A review on the metallic components direct production by additive manufacturing

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Abstract

Metals are important materials in engineering applications and the additive manufacturing is a set of processes and technologies presents in Industry 4.0. The direct production of metallic components by manufacturing additive is an interesting alternative for organizations add values to components and finished products. This article presents an overview on the metallic parts direct production by additive manufacturing. An analysis of the literature was conducted to investigate advanced metals and processes of additive manufacturing used to produce metallic components, specifically selective laser melting (SLM), selective laser sintering (SLS) and electron beam melting (EBM). The mechanism of layer fully melting and solidification process allow that SLM and EBM produce components with superior mechanical properties than SLS process, considering the same metallic material in manufacturing.

Keywords
Additive manufacturing, Industry 4.0, metals, direct production.

1. Introduction

In these days, society presents a scenario of increasingly demanding consumers and volatile markets where there is no space for industry failure. As a result, full production control is required to ensure quality, flexibility and productivity in the manufacturing process. Industry 4.0 requires interaction between automation, communication and information and manufacturing technologies, enabling productive differentials such as the possibility of mass customization of products and services and the pursuit of continuous innovation. Industry 4.0 is a term that encompasses some technologies for automation and data exchange and uses concepts of cyberphysical systems, internet of things (IoT), and cloud computing. Other important dimensions of Industry 4.0 are big data, autonomous robots, simulations, systems integration, cybersecurity, augmented reality and additive manufacturing.

Metals can be considered the most important engineering materials. Metallic materials are pure metals (copper, for example) and alloys, which are composed of two or more elements, with at least one being a metallic element. They have large numbers of nonlocalized electrons; that is, these electrons are not bound to particular atoms. Many properties of metals are directly attributable to these electrons. Metallic materials are good conductors of electricity and heat and are not transparent to visible light; a polished metal surface has a lustrous appearance. Furthermore, metals are strength, yet deformable, which accounts for their application in engineering. Metals and alloys are technologically interesting because they can be ductile (copper) or brittle (cast iron) and their properties can be altered depending on processes used in manufacturing (Santos, 2017).

Additive Manufacturing (AM) is a group of technologies and processes based in addiction of material to build layers making a part or component. Studies related to manufacturing technology show the influence of processes on the performance of products (Miranda et al., 2016; Miranda et al., 2017; Nascimento et al., 2017; Nascimento et al., 2018; Nascimento et al., 2019; Santos et al., 2017, Da Cruz et al., 2020, Dos Santos et al., 2020). This work is focused on the area of manufacturing technology, a greater emphasis is given to metallic components direct production by additive manufacturing, as it involves important technological concepts of materials and manufacturing processes.

2. Methodology

Specific literature were utilized when searching for bibliographic material to make this review, including (1) Papers, (2) Books chapters, (3) SpringerLink, (4) Google Scholar, and (4) Books. The selective list of works compiled upon common principle when searching for “metallic components direct production by additive manufacturing ” is shown in References.

3. Advanced Metallic Materials

Metals and alloys can be divided into two basic groups: ferrous and nonferrous. Ferrous metals are based on iron; the group includes steel and cast iron. Nonferrous metals include the other metallic elements and their alloys. In almost all cases, alloys are more important commercially than pure metals. Nonferrous metals include the pure metals and alloys of aluminum, copper, nickel, silver, titanium, zinc, cobalt and other metals. In general, mechanical properties of most metallic materials can be effectively improved by modification of their microstructure via alloying, processing, heat treatment, and so on (Groover, 2013).

Aluminum alloys still remain materials of fundamental importance for engineering applications owing to their light weight, workability and relative low cost, and relevant improvements have been achieved especially for 2XXX (Al-Cu group), 7XXX (Al-Zn group) and Al-Li alloys; these alloys are influenced by strengthening treatment (the temper) and they are attractive for aerospace applications because their properties. In general, the 2XXX series alloys are used for fatigue critical applications because they are highly damage tolerant; those of the 7000 series are used where strength is the main requirement. Aluminum–lithium alloys are advanced materials that have lower density and higher modulus than those of conventional aluminum aerospace alloys (Santos et al., 2017). Each weight percentage of lithium lowers aluminum density by approximately 3% and increases Young’s elastic modulus (E) by approximately 6%. Li additions enable the formation of potent hardening precipitates and impart higher fatigue-crack growth resistance (Gloria et al., 2019). As shown in Figure 1, Al-3wt.%Cu-1wt.%Li cast alloy is more strength that Al-6wt.%Zn cast alloy and aluminum cast.

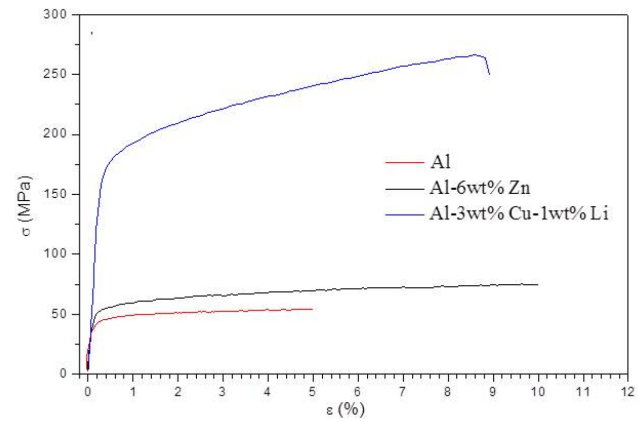


Figure 1. Typical engineering stress-strain curves from tensile tests of aluminum, Al-6wt.%Zn and Al-3wt.%Cu-1wt.%Li cast alloys.

Copper alloys are used in applications that require metals with superior corrosion resistance, high electrical and thermal conductivity, good surface integrity for bearings, and other special properties. Among the full range of copper alloys, aluminum bronzes are the best available engineering material for fulfilling these requirements. Aluminum bronzes are copper-based alloys that may include up to 14wt.% aluminum (the main alloying element), but lower amount of nickel and iron are also added to produce different alloy mechanical properties and corrosion resistance (Nascimento *et al.*, 2019). In the maritime field, nickel aluminum–bronze alloys are known as "propeller bronze", representing their application in the manufacturing of propellers of ships and submarines (Pierce, 2004).

In Cu-Al-Ni-Fe alloys, the aluminum content normally varying between 8% and 13%, wt.%. Greater contents are used for obtaining high hardness and reduce the ductility of the alloy. However, high levels of aluminum provide the appearance of γ2 phase, which is detrimental to its mechanical resistance and corrosion. Some elements such as nickel (Ni) and iron (Fe) combine with Al to form complex phases called κ (I, II, III and IV), avoiding the emergence of the γ2. Ni is added in amounts ranging from 1% to 7% (wt.%) and its presence improves corrosion resistance, increases strength, and contributes to increased erosion resistance in environments with high water flow velocity. Fe is present in nickel-aluminum-bronze to refine the structure and increase the toughness. The low solubility of iron at low temperatures in these alloys is the main reason for the appearance of precipitates rich in Fe, which can be combined to produce the required mechanical properties (Richardson, 2010). The distribution of different phases and intermetallic components of the nickel aluminum–bronze cooled slowly are showed in Figure 2.

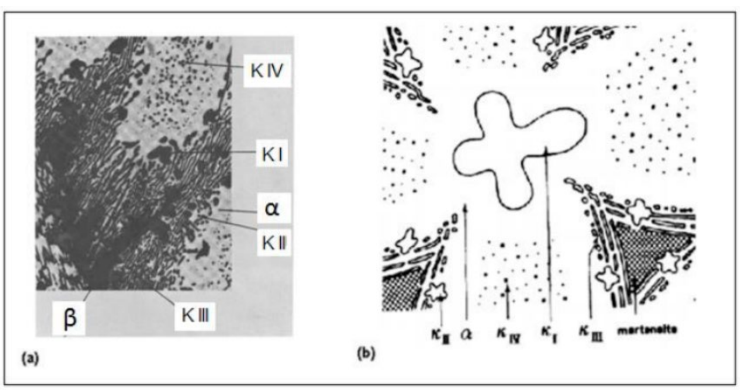


Figure 2. Distribution of the different phases and intermetallic components of the nickel aluminum–bronze cooled slowly: (**a**) optical microscopy (Culpan and Rose, 1978) and (**b**) schematic representation (Hasan *et al.,* 1982).

Titanium alloys have excellent specific strength and corrosion resistance, they are increasingly used for manufacturing structural components of aircrafts. They are also employed in engine sections operating at intermediate temperature (500–600 °C). Ti alloys can be divided into three main classes (α, β and α-β). Independently of the specific class, the mechanical properties of Ti alloys depend on O and N in solid solution. The solubility of these interstitial elements in both α and β phases is high, increases with temperature and the part of the gas absorbed at high temperature remains entrapped in the metal after cooling, causing lattice distortion. In addition to modifying the mechanical properties, this phenomenon plays a role also in manufacturing processes and stress relieving heat treatments (Gloria et al., 2019). Titanium is becoming one of the most promising engineering materials and the interest in the application of titanium alloys to mechanical and tribological components is growing rapidly in the biomedical field, due to their excellent properties (Santos, 2017).

Nickel-based superalloys are usually employed to manufacture components of aeronautic engines such as blades and rotors operating in the highest temperature range (1100–1250 °C). These superalloys are of great industrial relevance because their microstructural stability in high work temperatures. The microstructure is the main influencer of the mechanical behavior of metallic materials (Santos, 2015). Inconel 625 is one of the most widely used in high-temperature applications, such as in the aerospace, petrochemical, marine, and nuclear industries. This can be attributed to its excellent corrosion resistance and mechanical properties. This superalloy is strengthened by the solid-solution-hardening effects of alloying elements such as chromium, molybdenum, niobium, and iron, and the precipitation-hardening effects of their intermetallic phases (De Oliveira *et al.*, 2019).

Austenitic stainless steel presents excellent weldability and higher corrosion resistance in relation to the steels of the other groups of stainless steels. It combines the yield strength with the high tensile strength and good elongation, offering the best properties for cold work. These steels have good mechanical properties combined with excellent corrosion resistance. They have high resistance to attack by corrosive agents and have good toughness at low temperatures. The thermal conductivity corresponds to a quarter of the carbon steel. In the machining process, the heat concentrates in the cutting edge is not transferred to the material or to the chips. Such materials cannot be hardened by heat treatment, however, they can be hardened by cold forming, which worsens machinability and reduces their potential for corrosion resistance (dos Santos et al., 2020).

Ultra-High Strength Steels (UHSS) are commonly used for manufacturing aircraft components such as landing gears, airframes, turbine components, fasteners, shafts, springs, bolts, propeller cones and axles. These steels allow designs with lower thicknesses, good formability and some of them exhibit very high yielding strength (YS), e.g., 300M (1689 MPa), AERMET100 (1700 MPa), 4340 (2020 MPa) (Gloria et al., 2019).

Metallic biomaterials are used for load bearing applications and must have sufficient fatigue strength to endure the rigors of daily activity. Examples of metals used for biomedical applications are ASTM F138 stainless steel, cobalt chromium alloys (CoCrMo), titanium-based alloys (for example, Ti6Al4V, wt.%) and miscellaneous others (including tantalum, gold, dental amalgams and other "specialty" metals). Table 1 lists some metals that are used in total hip joint replacement (Santos, 2017).

Table 1. Metals used in total hip joint replacement.

Metallic Material		Applications
Titanium-based	Ti (comercially pure)	Porous coatings second phase in ceramics and PMMA composites
	Ti6Al4V	Porous coatings, femoral stems, heads, tibial and femoral components
	Ti5Al2.5Fe	Femoral stems, heads
	Ti-Al-Nb	Femoral stems, heads
Miscellaneous metals	F138 stainless steel	Femoral stems, heads
	Cobalt-based alloys	Porous coatings, femoral stems, heads, tibial and femoral components
	Cast Co-Cr-Mo	
	Wrought Co-Ni-Cr-Mo	
	Wrought Co-Cr-W-Ni	

Ferrous and nonferrous metals continue to be crucial in engineering because they allow technological viability in terms of optimization of manufacturing processes, materials and desired properties.

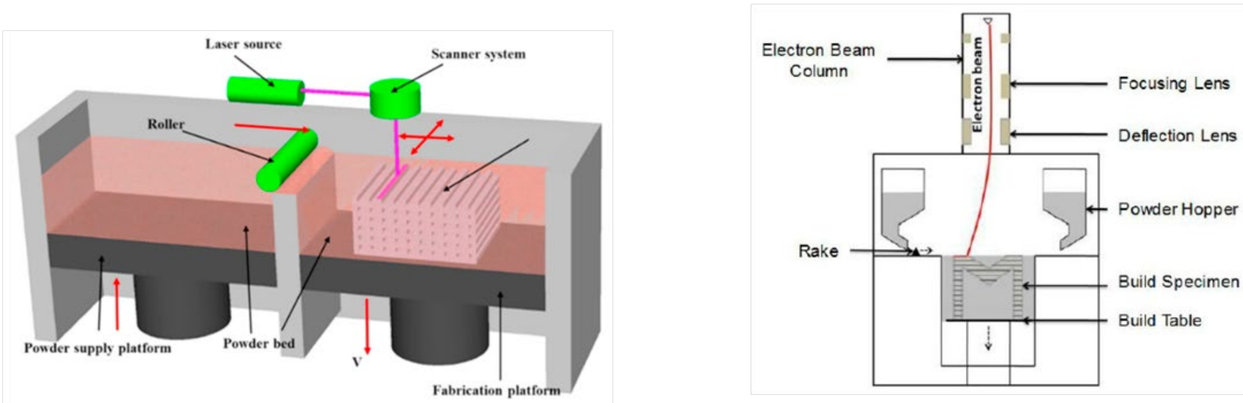
4. AM for Metallic Components Direct Manufacturing

In relation to the manufacturing processes, the metals are more advantageous in comparison to the polymers and the ceramics. Ferrous and non-ferrous metals can be manufactured through a wider range of manufacturing process possibilities such as shaping processes, property-enhancing processes and surface processing. Basically, polymers are restricted to the shaping processes for plastics and the ceramics to particulate processing.

In the case of metals, shaping processes are operations that apply heat, force (mechanics) or a combination of these to effect a change in shape of the work material. These operations include solidification process, powder metallurgy, bulk deformation, sheet metalworking, subtractive manufacturing, welding, and other processes. They are designed procedures that results in physical changes to a work material with the intention to achieve the desired properties. That is, the necessary properties (strength, for example) for the application of the material. Forging is an important industrial process used to make a variety of high-strength components for engineering. The high precision micromachining of titanium, stainless steel and other special metallic alloys is an example of importance of modern manufacturing in bioengineering (Dos Santos et al., 2020).

Property-enhancing processes are performed to improve mechanical or physical properties of the metallic materials. They include heat treatments (annealing in steel, for example) and sintering of powered metals. Surface processing is performed to prepare and/or change properties of metal surface. These operations include cleaning, surface treatments, coating and thin film deposition processes. Chemical vapor deposition (CVD) and physical vapor deposition (PVD) are thin films processes used to form extremely thin coatings in components, for example.

In addition to the aforementioned manufacturing processes, additive manufacturing (AM) is a family of production methods to make components in minimum possible lead times based on a computer-aided design (CAD) model of the item. The AM technologies work by adding layers of material one at a time to build the solid part from bottom to top (Groover, 2013). The early applications of additive manufacturing technology include the rapid prototyping (RP) of machine tools and to support continuous product development by providing prototype models for physical product validation. However, over the last decade, AM has seen swift advancements in technological capability and has been increasingly used as a form of direct production (Mohd Yusuf, Cutler and Gao, 2019). In this work, we show some additive manufacturing processes for direct production of metallic components: selective laser melting (SLM), selective laser sintering (SLS), and electron beam melting (EBM). SLM, SLS and EBM are powder-based AM technologies, that the starting material is powder. Figure 3 shows a schematic of SLM, SLS and EBM additive manufacturing technologies.



(a) (b)

Figure 3. Schematic of powder-based AM technologies: (a) SLM or SLS process, and (b) EBM process (Adapted from Mohd Yusuf, Cutler and Gao, 2019).

4.1 SLM and SLS

SLM and SLS are additive manufacturing processes that use a laser moving point to melt or sinter the material, respectively. The term *laser* is an acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. Lasers are being used for a variety of industrial applications, including welding, heat treatment, measurement, as well as cutting, drilling, and scribing. A laser is an optical transducer that converts electrical energy into a highly coherent light beam. A laser light beam has several properties that distinguish it from other forms of light. Laser is monochromatic and the light rays in the beam are almost perfectly parallel (highly collimated). These properties allow the light generated by a laser to be focused, using conventional optical lenses, onto a very small spot with resulting high power densities. Depending on the amount of energy contained in the light beam, and its degree of concentration at the spot, the various laser processes identified in the preceding can be accomplished (Groover, 2013).

Figure 3(a) shows a schematic of SLM or SLS process. Selective laser melting (SLM) is primarily focused on particular metals such as aluminum, steel, and titanium. In this process, the build operation typically takes place in a vacuum or inert atmosphere (argon or nitrogen) to prevent the formation of surface oxides on the molten metal layers. The SLM process is very similar to selective laser selective (SLS). The difference is that SLM has the capability to fully melt the deposited powder material while SLS has not the ability to do so. The laser beam provides sufficient energy to raise the powder above its melting temperature, creating a small region called melt pool at an exact location that corresponds to the 2D projection of the CAD model (Mohd Yusuf, Cutler and Gao, 2019).

The metals used in SLS are binder-sprayed metals (eg stainless steel, tool steels and alloys, titanium, tungsten, copper alloy, aluminum and nickel superalloys). In areas not sintered by the laser beam, the powders remain loose so they can be poured out of the completed component. Meanwhile, they serve to support the solid regions of the component as production proceeds. SLM process result in the superior mechanical properties than SLS process.

4.2 EBM

Electron beam melting is one of several industrial processes that use electron beams such as welding, non-traditional machining, selective surface-hardening, evaporation physical vapor deposition, ion plating, and lithography. Figure 3(b) shows a schematic of EBM process. The EB technique in additive manufacturing uses a high-energy electron beam to melt a metallic powder bed region and is typically carried out in a vacuum to prevent unwanted oxidation and the reflection of highly energized electrons with the surrounding atmosphere (Watson and Taminger, 2018). EBM follows similar principles to electron beam welding (EBW). EBW is a fusion-welding process. The heat for welding is produced by a highly focused, high-intensity stream of electrons impinging against the work surface.

In contrast with selective laser melting, electron beam melting transfers its energy at around 70% the speed of light via the kinetic collisions between accelerated electrons and the powder bed region. As a result, the energy supplied by the electron beam is not only enough to melt the powder; it also increases the negative charge of the powder. The effect of this electronegativity can result in a more diffuse energy beam as the powder repels incoming electrons (Carriere, 2018). Typically, the chamber that houses the powder bed for EBM is pre-heated prior to the printing process to mitigate the effects of large temperature gradients and residual stress build-ups and to prevent the formation of undesired microstructures that could compromise the quality of the as-fabricated components, e.g., α'-martensites in steels (Mohd Yusuf, Cutler, and Gao, 2019). EBM is also used to manufacture components of titanium and other metallic materials.

5. Discussion

Selective laser melting (SLM), selective laser sintering (SLS) and electron beam melting (EBM) are powder bed fusion techniques. SLM and EBM use thermal energy to selectively melt regions of a powder bed layer that are evenly spread across a build surface using a recoating system. SLM apply the same principle, the difference is that the material is sintered. Once the layer is deposited, a powerful laser (SLS and SLM) or electron beam (EBM) precisely melts a particular location on the powder bed in a layer-wise manner (usually 30–50 μm thick per layer) according to the initial computer aided design (CAD) design. These technologies have the potential to process dissimilar metals.

EBM, SLM and SLS utilize the same underlying material deposition method by using a raking or rolling mechanism to spread uniform powder bed layers over a build platform. SLM and EBM involve solidification of metals because the metal is fused and solidified after cooling in these AM technologies. SLS involves sintering and densification of metal processed. The mechanism of layer fully melting and solidification process allow that SLM and EBM produce components with superior mechanical properties than SLS process, considering the same metallic material in processing.

Metallic components direct production by additive manufacturing is increasingly being employed to produce parts and end products. Applications of final components production include: small-batch metals components to industry, avoiding the high cost of tools; components with complex geometries, avoiding assembly processes and loose components; and custom parts to exact size for each application. Examples of custom components are becoming increasingly common in medical applications, such as bone prostheses and dental devices, which require custom fitting. Note that direct manufacturing is no substitute for mass production. Instead, it is suitable for mass customization, where products are manufactured in bulk, but each product is unique in some way. In all cases, the requirement is that a component CAD model must be available. Table 2 shows a summary of the three processes reviewed in this paper including the shape of the raw material, additive manufacturing process, commonly used metals and the layering formation process. Note that SLS, SLM and EBM are flexible with respect to the range of metallic materials that can be manufactured by them.

Table 2. Shape of raw material, additive manufacturing process, commonly used metals and layering formation process.

Starting Material	**Process**	**Metallic Materials**	**Layers Formation**
Powder	Selective laser sintering (SLS)	stainless steel, tool steels and alloys, titanium, tungsten, copper alloy, aluminum and nickel superalloys	sintering by laser
Powder	Selective laser melting (SLM)	aluminum, steel, and titanium	melting by laser
Powder	Electron beam melting (EBM)	Steels, titanium and other metals	melting by electron beam

In comparison to subtractive manufacturing by computer numerical control (CNC), in which the machine tool operations are controlled by a part program, additive manufacturing processes have numerous advantages: design flexibility, low material wastage (do not form chips); efficient use of energy (sustainability); no fixing devices required; no tool change is required during component manufacturing; the component is manufactured in one component from start to finish; no complex calculations of tool paths are required; and AM avoids of the CNC part programming task.

The disadvantages of AM technologies include limited variety of materials [for example, steriolithography (SL) works only photopolymers]; components accuracy lower than components made by subtractive manufacturing (especially as layer thickness is increased); mechanical performance of the fabricated components by AM is worst than components produced by other processes such as forging or machining; and high equipment cost. Specifically, EBM includes the limitations associated with performing the process in a vacuum.

6. Conclusions

Selective laser melting (SLM), selective laser sintering (SLS) and electron beam melting (EBM) are interesting ways of produce metallic components, directly. In times of Industry 4.0, the advantages of additive manufacturing (AM), particularly its design flexibility and low material wastage, become these processes important alternatives the integration of metal AM into current and future production systems. Considering the same metallic material in manufacturing, SLM and EBM show better mechanical behavior than SLS because they have layer fully melting and solidification process, while SLS has not the ability to do so. Ferrous and nonferrous metals continue to be crucial in engineering because these materials allow technological viability in terms of optimization of manufacturing processes, materials and desired properties.

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