REVIEW PAPER

Investigation of metallic 3D porous scaffold prepared by selective laser sintering for dental applications

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ABSTRACT

This article examined the history of three-dimensional (3D) metal printing technology, various types of methods, and their advantages and disadvantages. Selective laser melting (SLM) was compared with regards to consumables, working methods, limitations, capabilities, and applications. Examining each method in turn reveals that the superiority of each one depends on the materials that are intended to be used as the basis of any type of light or heavy parts. The prepared sample by SLM process, which belongs to the family of 3D printing, is fusion powder, and the materials used in both processes are granular metals. This technology is suitable for complex parts, which cannot be made by traditional methods due to their high cost, with excellent mechanical properties for the industry, plastic, and dentistry applications. This technique uses metal 3D printing technology with various levels of porosity. Every day, metal printing provides greater benefits to industries. However, this technology has its own disadvantages, which include its lack of both suitablity and cost-effectiveness for manufacturing parts with traditional methods.

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INTRODUCTION

Today, three-dimensional (3D) printing plays an essential role in the production of many different parts. These printers use various methods and technologies, and each method is suitable for its own materials or specific parts [1-4]. About ten of the approximately 25 3D printing techniques that have been developed worldwide — some of which have been commercialized — can be found on the market and in the component manufacturing industry. For example, prototyping is common [5-7], and one of the things that is used to produce important parts is the 3D printing of metals. Being a new production method, the 3D printing of metals shapes the piece layer by layer with all possible details and complications. With this technology, any piece can be produced and used in various industries. In fact, metal 3D printing has revolutionized the way of doing things [8-11]. Despite its popularity in many fields, it still has a lot more to offer. Therefore, it is not surprising that researchers continue to improve this technology across the globe [12-15]. Knowing about the different types of 3D printing methods and their advantages and limitations is of special importance in understanding this technology. In this article, we discussed the 3D printing of metals and focused on selective laser sintering (SLS) and SLM methods. A 3D printer is actually a device similar to computer numerical control (CNC) machines that can turn a 3D file designed using 3D software or a 3D scanner into a tangible physical object [7,16-18].

The way 3D printers work is that they slice a 3D file, apply and transmit the settings for printing it to the device, load the consumables or the filament,

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and the device starts to work, building the physical model layer by layer [19-21]. 3D printers can be used for a variety of tasks, including the initial modeling and manufacturing of final products. Most 3D printers work with fiber materials, and thermoplastics can be made from fibers such as polylactic acid (PLA), polyethylene terephthalate (PET), and acrylonitrile-butadlene-styrene (ABS) to achieve desired mechanical properties. Nonetheless, they are still plastic, and in many areas, especially in industry, plastics cannot replace metals [14-17]. Metal printing provides greater benefits to industries every day [22-35]. With 3D metal printing, not only parts with complex forms and structures can be built, while molding and processing cannot do so, but also parts into other parts can be built that allow engineers to create complex assembly designs in assembly and preparation [24-27]. In addition, much time can be saved and troubles can be reduced for assembling parts or processes such as welding, thereby increasing the efficiency of the final part. The key positive and negative features of 3D metal printing technologies are as follows: 3D metal printers are used to make complex parts that are not possible with traditional methods [28-33]; metal 3D printed parts can be optimized to improve performance while reducing weight; metal 3D printed parts have excellent physical properties and a wide range of raw materials which can be used in metal 3D printers that are highly difficult to work with using traditional methods [34-40]; having said that, raw material cost and production with a 3D metal printer is high, and as a result, this technology is not suitable and cost-effective for the production of parts that can be made using traditional methods; due to special conditions and the need to fully control the manufacturing environment, the manufacturable dimensions of metal 3D printing systems are limited [41-46]; ready-made 3D models are usually not suitable for metal 3D printing, and changes must be made to make them suitable for manufacturing with a metal 3D printer.

Complex parts that are either too expensive to produce traditionally or are otherwise difficult to fabricate are suitable for 3D metal printing. Lowering the need for a support structure greatly reduces the cost of 3D printing of the part [47-51]. Topological optimization is necessary to use the capabilities of metal 3D printers. Metal 3D printed parts have excellent mechanical properties and can be made from a wide range of engineering raw materials, including metal superalloys (the characteristics of each alloy for use in 3D printing are listed in Table 1). SLM and direct metal laser sintering (DMLS) processes are two metal additive manufacturing processes that belong to the family of fusion powder 3D printing. The two technologies have many features in common. For example, both use lasers to scan and select particles of metal powder, selectively melt them, bond them together, and build them layer by layer. Further, the materials used in both processes are metals that come in granular form (Table 2 shows the main features of SLM, DMLS systems). The differences between SLM and DMLS come down to the principles of the particle bonding process. SLM uses metal powders with a single melting temperature and completely melts the particles, while in DMLS the powder is composed of materials with variable melting points. SLM produces parts from a single metal, while DMLS produces parts from metal alloys. Both SLM and DMLS are used in industrial applications to create end-use engineering products. There are other additive manufacturing processes that can be used to produce dense metal parts.

The SLM process, also known as DMLS or laser powder bed fusion (LPBF), is one of the additive manufacturing methods (3D printing) in which metal powders are melted and connected using a high-power laser source. The SLM process is capable of locally melting the desired metal powder and turning it into a solid 3D piece. SLM technology, as one of the 3D printing methods, was presented for the first time in 1995 at the Fraunhofer Research Center located in Anne, Germany, during a research project and in the form of a patent with the code 19649865. The first SLM model was designed in 1995 at the ILT Franhofer Institute in Germany. This technology was developed at the beginning of this century by F&S company in collaboration with MCP HEK GmbH, which was later renamed SLM Solutions GmbH. SLM technology is capable of additively creating various alloys in the form of prototyping or even industrial parts. Since the parts are created layer by layer in this method, it is possible to easily make parts with complex geometric design, along with internal surfaces that cannot be made with traditional methods such as casting and machining. This process starts with slicing the 3D CAD file in Slicer software and converting it into layers of typically 20 to 100 microns thick, resulting in a 2D image of each section [37-]. The file format chosen

Table 1: Characteristics of each alloy for use in 3D printing

Primary substance	Property
Aluminum alloys	• Good physical and thermal properties • Low density • High electrical conductivity • Low hardness
stainless steel	• Durability and high wear resistance • High hardness • Malleable and weldable
Titanium alloys	• Rust resistance • High resistance to weight ratio • Low thermal expansion • Biocompatible
Cobalt-Chrome alloys	• Excellent abrasion resistance and durability • Good properties at high temperatures • Very high hardness • Biocompatible
Nickel alloys	• Excellent mechanical properties • High abrasion resistance • Heat resistance up to 1200 degrees • Can be used in adverse weather environments
Precious metals	• Use in making jewelry • Not widely available

Table 2: The main characteristics of SLM, DMLS systems

Property	Characteristics
Raw material	Metal and metal alloys (aluminum, steel, titanium, etc.)
Dimensional accuracy	+0.1 mm
Largest buildable dimensions	-0.1 mm
Typical layer thickness	250 × 150 × 150 mm
Support structure	(up to 500 × 280 × 360 mm)

for slicing is generally standard in stl format, which is compatible with almost all additive manufacturing methods. This file entered into the slicer software, while considering the parameters of the manufacturing process, desired values, supports, and readiness for printing. During the process, the metal powder made by gas atomization is spread as a thin layer on the production table (production cylinder) and through a cotaing blade. The atmosphere of the device chamber is filled in a completely controlled manner with a neutral gas, generally argon or nitrogen. When a layer of powder is spread on the substrate, the laser scanning and local melting of the powder surface are done based on the scanning pattern of that section; as a result, the device creates that layer of the piece [48-51]. The scanning operation is generally performed by a high-power laser beam of the ytterbium fiber laser type, with a power of several hundreds of watts. The laser beam is directed by two high frequency mirrors in the X and Y directions [34-38]. The laser scanning may happen layer by layer and upon the completion of scanning of each layer, the sat cylinder will be lowered to the thickness of the layer and the powder will be distributed on the substrate again; this will continue until the last layer of the part is printed [41-51].

MATERIALS USED IN SLM TECHNOLOGY

The SLM process involves using a varaiety of metals such as copper, aluminum, stainless steel, tool steel, cobalt chrome, titanium and tungsten. The suitable powder for SLM process should be the product of gas atomization method and its morphology should be spherical. Recently, new alloys such as maraging steel, cobalt chrome, inconel, inconel 718, Al-Si-10Mg, and Ti-6Al-4V have also been developed. Using this 3D printing technology, some of the most difficult, complex shapes or internal features can be printed that are impossible to envision using traditional manufacturing techniques. SLM 3D printing technology reduces delivery time because it does not need time for setting up the tool. This technology allows the assembly of parts and the production of several parts at the same time. It allows for reducing the weight of components and functional prototypes in various applications. However, this technology is much more expensive compared to stereolithography (SLA), fused deposition modeling (FDM) (resin and thermoplastic), and 3D printing technologies. Therefore, it is justified only for large organizations with specific goals. This technology is currently limited to the production of low to medium-volume parts. Using an SLM 3D printer, very large volumes like FDM (thermoplastic material) devices cannot be printed. All parts and functional prototypes produced using SLM technology have a relatively rough surface and therefore require post-printing finishing and sometimes even increasing overall print time. Aluminum and other metal alloys utilized in SLM have very high resistance to pressure and heat, and consequently, this technology is in high demand in the fields of mechanical engineering and chemical engineering. The presence of SLM technology yields benefits including less weight, better performance, cost reduction, and simpler operation. The most appropriate applications of the SLM process are in the manufacture of parts with high geometric complexity as well as structures with thin walls and internal channels and cavities and small dimensions. Today, most of the advanced and specialized applications of SLM are in the manufacture of light parts for the aerospace industry, as traditional and old manufacturing methods are unable to meet the possibility of manufacturing parts with optimized geometric designs and establishing a proper connection between design and production. One of the other capabilities of SLM is that it can directly manufacture the precise geometry of the part without the need for any machining, which prevents the wastage of materials, especially precious metals. The efforts of NASA's Marshall Space Flight Center to 3D print parts made of nickel-based alloys for J-2X and RS-25 rocket engines to reduce the need for welding and integration of sensitive space parts represent the unique capability of SLM in this industry. This technology has countless applications for the direct manufacture of parts for various industries including aerospace, dentistry, medicine and other sensitive industries that encompass small to medium-sized parts with high geometric complexity. At Northwestern Polytechnic University in China, researchers are using an SLM system to develop titanium parts for a spacecraft. An EADS study shows that the use of this technology will significantly reduce the consumption of materials in the aerospace industry. DMLS is a technology that can provide functional metal parts with high density (99.8%) and high thermal conductivity (compared to traditional manufacturing methods).

Aerospace

One of the most important goals of using 3D printing in the aerospace industry is to simplify, integrate, and remove connections. Among the activists in this field, we can name Airbus, Boeing, etc., which, in cooperation with companies specialized in this technology, such as General Electric and Rolls-Royce, benefit from additive manufacturing in the production of airplane components, jet engines, fuel nozzles, and satellite platforms.

A power plant

Siemens and General Electric companies have

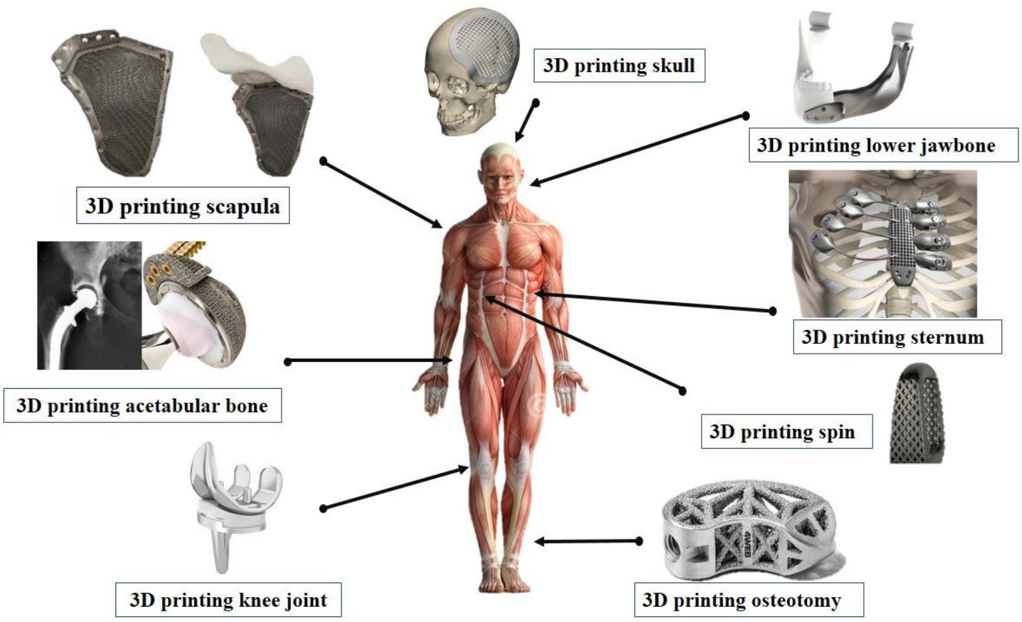

Fig. 1: Some metal implants via 3D printing

been the main activists in the application of additive manufacturing in the field of power plants. Until now, these companies have incrementally produced things like gas turbine components, turbine blades, measuring probes, and so on. Another important application of Nimi can be the use of FGM capability of parts by digital micromirror device (DMD) systems.

Medical

Today, various areas of medicine and medical engineering require the design and manufacture of damaged or missing items in patients' bodies, molding of organs for prototyping, etc., and 3D printers will be the bridge of communication for these people. Fig. 1 shows some implants produced with 3D printing for medical applications.

Electronic

The small scale of work required for the production of electronics industry parts, along with the difficulty of performing such operations, strongly feels the need for an intelligent and automatic system that can be implemented on a small scale with access to various materials such as polymer and metal. 3D printers will greatly facilitate the production of parts required in this industry. Due to the highly competitive market, the automotive industry needs systems that can offer the design, modeling, and construction of the body or the internal components of the car in a way that are cheaper, faster, more beautiful, and if possible, more innovative as well as according to the customer's favorite mental plan. 3D printers will answer many of these needs in this vast industry.

THE DIFFERENCE BETWEEN SLS AND SLM TECHNOLOGY

The SLS 3D printer is one of the devices that manufactures parts using powder raw material; hence it is the base powder. In Table 3, common raw materials in SLS 3D printer are mentioned. Different systems in an SLS machine work together to make the part. The main parts of the device that must work together to make the part are laser scanning system, thermal systems, ineffective gas circulation system, powder feeding system, platform system, and control unit (electronics and software). For this purpose, numerous software projects have been conducted globally. The desired CAD file must be layered. Therefore, first the CAD file is placed in the machine in the preferred direction, and from the lowest part of the parallel part of the X-Y plane, planes of the part are passed and closed contours are obtained from the intersection of this plane with the edges of the desired object. Then, another plate is cut higher than the previous plate as much as the thickness of one layer with the object, and this work continues until it reaches the highest part of the object. At the

Table 3: Commonly used raw materials in SLS 3D printer

Material	Property
Polyamide 12 (12 PA)	Good mechanical properties High chemical resistance Rough and matte surface
Polyamide 11 (11 PA)	Completely isotropic behavior High flexibility
Nylon filled with aluminum (Alumide	Metallic appearance High hardness
Nylon filled with glass fiber or fiberglass (PA-GF)	High hardness High thermal and abrasion resistance Anistropic behavior
Nylon filled with carbon fiber (PA-FR	Very high hardness High resistance to weight ratio High anistropic behavior

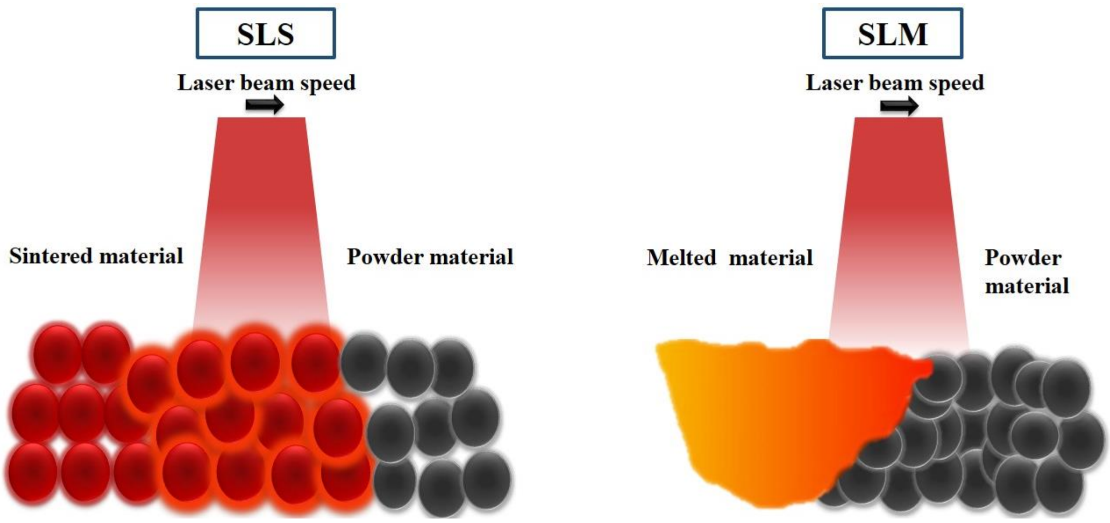

Fig. 2:Comparison of SLS and SLM processes

end, a large number of closed contours representing the surroundings of the object are obtained. In the following, we will see that these contours indicate the place where the laser passes on the powder surface. The difference between Selective Laser Melting (SLM) machine and the SLS machine is very small. The machines that directly produce metal parts with SLS technology are called SLM, because the metal powder is completely melted in them (Fig. 2 compares SLS and SLM processes). The manufacturing of parts in the SLS machine happens in such a way that the CAD file of the desired part must be introduced into the machine before production can begin. After obtaining the contours, the physical construction of the piece is completed. In this step, first, a single layer of powder is spread on the surface of the platform by the layering mechanism [42-51]. Although the thickness of the layer can vary, it is usually a number around 100 microns, and as it decreases, the speed and accuracy of the device decline. After the powder is spread, its surface is preheated to a certain temperature by the radiation heaters of the device. In fact, this is specific to polymer SLS devices, while in the metal SLS process, this preheating is not required for technical reasons. Then, the desired design, which originates from the contours around the object, is marked on the surface of the powder by the laser scanning system. The thermal power of the laser causes the powder

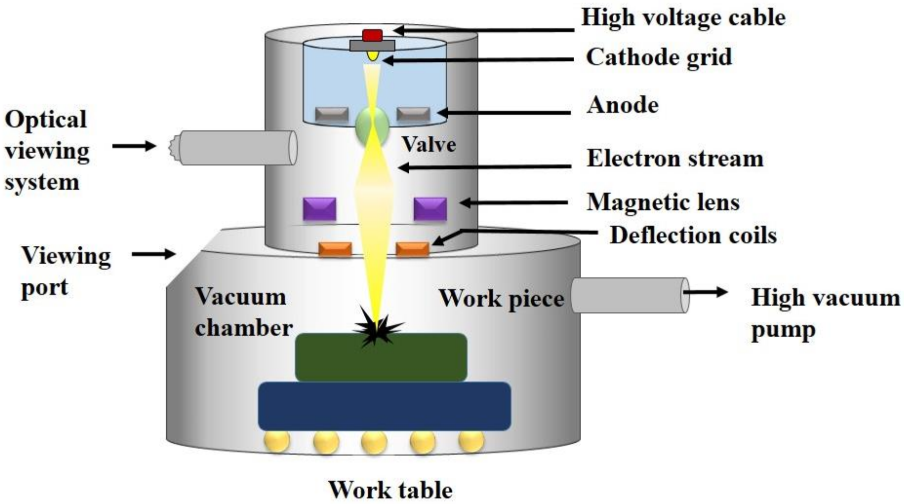

Fig. 3: The operation process of the EBM device. The triode beam of electrons emitted from the electron gun consists of the cathode (a hot tungsten filament that emits electrons at a high-ve potential), the grid cup (negatively to the filament) and the anode (held at ground potential and high-speed electrons pass through it).

particles to fuse together at the marked points and form a solid object. Then, this cycle is repeated and another layer of powder is poured on top of the previous layer and this process continues until the end and complete construction of the part [48-51]. Nowadays, the use of artificial intelligence (AI), machine learning and numerical simulation can be used to predict mechanical properties with the help of material engineering science and predict the properties with desirable conditions for industrial and robotic approaches [47-50]. In marking the upper layer, the laser power should be sufficient to fuse the upper layer to the lower one to maintain the integrity of the piece. The advantages of SLS-3D printer may include the ability to produce practical and operational parts, high strength and shock resistance of parts, high thermal and chemical stability, biocompatibility and application in the production of surgical guides and models, prosthesis, orthosis and tissue engineering scaffolds, ability to machine, polish and color, being economical in producing a higher circulation than other 3D printing methods, high production speed of parts in production circulation up to 500, high cost for applications that do not require high mechanical strength [49-51], average accuracy of this method compared to more accurate methods such as DLP and PolyJet methods, and inability to produce hollow parts like the FDM method.

SLM and DMLS are two metal additive manufacturing technologies from the family of powder 3D printers. The two technologies have many similarities: both use a laser to scan and selectively melt metal powder particles. With laser light and powder melting, these particles are connected, making the piece layer by layer. The basic material of both technologies is metal powder in the form of granules. The difference between SLM and DMLS-3D printers is in the way the particles are connected: the SLM 3D printer brings the metal powder to the melting temperature and completely melts and connects the particles, while the DMLS-3D printer powder is composed of various materials with different melting temperatures, which are connected at the molecular level when exposed to high temperature. The electron-beam machining method (EBM) was first developed in 1997 by the Swedish company Arcam in order to produce metal parts. These devices include components such as electron gun with scanning system, vacuum chamber with build tank and powder holder and regulator, monitor vacuum pumps, linear equipment, high voltage unit, electronic control system, and control unit. Fig. 3 shows the operation process of the EBM device. The process of EBM is similar to that of SLS; however, in EBM, the powder particles are exposed to an electron beam rather than a laser, causing the particles to melt instead of sinter. In this system, after the information preparation process, a thin layer of metal powder, usually H13 tool steel powder, is spread on the production plate. Then, an electron gun solidifies the desired points and this cycle is repeated until the end of the piece. In this method, their melting

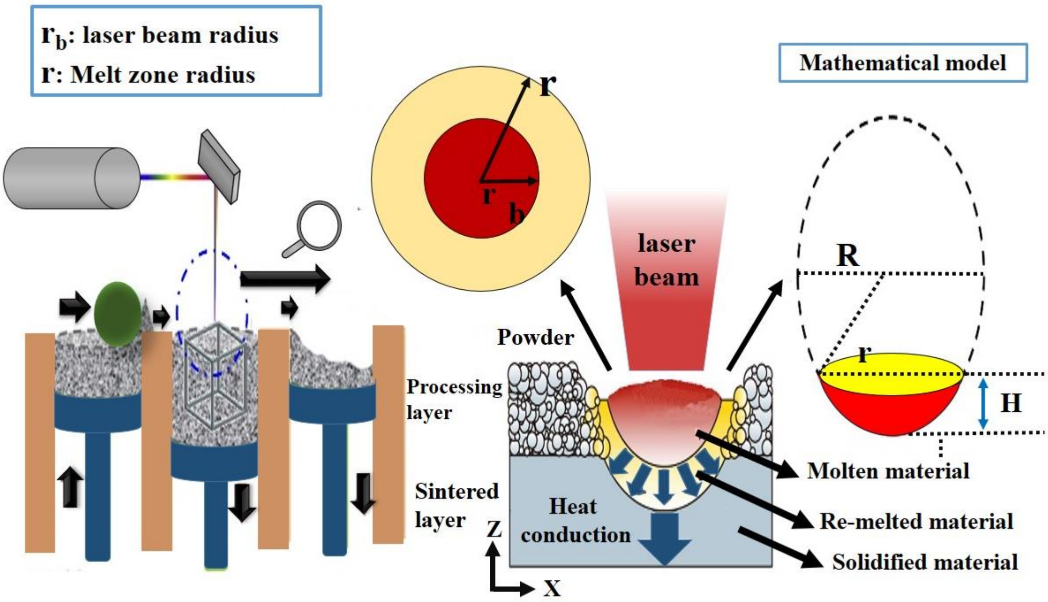

Fig. 4: A schematic of the SLM process and heat transfer in the molten pool

is used to connect the powder particles. After high-energy electrons hit the powder particles, their very high level of kinetic energy is converted into thermal energy, which causes the powder particles to melt and connect together at the desired points. Electrons are ejected from a metal thread heated to more than 2500°C, and their speed increases to about half the speed of light. Then, the electron beam is focused by a magnetic field and hits the desired surface. Due to the powerful and high energy of the electron beam in these devices, this process can be used in making molds or parts of low circulation. Directed energy deposition (DED) methods make parts by melting the powder at the same time as it is dispensed. This technology usually works with metal powder or metal wire. DED 3D printing technologies are exclusively used in metal additive manufacturing. The nature of the manufacturing process of these technologies makes them ideal for repair applications or adding materials to manufactured parts such as turbines. The dependence of this 3D printing technology on dense support structures makes DED unsuitable for making parts from scratch. In this technology, laser head and electron beam are used to provide the necessary energy. This process includes melting and integrating metal powder using a high-power neodymium-doped yttrium aluminium garnet (Nd:YAG) laser and producing or repairing metal parts with complex geometry and completely integrated and dense. Today, using this method, parts of stainless steel 316 and 304, nickel-based superalloys such as Inconel 625, 690, 718, tool steel HB, tungsten, titanium alloy Ti-6Al-4V, nickel aluminide, aluminum and copper can be produced for various applications. Produced or reconstructed part include mold attachments, biological implants, etc.

ASICS OF THE PROCESS

The laser with very high power is focused on a point of the previously formed layer and creates a molten pool at that point. Simultaneously, metal powder is sprinkled into this molten pool, resulting in an increase in the volume of the material. The metal powder from around the device head and the laser beam from its center enter the print position at the same time. A movement system simultaneously with laser radiation and powder spraying moves the machine table in the longitudinal and transverse direction, corresponding to the cross-sectional surface of the part, so that the cross-sectional surface is created by the laser. After the formation of one layer, the powder transfer nozzle goes up to make the next layer [49-50].

CONSTRUCTION PROCESSES

A head, which is responsible for transferring the metal powder and guiding the laser, feeds the metal powder to the focus point of a high-power laser beam so that the metal powder is completely melted. This laser is guided to the desired location by means of optical fiber or by using accurate reflective mirrors. As shown in Fig. 4, in the device head building, the powder transfer channels are located around and the laser guidance system is positioned in the center. The laser beam is focused and fixed at a certain point using a set of lenses and the drive system built into the device moves the platform longitudinally and transversely. In this way, each layer is formed by creating a cross section by laser. Simultaneously with the process of laser irradiation and powder spraying, argon gas is injected into the place of laser beam radiation to prevent the negative effects of oxygen in the air on the quality of the particle connection and the integrity of the part. After finishing one layer, the head moves up and continues creating the next layer [49-51]. The parts produced in this way have outstanding internal structures, material properties, and suitable microscopic characteristics. The impressive capability of this process is the production of functional metal parts with complex geometry. The production time is shortened since fewer additional operations, such as removing supports, are required. Making titanium parts for use is important in various industries such as titanium implants for medical applications, automotive, etc. Using 5-axis motion systems for the machine head, this process is able to easily produce parts with a much higher geometric complexity. Sciaky company can be mentioned as one of the companies specializing in the manufacture of these devices. EBAM 3D printing technology is used to make metal parts using metal powder or wire; these materials are welded together using an electron beam as a heat source. This 3D printer works in vacuum conditions and is designed for use in space. EBAM has a process similar to the LENS 3D printer although its energy consumption is more optimized. In these systems, the radiation used in the head is highly strong and energetic, instead of the electron beam laser. In addition, the feeding system of these devices usually uses metal wire (or powder) as consumables, which are generally cheaper and more available than metal powder. The device head consists of a very strong electron beam central radiation system and a wire feeding system from around and simultaneously to the print position. With the simultaneous arrival of these two factors to the desired location, the complete melting of the wire by the high-energy electron beam, the process of sedimentology, and the formation of that point of the piece take place. Further, with the relative movement of the table and the head of the device in X, Y and Z directions, following the commands of the slicer software, the entire geometry of the piece is gradually formed. The merits of this device include a cheaper and more accessible metal wire compared to its powder, more energetic radiation power, the possibility of obtaining a denser and stronger piece due to the very good melting of the position, appropriate speed of technology, fairly wide range of applications of the process due to the type of its applied mechanism (using energy source and feeding system in one place and in a small head), and the possibility of using it in cases of local repair of damaged equipment.

CONSUMING MATERIALS

In general, a wide range of metal powders can be processed due to the high power of the laser in metal 3D printing, such that all kinds of alloys, superalloys, composites and functionally graded materials (FGM) can be produced. Important parameters in choosing the right powder include sphericity, proper fluidity, size distribution, and chemical composition. Metal powder substrate-based 3D printing methods have emerged in the last decade, and the techniques have recently grown prevalent. There are two representatives, namely selective electron beam melting (SEBM) and SLM, which are growing due to their advantages including good dimensional accuracy, high manufacturing resolution, clean manufacturing environment, material saving, and customization capability Metal for orthopedic implants shows that the increase in the possibilities of 3D printers through different metals with different colors to attach the prototype of jewelry has made it possible to offer a variety of methods of mass production of jewelry [50-53].

CONCLUSION

Metals have many advantages over plastics, and stronger metals are more heat-resistant as well as more flexible .In general, the 3D printing of metals is a relatively new technology that is based on existing technology and almost addresses the needs of the public, and over the years, it has revealed its value and usefulness not only in the prototyping process, but also in the mass production of parts. This is why almost every industry can benefit from metal printing and employ it in different industries.

By examining each method, we can see that the superiority of each one is different depending on the materials intended to be used, or based on any type of parts (light, heavy, industrial, or normal). For example, the SLM/DMLS process belongs to the family of 3D printing of fusion powder and they have numerous similarities. Moreover, the materials used in both processes are metals that are granular. On the other hand, they also have differences, which can be attributed to the principles of the particle joining process. This technology is suitable for complex parts that cannot be made by traditional methods or when the cost is high. Furthermore, the parts made with this technique have excellent mechanical properties. In many areas, especially in the industry, plastics cannot be employed and replaced by metals; instead, new metal 3D printing technology can be applied in these situations. Metal printing provides more benefits to industries every day; however, this technology has some disadvantages, including the high cost of raw materials and its production. As a result, this technology is not suitable and cost-effective for manufacturing parts with traditional methods.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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