisotropy, and low density. Producing quality parts using MEX processes requires certain design considerations and strategies. As shown in the fishbone diagram in *Figure 10*, the first parameter to be properly controlled is the temperature of the nozzle and the build plate, which depends mainly on the type of material to be printed. Among the frequents problems are the adherence of the piece to the bed, and the warping problem due to incorrect parameters. In summary, the thickness of the first layer with a printing speed lower than the rest of the construction of the piece, an adequate speed of the cooling fan, the addition of additional structures such as a raft, brim and skirt, heating bed, and using enclosed 3D printer [54]. Based on previous studies on the printing parameters to be considered for a quality product, we summarize from their results in *Table 3* the considerations to be addressed.

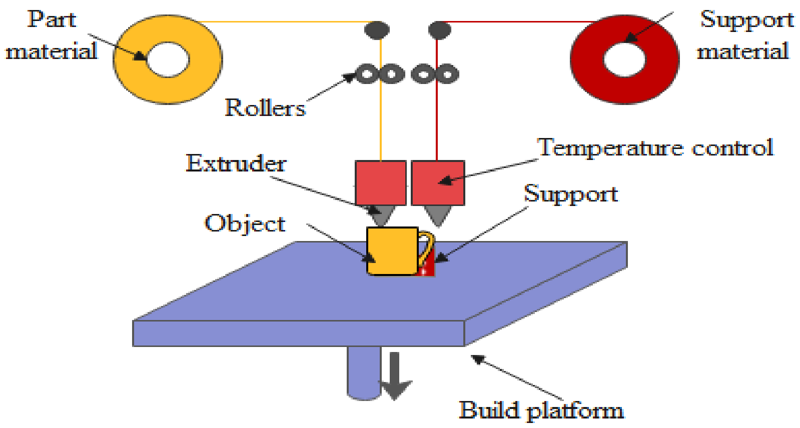


Figure 9 Scheme of principle of MEX process

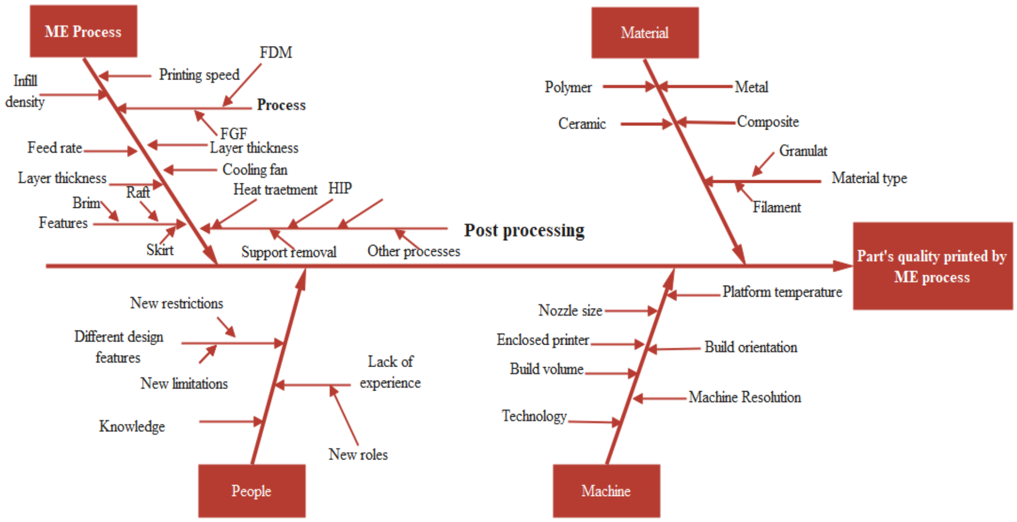


Figure 10 The fishbone diagram of the MEX process parameters affecting product quality

Table 3 Printing parameters of the main 3D MEX process

Printing defects	Printing parameters	Considerations	Ref.
Warping	Build platform temperature. Extruder temperature. Cooling fan. Structures as raft, brim and skirt. Printing speed.	Material type. Material proprieties. Enclosed 3d printer to avoid air temperature effect. Use glass transition temperature of material printed in fixing bed temperature. Prime the extruder by using additional structure as raft, brim and skirt.	[54, 55]
Adhesion	Build platform temperature. Extruder temperature. Cooling fan. Structures as raft, brim and skirt. First layer thickness. First layer temperature print speed. Non cooling for first layer.	Material type. Material proprieties. Enclosed 3d printer. First layer thickness less than others. First layer build temperature higher than others. Decrease the first layer print speed.	[54–56]
Mechanical proprieties	Layer thickness. Infill density. Infill pattern. Number of contours.	Types of infill pattern (Triangular or Rectilinear pattern provide strongest parts). Balanced with overall strength (40% is almost sufficient).	[54–56]

Printing defects	Printing parameters	Considerations	Ref.
	Feed rate. Build orientation.	Number of contours influence strength.	
Geometrical accuracy	Build platform temperature. Extruder temperature. Layer thickness. Cooling fan. Printing speed. Nozzle size. Build orientation.	Consider nozzle size for small feature. Consider and test printer accuracy. Reduce layer thickness. Decrease extrusion temperature.	[54, 55]
Anisotropy	Build orientation. Support structure.	Part build direction optimization. Minimizing overhangs. Keep overhangs less than 45°.	[54–56]

3.2.5BJT

BJT was invented and patented in 1995 by a group at the Massachusetts Institute of Technology [16], and is known as 3d printing. However, before the publication, Soligen company used the process and began commercializing the first printer, which is currently commercialized under 3D printing technology. As illustrated in *Figure 11*, the process consists of applying a binder to a powder layer at a given point. The binder droplet particles in the range of 0.2–200 µm in diameter can be applied in several colors through several nozzles on the powder material. Like most AM processes, the steps are repeated until finishing building the part. Like the PBF Family, the part can be built self-supporting, with the unused powder acting as a support. The fact that no power source is required allows optically reflective and thermally conductive metals to be processed [57].

Several factors in the BJT process can influence the properties of the final product, which are related to the process parameters, the material characteristics, the machine used, and the design features. The low density of the parts manufactured with BJT is a common problem, which leads to parts with porosity and shrinkage that requires additional sintering densification. The powder shape and particle size distribution are the main reason for this, as it is difficult to recoat small particles due to the low fluidity and agglomeration of the powder. Furthermore, it controls the layer thickness, the surface smoothness, and the binder saturation levels for the green and final parts. It has been reported that using a bimodal powder mixture in the BJT process resulted in a 9.4% improvement in part density and improved powder recoating, where the fine particles guarantee the density and the coarse particles the fluidity [58]. Several studies have been conducted on the effect of powder size and distribution on product quality [57–60]. The most studied powder properties are powder packing density, powder flow, and spreadability, powder segregation. In the BJT process, the use of the binder is temporary, which will be removed by evaporation during the sintering process. Two technologies can be used to spray the binder: continuous-jet and drop-on-demand [57]. The resolution of BJT printed parts depends mainly on the binder characteristics, especially binder droplet size, surface tension (Defined by We Weber number) in Equation 2 and viscosity (defined by Re, Reynolds number) in Equation 3 [61]. A binder must have a low viscosity with good interaction with the powder to ensure a successful jetability defined by Ohnesorge number in Equation 4 [61, 62].

$$Re = \frac{\rho d V}{\eta} \quad (\text{Reynolds number}) \qquad (2)$$

$$We = \frac{\rho d V^2}{\gamma} \quad (\text{Weber number}) \qquad (3)$$

$$1/Oh = Re/\sqrt{We} \qquad (4)$$

ρ is density of liquid (kg/m^3), V is the velocity (m/s), d is the droplet diameter (m), η is the dynamic viscosity of liquid (N s/m^2), and γ is the surface tension (N/m). A proper binder has an Oh value between 0.1 and 1, while an Oh greater than 10 (the fluid is not sprayable) or less than 1 (high pressure to spray) will make jetability difficult.

The volume of the air space in the build bed filled with printed binder defines the print saturation and is defined by the following Equation 5 and Equation 6:

$$S = \frac{V_{binder}}{V_{air}} = \frac{V_{binder}}{(1-PR)\times V_{solid}} \qquad (6)$$

Where $PR = \frac{V_{powder}}{V_{powder}+V_{air}}$ (Packing Rate) (7)

The print saturation is simply the amount of binder to be deposited in the powder to build the part. A low amount leads to a weak part and, in the opposite case, gives a part with undesired geometry [62]. As reported in some studies, 60% is a good printing saturation. However, the printing saturation should be chosen according to an adequate layer thickness [63].

The layer thickness affects the mechanical properties of the printed part more than the orientation during construction. It has been reported that the part's strength increases by 25% to 30% by decreasing the thickness from 200µm to 50µm [57]. After depositing the binder, the powder bed is passed under a heating source sufficient to dry the binder. Depending on the part's desired properties, a series of post-treatments to make an end-use part, by the first de-powdering to remove the powder incorporated into the part, sintering for a more dense part, curing for the structural integrity of the part, de-binding [62]. According to this review, we summarize in the fishbone diagram, in *Figure 12*, the most significant parameters influencing the properties of the part manufactured by the BJT process.

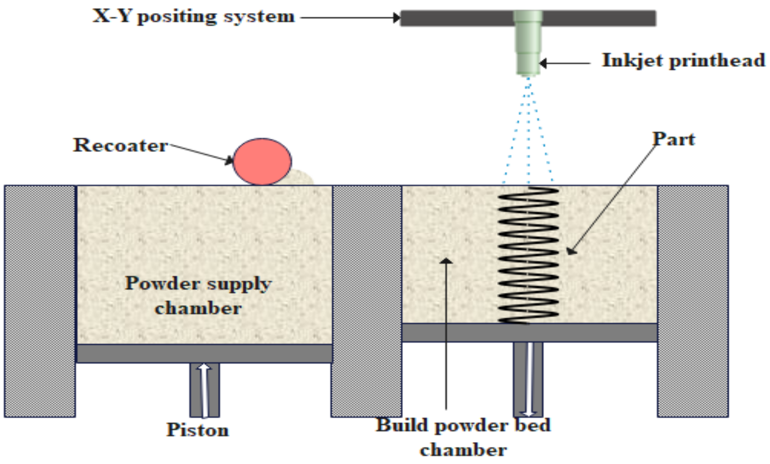


Figure 11 Scheme of principle of BJT process

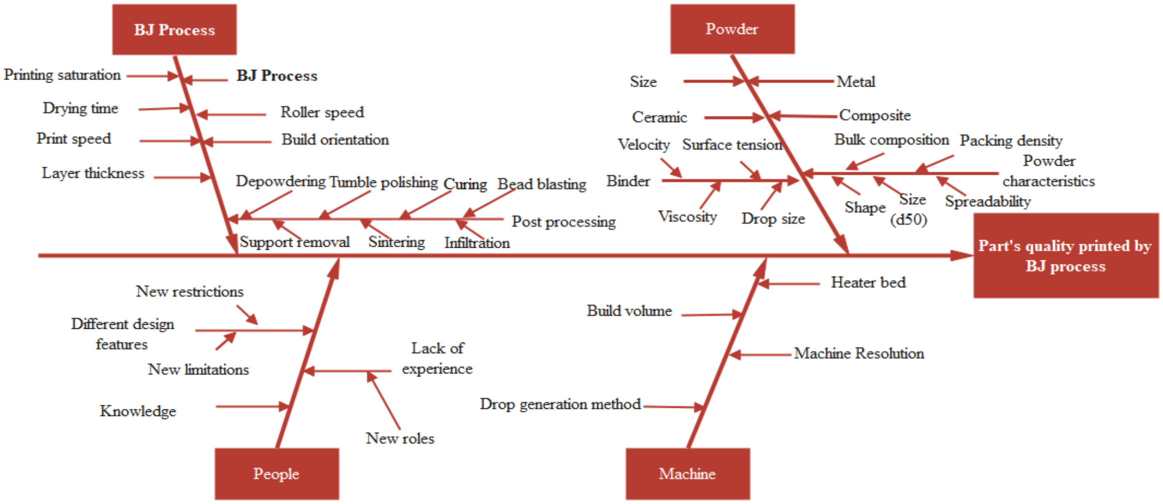


Figure 12 The fishbone diagram of the BJT process parameters affecting product quality

3.2.6Directed energy deposition (DED)

Directed energy deposition the patent first filed in 2000 by Sandia Corporation labs, and in 1997 Optomec company commercialized the first machine, “LENS 750” [64]. DED process is also referred to as laser cladding. Various thermal sources can be employed, such as a laser, an electron beam, a plasma arc, and an electric arc, to melt the material at the work-piece surface in a closed chamber under a vacuum atmosphere or using an inert gas [65]. As illustrated in *Figure 13* DED technology can be divided into two categories according to the material used: wire or powder. The laser beam is focused on the building platform using a lens system, and instantly, the powder is shot and melted into the laser spot through the nozzle [45]. The multi-axis process allows printing complex 3D geometry in multi-materials, in most cases, without support and printing on curved surfaces. Thus, DED technology is used in aerospace to repair existing parts or fill cracks [65].

Its main advantage is the ability to print at high speed in large sizes, with a wide range of materials and coarse powder particles compared to PBF processes. Parts built with DED have some defects that are similar to PBF processes; deformation due to temperature difference, porosity, shrinkage, cracking, residual stress, low resolution, surface roughness, and the reuse of powder is a little difficult [66]. Certain defects are due to inadequate manufacturing conditions and/or the raw feedstock's characteristics. Research areas entailing solutions to current problems, advanced materials, and new applications in defense, aerospace, and biomedical fields. Previous studies have shown that laser parameters (power and scan speed) and material feeding rate are the most important factors influencing the built part. Based on these studies, it is possible through adjustment process parameters to create desirable microstructure, depending on the material and the geometry. In the fishbone diagram presented in *Figure 14*, we summarize the parameters that must be considered in the design. For a correct construction, the following considerations are recommended [67]:

- The first layers can be thinner than the defined thickness, depending on the location of the focal plane relative to the substrate surface.
- In powder processes, it is necessary to deliver more powder than is needed since not all the powder is captured for melting.
- In the wire process, deposit just the necessary volume
- Randomize layer orientations between layers according to predefined multiples (15°, 30° etc)
- Use powder size typically ranges from 20–150 µm.

Laser parameters (power, P) and those related to the mass flow of the powder (feed rate, f) are decisive for successful manufacturing, which are related by the linear function $E = P/f$ (J/m) that implies the energy input [68]. Saboori et al. examined the effect of two different deposition strategies (67% and 90%) on the mechanical properties and residual stress of 316L. They found that samples with 90% rotation per layer have better mechanical performance compared to 67% samples [69]. Conducted a study on DED processing parameters. They found that surface uniformity and deposition improved when the powder focus point coincided with the cladding surface and the laser focus point was 2 mm below it, along with a Z-calibration of the laser head [9]. They tested the influence of each parameter separately and found that porosity is closely impacted by laser power, laser scan speed, and powder feed speed [9]. Printed parts require, in some cases, additional treatments achieved during a post-processing step. Either to remove the support of the structure and/or the substrate, perform finishing machining operations to improve the surface quality and precision, and heat treatment to achieve the desired microstructure [67]. Different companies have developed various techniques, depending on the energy source and the type of feedstock: laser metal deposition (LMD), LENS, direct metal deposition (DMD), 3D laser cladding, laser solid forming (LSF), wire and arc AM /wire and laser AM/ wire and electron AM (wire and arc additive manufacturing (WAAM), wire and laser additive manufacturing (WLAM), wire and electron additive manufacturing (WEAM)), laser direct casting (LDC), directed light fabrication (DLF), and others [66, 67, 70].

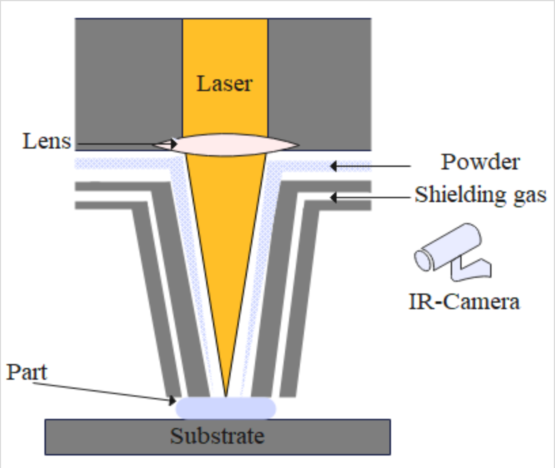


Figure 13 Scheme of principle of DED process

3.2.7Material jetting (MJT)

Material jetting is a technique inspired by two-dimensional inkjet printing. Gothait of Objet Geometries Ltd. institute created and patented MJ in 2001 [18]. The material jetting family referred to as the polyjet process or ink jetting technology, consists of depositing droplets of photopolymer liquid onto the built platform to form part layer by layer. Like the BJT category, material jetting uses several techniques for spraying the material, including drop-on-demand and polyjet by object.

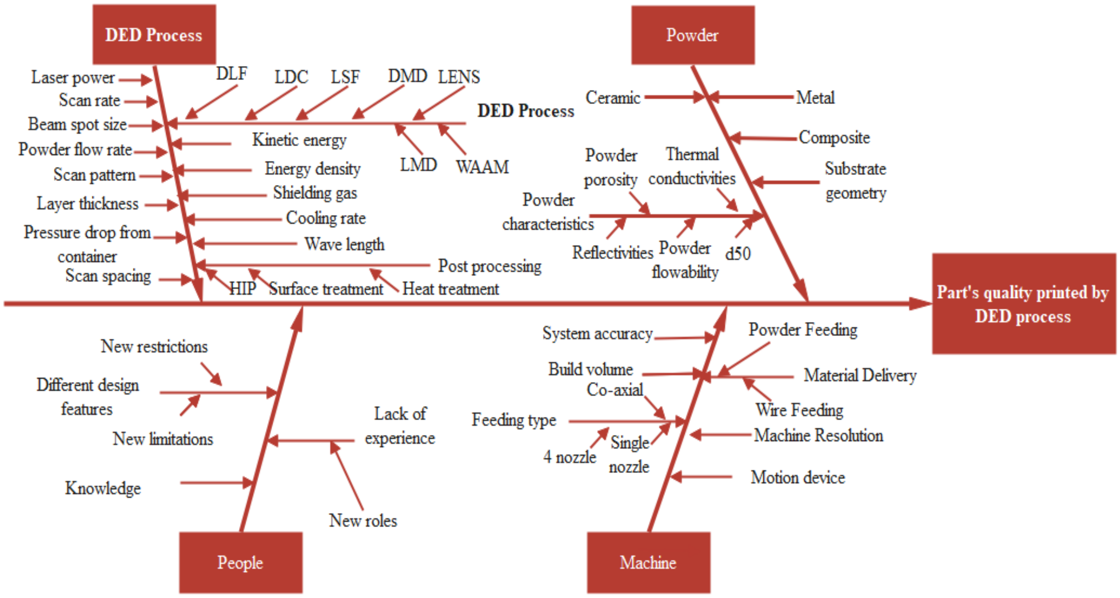


Figure 14 The fishbone diagram of the DED process parameters affecting product quality

The model is supported by a support structure built similarly by another liquid and cured by ultraviolet light [40]. The principle is presented in *Figure 15*. MJT 3D printing produces products with excellent dimensional precision and a very smooth surface finish and provides multicolor construction possibility. These features make MJT a highly desirable alternative for rapid manufacturing. It is an extremely complicated process requiring a proper combination of technical variables to tackle issues. Print heads, ultraviolet light sources, the build platform, and material tanks are the primary components of the MJT 3D printer.

The three challenging problems are the liquid formulation, the droplet formation, and the control of the deposit of the formed droplets. The formulation of the liquid is important to avoid clogging the print head, which can be solved by melting, adding a solvent, or mixing the primer with a polymerization initiator. Droplet formation is a crucial factor for a successful print, depending on the device used, material properties, and the set printing parameters. The third problem is the control of the droplet deposition by optimizing the trajectory, the droplet size, and their interaction with the substrate [40]. All these aspects influence the dimensional accuracy, the surface quality, and the mechanical properties of the printed part. The MJT process has enabled the construction of micro-structured components. In this context, Yun and co-workers investigated the printing quality of micro-composites. Their studies showed that parts larger than 250µm could be printed with micro-scale features, and the mechanical properties are affected by the geometry and directional trajectory of the particles, with a preference for perpendicular directions [71].

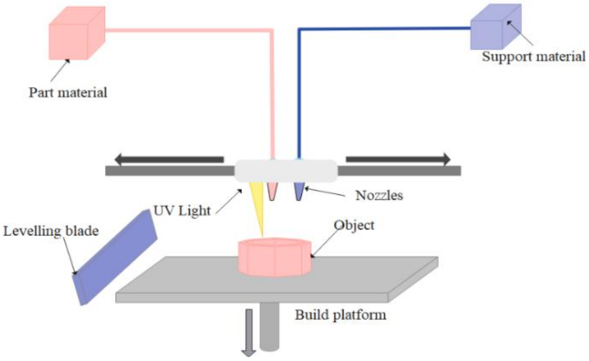


Figure 15 Principle of MJT process

The important advantage of the MJT process is the multi-color printing, a particularity that Tsai and co-authors have experimented with by developing a piezoelectric print head with six nozzles, one for constructing the support and each of the others for a different color. This study showed the possibility of manufacturing a three-dimensional part [72]. In order to reduce the cost of printing, it is recommended to print several parts in one construction and by minimizing the use of support material given its cost, which is very high [56]. The quality of the surface in the MJT process depends mainly on the construction orientation concerning the scanning direction and the type of finish (glossy or matt), or the glossy finish gives a good result compared to the second [6]. The dimensional accuracy in the MJT process depends on the print axis, where the z-axis construction is more accurate, and on the printer accuracy. As all AM processes that built part support, removing support is required. Finally, we summarize in the fishbone diagram in *Figure 16* the main parameters to be controlled in the design for the MJT process.

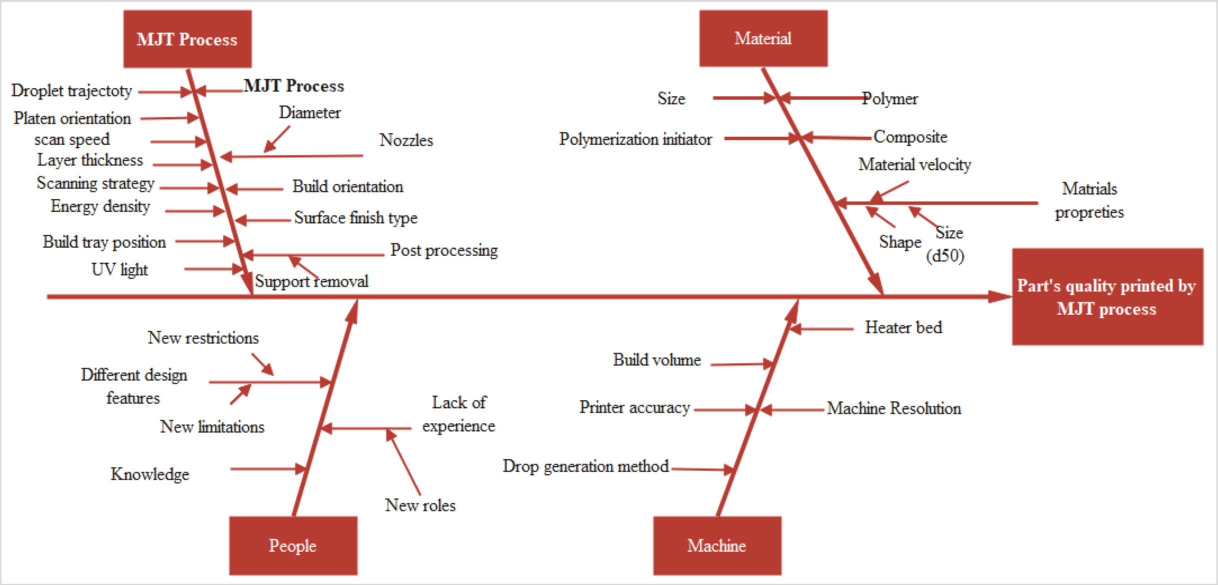


Figure 16 The fishbone diagram of the MJT process parameters affecting product quality

3.3AM industrials applications

AM advantages, among others, are reducing costs, forming complex parts, tool-free manufacturing, no waste of unused material, short production line, and lightweight product. Scientific research works and the industrial sector's enthusiasm for developing new materials or process innovation will allow this technology to offer further business opportunities. This means that their applications and implementation in diverse industrial areas may only be in growth. It is widely used in aerospace, automotive, education, medical and biomedical industry, electronics components, storage energy, fashion, and art [4, 73, 74].

The Gartner hype cycle charts predict emerging technology's evolution, maturity, and adoption. Comparing the graphs from 2011 to 2018, we observe an evolution in the diversity of industries adopting this technology. The graph of 2011 predicted the adoption of 3D printing in the next 5 to 10 years, again confirmed by the graph of 2012. We noticed in the 2013 and 2014 graphs an increase in the development of 3D printing-specialized enterprises over the following two to five years. The 2018 graph dedicated to 3D printing predicts the birth of new fields in the next 5 to 10 years, such as intellectual property protection in 3D printing, 3D printing in oil and gas, 3D printed clothing and 3D printed pre-surgical anatomical models. Areas such as bioprinted 3D organ transplants, nanoscale 3D printing, 3D printing of drugs, and blockchain in 3D printing are the technologies of tomorrow that will emerge, bringing new solutions and developments [75].

3.3.1Aerospace

Researchers are currently focusing on AM trends and applications in different industrial sectors, notably aerospace. This field requires high quality, high precision, lightweight yet complex parts that AM can provide while reducing the cost of production. The applications of AM in this field are of two types: manufacturing and repair. Repair is mainly done with the LMD process to repair damaged parts, by depositing the powder particles only on the section to be repaired [76]. The use of AM in aerospace because it is possible to manufacture dense parts with less post-processing. This quality is, in fact, due to the high power of the energy sources used, mainly in the EBM process [77]. Finding spare parts for aging equipment can be challenging in the aerospace industry. Aerospace companies' services aim to overcome this problem by allowing on-site customization of spare parts. The low cost of rapid prototyping is an interesting aspect that helps modify equipment while reducing waste with greater design flexibility [78]. Research has shown that combining 3D printing with artificial intelligence allows aerospace manufacturing companies to produce more accurate and better-performing aerospace parts. A system based on artificial intelligence so the machine can understand the influence of one parameter on another and decide the best printing parameters to use [76].

Materials that resist high pressures and temperatures, such as nickel alloys, are suitable for high-performance aerospace applications, which are difficult to cast and machine [79]. AM processes used in aerospace fabrication are FDM to reduce tooling cost, DMLM providing high quality and strengthened parts, EBM process due to high source energy, and SLM process [77]. Wohlers published in 2019 that GE Aviation has produced more than 30 000,00 metal fuel nozzles, which is expected to grow in the next few years. Airbus has designed and built by FDM process (ULTEM 9085) more than 100 000,00 plastic brackets, clips, and other devices [22]. GE Aviation and United States Air Force produced a sump cover for the F110 engine [80]. From July 2020, the company planned to start mass production with the Concept Laser X Line 2000R machine (DMLM process) [81]. According to the Airbus 2019 report, Premium AEROTEC, one of the world's leading aviation structures, designed new aircraft components made of titanium or aluminum [82]. The AM opportunities, such as lighter and more robust parts, imply reducing the aircraft's fuel consumption. Consequently, it has prompted major companies to support research on this technology [83]. Studies aim to reduce the mass of manufactured parts through topological optimization or lattice structures. In 2017, SAFRAN company produced a turbine nozzle for the eAPU60 by SLM using Hastelloy X material (nickel-based material), allowing 35% lighter and comprised less part than the part conventionally machined [84].

3.3.2Automotive industry

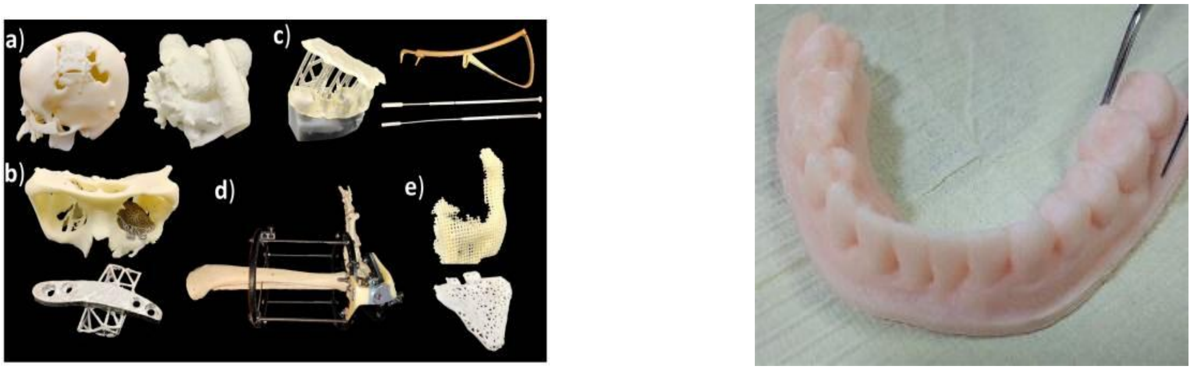
According to a recent survey, AM in the automobile sector will reach 1.8 billion US dollars in 2023 [85]. AM technology can be used in the automotive industry for serial parts and customization vehicles, expanding the market for more personalized offers and driving competitiveness. As stated in BMW company’s 2019 report, claims that its production network leverages 3D printing [86]. The German automotive company BMW Group was able to manufacture 100 window guide rails in 24 hours and a fastener for the soft top attachment that was 44% lighter than the ordinary fastener, using the MJF metal 3D printer [74].

Patalas-Maliszewska et al. have conducted a survey among automotive companies [87]. The study outlined the following AM potentials that encourage adopting this technology, production costs reduction, material conservation, freedom of design, no assembly stage, satisfy consumer desires, quick response to market needs, and optimization of product functions. Hettesheimer et al. have carried out a quantitative and environmental study. This study of the overall energetic impact of components manufactured using SLS and used in the automotive industry found that the use of AM influences energy consumption in the various life cycle phases of the product [88]. Juechter et al. have investigated the production of dense turbocharger wheel parts using titanium aluminide alloy and the EBM process. The roughness of the final part must be improved to achieve its marketability [50]. AM of stamping tools for the automotive industry allows a good trade-off between manufacturing costs and tooling time. Given the rigid milestones imposed on the automotive sector, A's ability to produce quickly will enable tools to be delivered in time [89]. According to an empirical study conducted among 250 Polish metal and automotive manufacturing companies, managers are more aware of the need to use AM to be more flexible in responding to customer needs [87]. According to the Deloitte 2019 report [90] AM as a rapid prototyping tool allows Ford to save money and time in product development. Usually, the prototype of an engine manifold takes four months and costs about $500,000. Using AM, the development and production take four days at $3,000. Additionally, Ford Company uses this technology to reduce operational stress and repetitive tasks. AM processes as FDM processes employed by BMW to manufacture hand tools, and SLS and SLA processes by GM to build about 20,000 parts. FDM, DMLS, and EBM methods are promising processes for automotive companies [89].

3.3.3 Medical field

According to Allied Market Research's 2021 report [91], the market for 3D printing in healthcare is projected to increase at a CAGR of 20.10% between 2021 and 2030, from $1,036.58 million in 2020 to $5,846.74 million in 2030. The fastest-growing of this technology leads to more important medical applications. AM technology allows building medical parts respecting each patient's anatomy. It is used in healthcare to build end-use parts as a tool for testing before surgery and for medical teaching purposes [92, 93]. AM technology is considered an easier way of production that provides good products for this field. The study of Javaid and Haleem summarizes

AM applications in the medical area; support to doctors by creating a physical model that helps surgeons; fabricating Substitute bones, designing and producing lightweight implants; participating in medical students' education and training; tools and instruments for medical devices; supportive guide and reconstruction of skull/nos [92]. *Figure 17* show some example. Albanna et al. have carried out a study that describes, more precisely, the bioprinting system that can provide rapid and tailored to an individual wound, a skin tissue directly printed onto the patient [94]. The creation of 3D models is performed by the use of computed tomography, magnetic resonance imaging scans, and reverse engineering. The model is converted by a specific software like Mimics Inprint, from Materialise company to a format compatible with bioprinters [92]. The use of AM in dental is one of the earliest. The SLA technique and FDM are generally used for, dental devices crowns, bridges, etc. Researchers use SLM process for maxillofacial implants where the metal powder replaces the entire jaw of the patient [77].



(a) (b)

Figure 17 (a) Some applications in medical field reproduced from (Mika Salmi, 2021[95]), (b) Orthodontic models by DLP

Various kinds of research have been carried out on polymer materials used in bio-printing. Including synthetic polymers such as biodegradable photopolymers or thermoplastic. For cartilage and tissue regeneration, synthetic polylactide (PLA) and its derivatives (poly-d,l-lactide and polylactic-co-glycolide) have been investigated [93]. For example, biological polymer, alginic acid, or alginate are very expensive and complex and provide fewer mechanical properties. Certain known metals are additively manufactured into metallic devices for the medical field. Ti-based alloys have good mechanical properties with good biocompatibility. NiTi-based shape memory alloys due to the superelastic behavior, reversible strains, generation of high recovery stresses, and work output with a high power/weight ratio. Stainless steels are commonly used materials due to their good mechanical properties [25]. A biomaterial should fulfill certain criteria to be used for medical purposes. Da et al. summarized them in six points: physical properties, mechanical properties (such as fatigue strength and ultimate strength), chemical properties, biocompatibility, osseo-integration and tribological properties (such as wear resistance) [96].

AM processes used in the health field are, DLP, SLA, SLS, FDM, BJT, inkjet bioprinting, EBM technique, and direct metal [97]. The current medical research challenges include a limited range of materials approved by the United States Food and Drug Administration, which complicates the commercialization strategy and 3D bioprinted devices.

3.3.4 Additive manufacturing fight against covid-19

The COVID-19 pandemic crisis has disrupted all scales, economic, political, and above all, public health. The world is in a position to beat the COVID-19 virus. Companies are forced to shut down their operations, and the supply chain is disrupted and unavailable. The global health system has proven unable to control the new disease. In this section of this manuscript, we highlight the potential and impact that 3D printing has been able to bring to medical services and how 3D printing has proved a fast reaction in the current scenario. The need for medical devices has recorded a world record during this period. Considering the lockdown and interruption of air travel, the world health organization (WHO) has sounded the alarm about a possible shortage of PPE [98, 99]. Moreover, to respond to the growing and unusual demand, WHO has asked the government to double efforts and increase production by at least 40%. Considering the versatility of 3D printing, with local production and reduced time-to-market advantages, companies and printing hobbyists have built several objects used to fight against contracting coronavirus. Various specialized medical and protective equipment has been produced, such as masks, PPE, ventilator couplers, nasopharyngeal devices and swabs, ventilators, respiratory components, face shields, oxygen connectors, oxygen splitters, non-invasive ventilation helmets, ear saver and other protective equipment [100–103].

3D Systems developed stopgap face mask as seen in *Figure 18 (a).* In 2021, Stratasys announced that 275,000 sterile 3D-printed nasopharyngeal swabs had been shipped to hospitals as seen in *Figure 18 (b)* [104]. Oland and co-authors evaluated the printed nasopharyngeal swabs, showing a high coherence with traditional nasopharyngeal swabs. The printed nasopharyngeal swabs presented an opportunity in this situation and should be produced by suppliers to supplement current deficits [105]. The swab nasopharynx produced for $0.06 to $0.12/piece, with favorable mechanical and clinical trial properties. Westphal et al. designed a frame for face shields, printed by FDM and SLA process using PLA+ and polyethylene terephthalate glycol (PETG) material; in comparison, SLA has produced quality frames, but FDM has competed on cost [103, 106]. Bishop and Leigh have produced PPE devices in an average of 5 minutes using LSAM printers, which is cost-saving compared to the 1 to 2 hours required by FDM technologies [107]. Moroccan researchers created the first version of Covid-19's "intelligent mask for autonomous remote detection" dubbed "MIDAD" using 3D printing. MIDAD includes a temperature and humidity sensor, a pressure measuring instrument, a breathing cycle, and an oximeter to determine the oxygen level [108].

Despite the advantages mentioned, the use of AM in this case and this public health situation raises several questions regarding safety and regulation [109]. The study questioned the viability and safety of printed N95-type respiratory protective masks from many open-source respirator designs in the absence of adequate quality assurance processes [110]. The results showed that most respirators provide less than 60% filtration efficiency. Gallup and co-authors developed a solution for the distributed manufacturing of a swab nasopharynx using open source code [111]. Materials used in device production are PLA, PETG, Photopolymer resin, Azul3D developed material, ABS-42 Filament, and Medical-grade nylon [112]. AM processes employed for this purpose are SLA to build face shields, facemask, nasopharyngeal swab and FDM to produce face shields. MJF and SLS processes to manufacture ventilator parts, hand-free door open, and face masks.


(a) (b)

Figure 18 Stopgap Face Mask (a) (Source 3D systems Website) [113], nasopharyngeal swabs (b) (Source Stratasys Website) [114]

4.Discussion

From the results and analysis of this literature review of the advances, challenges, and applications of AM, we can conclude that AM's future depends on overcoming the challenges and disadvantages [115]. The size and number of parts to be printed are limited by the size of the printing chamber, which increases the manufacturing time by adding an assembly step for parts produced in individual pieces [116]. Printing large-scale with accuracy can lead to more opportunities in the aerospace, defense, and automotive industries. Printing faster with good mechanical properties, especially for the metal part, will produce the final part without post-treatment [74]. Improving the printer's technical properties for more resolution and quality, especially in the esthetic aspect of the parts, and multifunctional components, which require multi-materials and more flexibility in printing [117]. As we have discussed, the industrial applications of AM are very varied, so many materials can be used. However, unfortunately, only a few are available, and the choice is limited [118]. As we have presented before, product quality remains a great challenge, as there are many parameters to optimize, and each one impacts the other. Recent studies have investigated machine learning as an appropriate technology to solve this problem, namely the selection of parameters and process supervision [119]. Combining more AM processes can be a vehicle to combine the advantages of each. Finally, another limitation pointed out by several researchers is the need for more qualified and competent personnel, which requires specific training on the characteristics of this technology and specifically on the design for manufacturing [74]. Enhance the knowledge of designers and people working in this field to take full advantage of the opportunities AM offers.

A complete list of abbreviations is shown in *Appendix I.*

5.Conclusion

AM is an emerging technology that continues to attract the interest of scientists and business people. Among the additional advantages of this new manufacturing method are design freedom, the ability to build complex parts, mass customization, using just needed material without waste, printing at the nanoscale a short time to market, and the ability to produce lightweight products. This article examines the current state and evolution of AM and 3D process properties and their industrial applications. The expiration of some patents has allowed the AM market greater opportunity to evolve and transition from prototyping to rapid manufacturing. According to a report by the Gartner analysis office, industrial applications of AM will expand into various fields. Companies and printing amateurs have produced many anti-coronavirus objects using 3D printing's local production and decreased time-to-market advantages.

In order to guarantee a quality product, it is required to control the manufacturing process through sufficient control of the process parameters. In studying the different processes, each has crucial parameters that need to be optimized, which we have highlighted using fishbone diagrams for each AM category. Dimensional accuracy, mechanical properties, and surface quality are the major issues studied. The main aspects from the analyses are as under:

- **VPP:** New processes, as volumetric 3D printing PμSL, are now developed that allow to produce parts with great precision, quickly and in nanoscale but the problem of the separation force needs further investigation.
- **SHL:** The emergence of two processes has enabled this technology to manufacture complex parts, namely FSAM and UAM, but delamination and warping are two issues that need to be addressed.
- **PBF:** This family has seven different processes; each one is classified according to the mechanism used. The laser's power and the materials' properties are the most important parameters influencing the success of a construction.
- **MEX:** The control of the process requires a good understanding of the material properties, which determines the temperature of the nozzle.
- **BJT:** Powder and binder characteristics, such as viscosity, speed, etc., influence print saturation as an important factor to monitor in BJT process.
- **DED:** A broad category of processes that use wire or powder as raw materials. By selecting the laser power in accordance with the powder's rate of flow, the manufacturing process can be optimized.
- **MJT:** a process that succeeds at using a variety of colors and materials, but it necessitates choosing the tray's and the piece's orientation correctly.

We have attempted to conduct a comprehensive literature review. More research is needed to characterize a solution for optimizing factors to ensure a defect-free quality product and to develop a design methodology to assist designers and engineers in deciding and choosing the most appropriate actions. For this, it is wise to explore the AM characteristics that industries seek to benefit from.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Rajae Jemghili: Conceptualization, data collection, writing-original draft, writing-review and editing. **Abdelmajid Ait Taleb:** Supervision, writing- reviewing. **Khalifa Mansouri:** Supervision, writing- reviewing.

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Appendix I

S. No.	Abbreviation	Description
1	AM	Additive Manufacturing
2	ASTM	American Society for Testing and Materials
3	BJT	Binder Jetting
4	CAD	Computer Aided Design
5	CNC	Computer Numerical Control
6	CLIP	Continuous Liquid Interface Production
7	DLP	Digital Light Processing
8	DMD	Digital Micro-Mirror Device
9	DMD	Direct Metal Deposition
10	DMLM	Direct Metal Laser Melting
11	DMLS	Direct Metal Laser Sintering
12	DED	Directed Energy Deposition
13	DLF	Directed Light Fabrication
14	EBM	Electron Beam Melting
15	FEP	Fluorinated Ethylene-Propylene
16	FSAM	Friction Stir Additive Manufacturing
17	FDM	Fused Deposition Modeling
18	FFF	Fused Filament Fabrication
19	FGF	Fused Granular Fabrication
20	HP	Hewlett-Packard
21	LOM	Laminated Object Manufacturing
22	LDC	Laser Direct Casting
23	LENS	Laser Engineered Net Shaping
24	LMD	Laser Metal Deposition
25	LSF	Laser Solid Forming
26	LCD	Liquid Crystal Display
27	LCM	Lithography-Based Ceramic Manufacturing
28	MPSL	Mask Projection Stereolithography
29	MEX	Material Extrusion
30	MJF	Multi-Jet Fusion
31	PPE	Personal Protective Equipment
32	PDMS	PolyDiMethylSiloxane
33	PETG	Polyethylene Terephthalate Glycol (PETG)
34	PLA	Polylactide
35	PBF	Powder Bed Fusion
36	PμSL	Projection Micro-Stereolithography
37	3SP	Scan Spin And Selectively Photocure
38	SHS	Selective Heat Sintering
39	SLCOM	Selective Lamination Composite Object Manufacturing
40	SLM	Selective Laser Melting
41	SLS	Selective Laser Sintering
42	SHL	Sheet Lamination
43	SGC	Solid Ground Curing
44	SLA	StereoLithography Apparatus
45	STL	Stereolithography File
46	3D	Three-Dimensional
47	TPP	Two- Photon Polymerization
48	UAM	Ultrasonic Additive Manufacturing
49	VPP	Vat-Photopolymerization
50	WAAM	Wire and Arc Additive Manufacturing
51	WEAM	Wire and Electron Additive Manufacturing
52	WLAM	Wire and Laser Additive Manufacturing
53	WHO	World Health Organization