Chapter

Tribological and Wear Behavior of Metal Alloys Produced by Laser Powder Bed Fusion (LPBF)

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Abstract

Laser powder bed fusion (LPBF) is an additive manufacturing technique for the production of parts with complex geometry, and it is especially appropriate for structural applications in aircraft and automotive industries. Wear is the most important cause of malfunction of mechanical systems. Abrasive wear accounts for 50% of wear in industrial situations, and it is most common in components of machines. LPBF is very attractive due to its extremely high melting and solidification rates that make possible to obtain materials with particular tribological and wear behavior than those by traditional manufacturing routes. The aim of this chapter is to investigate the different behaviors of principal metallic alloys by LPBF.

Keywords: additive manufacturing (AM), laser powder bed fusion (LPBF), metallic alloys, wear

1. Introduction

According to ASTM F2792-10, additive manufacturing (AM) is defined as "The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies." The fundamental principle of AM is that a geometric representation, originally generated using 3D-CAD system, can be manufactured directly without a need to process planning [1].

Today AM is receiving a very high attention from the mainstream media, investment community, national governments, and scientific communities. Nearly 10 years ago (2008), only 231 articles were published with AM topic, 5 years ago (2013) about 800 articles, and in 2018 about 4900 articles; in 10 years the number of articles per year is increased more than 20 times (**Figure 1**).

AM technologies have a strong potential to change the characteristic of manufacturing process, away from mass production in large factories with dedicated tooling and with high costs, to a world of mass customization and distributed manufacture.

Everyday new and innovative applications are emerging for the additive manufacturing [2]:

- Prototyping
- Art and jewelry
- Tooling

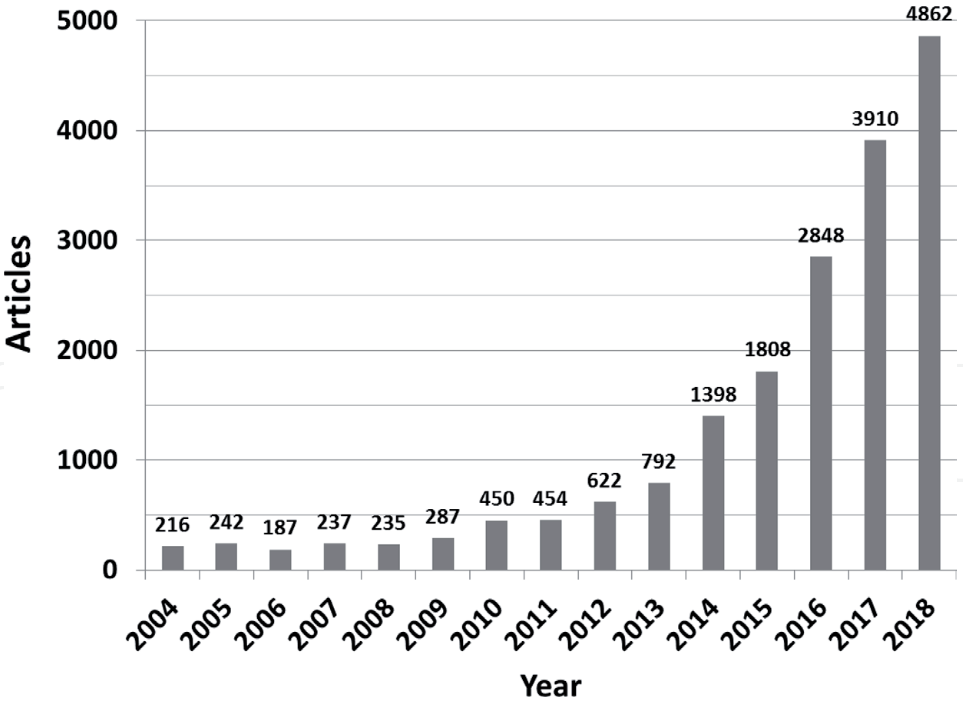

Figure 1.
Number of scientific articles per years with AM topic (source: Scopus).

- Medical and dental
- Automotive
- Aerospace

In many application of the AM, the wear resistance is important to guarantee the efficacy and the safety. Wear is the most important cause of malfunction of mechanical systems; for this reason, it is important to study the effect of wear and generally, the tribological characteristic of material used and processed by AM [3].

The aim of this chapter is to investigate the different behaviors of principal metallic alloys processed by laser powder bed fusion (one of the most diffused AM technologies) in terms of tribological properties, with a particular focus on the wear resistance and the coefficient of friction (COF). At the moment, few studies are available about tribological properties of metallic alloys produced by LPBF; this chapter searches to organize the works present.

2. Additive manufacturing

2.1 Introduction

Seven different technologies are classified for additive manufacturing agreed by the AM SIG (special interest group) as can be seen in detail in **Table 1** [4].

2.2 Laser powder bed fusion (LPBF)

The SLM process has been defined as the laser powder bed fusion process (LPBF), according to ISO/ASTM 52900. It is also known by the trade names LaserCUSING or DMLS (Direct Metal Laser Sintering), which directly produces homogenous metal objects, layer by layer, from 3D CAD data, by selectively melting very fine layers of metal powder (**Figure 2**) with a laser beam.

Classification	Description	Technology	Materials
Direct energy deposition	Builds parts using focused thermal energy and wire to fuse materials and they are deposited on a substrate	Laser deposition Laser consolidation Direct metal deposition Electron beam direct melting	Metals
Binder jetting	Creates objects by deposition of a binding agent to join powdered material	3D printing Ink-jetting S-print M-print	Metals, polymers, and ceramics
Material extrusion	Fused deposition modeling	Fused deposition modeling	Polymers
Material jetting	Builds parts by depositing small droplets of build material, which are then cured by exposure to light	Polyjet Ink-jetting Thermojet	Photopolymers, wax
Powder bed fusion	Creates objects by using thermal energy to fuse regions of a powder bed	Selective laser melting Laser powder bed fusion Selective laser sintering Electron beam melting	Metals, polymers, and ceramics
Sheet lamination	Builds parts by trimming sheets of material and binding them together in layers	Ultrasonic consolidation Laminated object manufacturing	Metals, ceramics, and hybrids
VAT photopolymerization	Builds parts by using a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required.	Stereolithography Digital light processing	Photopolymers and ceramics

Table 1.
Classification of AM adapted from ASTM AM classification.

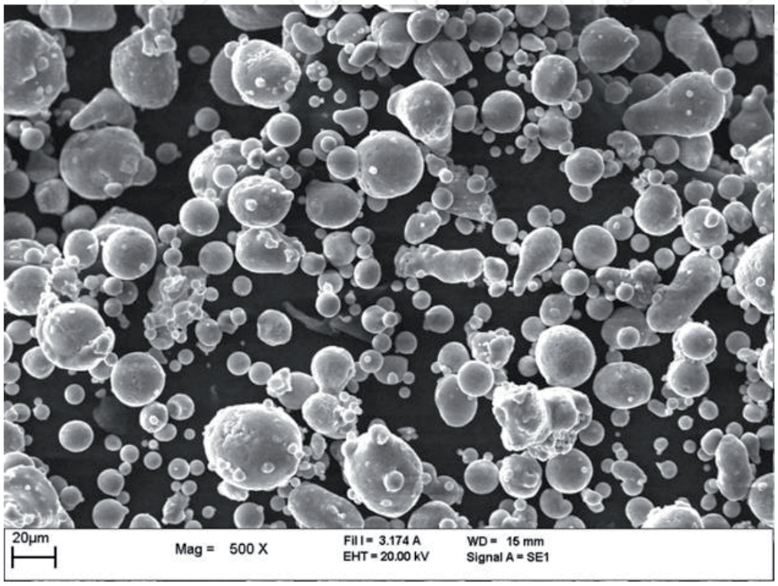

Figure 2.
Scanning electron magnification (SEM) observation of typical powder used in LPBF process ($AlSi_{10}Mg$).

Laser powder bed fusion (LPBF) is an additive manufacturing technique for the fabrication of near net-shape parts directly from computer-aided design data by melting together different layers with the help of a laser source. LPBF process produces parts with good surface quality, high accuracy and detail resolution, and excellent mechanical properties. The components are built layer by layer; it is possible to project internal channel and features that are impossible to obtain by casting or machining. LPBF does not require special tooling like casting, so it is more convenient for not so big production. It is a good alternative to conventional machining for complex metallic parts [5].

It has been demonstrated, in recent literature, that SLM can also be used to fabricate metal matrix composites (MMCs). These could have applications in automotive and aerospace industries, where it is necessary to improve mechanical properties (stiffness and hardness) and specially the wear resistance [6].

3. Aluminum alloys

3.1 Introduction

The most used Al alloys are Al-Si alloys, which represent 80% of aluminum casting alloys, thanks to their high fluidity, high weldability, good corrosion resistance, and low coefficient of thermal expansion. The binary Al-Si system is a eutectic alloy when the amount of Si is 11–13 wt%, a hypoeutectic alloy when Si is less than 11 wt%, and a hypereutectic alloy when Si is more than 13 wt%. The strengthening of these alloys is generally possible, through the addition of other alloying elements such as Cu and Mg that make the Al-Si alloys hardenable either by means of a heat treatment. There is a large demand for Al-Si-Mg alloys for different applications, such as the aerospace industry, and for automotive and heat exchangers, due to their high mechanical properties, like strength and hardness, in the heat-treated state [7–9].

The most popular Al-Si alloy processed by LPBF is $AlSi_{10}Mg$ alloy (similar to A360). Other Al-Si alloys by LPBF are $AlSi_7Mg$ (called also A357) [10–11] and $AlSi_{12}Mg$ [12].

Despite this growing interest in the AM processability of Al-Mg-Zn-Cu alloys, to date, few studies are available on the AM process of high mechanical properties' (harness and strength) aluminum alloys. It is well-known that the alloys belonging to the Al-Mg-Zn-Cu alloys are appropriate for different applications in aerospace as they are characterized by toughness and high strength reached mainly through the precipitation of the $MgZn_2$ phase. These alloys are not well weldable because they suffer strongly from liquation cracking [13–14].

3.2 $AlSi_{10}Mg$

In the literature, it is demonstrated that $AlSi_{10}Mg$ alloy produced by casting has a coefficient of friction (against a WC cemented with CO pin) lower than $AlSi_{10}Mg$ alloy by LPBF since their microstructure and hardness are different. The typical microstructure of metallic alloys by LPBF without heat treatments is characterized of a small grain size. At higher magnification after hatching, it can be seen as a fine cellular-dendritic structure made by agglomerates of grains with mean diameters of a hundred of nanometers or less. It is generally observed that materials with large grains have a COF lower than materials with a fine microstructure; this is one of the most important reasons of higher COF of $AlSi_{10}Mg$ by LPBF [15].

The different sizes of microstructure influence the hardness very strong. The hardness is higher for the finer grain size. As suggested by the theoretical considerations, the material with the highest hardness has the highest wear resistance. The difference between the wear resistance of the $AlSi_{10}Mg$ alloy produced by casting and by LPBF is immediately evident. During pin on disc test, the volume per meter loss of the $AlSi_{10}Mg$ produced by LPBF is 35% less than the volume per meter loss of the $AlSi_{10}Mg$ produced by casting.

3.3 Other aluminum alloys

In general, for the conventional casted alloys, the Al-Si alloys with small primary silicon phase present a higher wear resistance than that of the alloys with large silicon phase, due to their high surface-volume fraction. The aluminum alloys by LPBF show the inverse results that could be attributed to their ultrafine microstructure.

During the wear process, the fine primary silicon particles form a full contacted wear layer; the primary silicon is directly pressed into Al-matrix and then forms the full contacted wear layer [7]. For this reason alloys with small primary silicon have a relative poor wear resistance. The A357 aluminum alloy has less silicon (6.5–7.56%) than $AlSi_{10}Mg$ (9–11%) but higher COF and wear [16].

For the Al-Zn-Mg alloys, the microstructure has a strong influence on the wear behavior that is due to higher content and the higher amount of $MgZn_2$ precipitate that is harder than α-aluminum matrix and helps to protect the surface of material [13].

3.4 Aluminum matrix composites (AMCs)

Aluminum matrix composites (AMCs) have generally excellent mechanical properties such as improved stiffness, strength, and hardness when compared with the aluminum matrix. AMCs attract much attention because they are characterized by low density and high specific strength and good tribology properties. The limits of this material are the high difficulty in the process of production and in the post-processing phases. The principal problem when a ceramic is used as reinforcement is the clustering and agglomeration caused by the poor wettability and a large surface-to-volume ratio that does not promote a homogenous dispersion.

The LPBF process seems to be particularly suitable for the production of AMCs because near net-shape complex components can be made, which reduces the post-processing phases. The most used ceramic reinforcements in AMCs produced by LBPF are magnesium spinel ($MgAl_2O_4$) and titanium diboride (TiB_2) [15].

The sufficiently high densification rate combined with the homogeneous incorporation of nanoscale TiC reinforcement throughout the matrix led to the considerably low coefficient of friction (COF) and resultant wear rate [17].

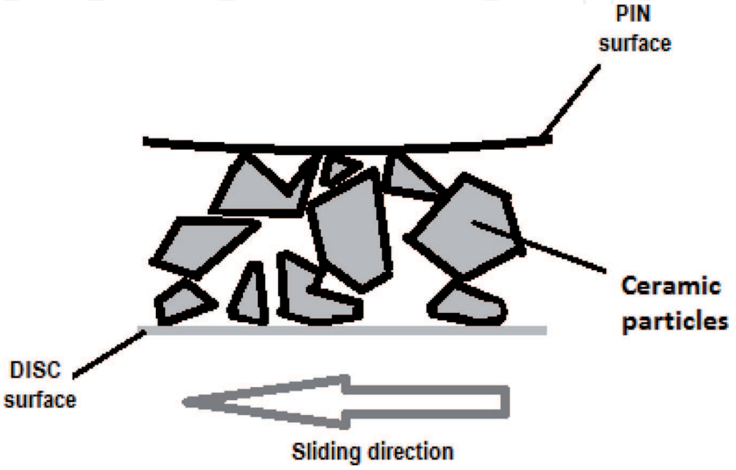

Figure 3.
Example of detached particles that have an effect of solid lubrication (third part).

The presence of reinforcements causes a reduction of COF. If the reinforcements have a micro-size, the effect is bigger than with nano-sized reinforcement. The reduction of COF is probably due to the detachment from the aluminum matrix of micro- or nanoparticles of ceramic reinforcements that can act as a third body (**Figure 3**).

4. Nickel alloys

4.1 Introduction

The most used nickel alloys produced through LPBF for their high weldability are Inconel 718 and 625. Inconel 718 and 625 have been used in high-temperature applications, such as nuclear reactors, pumps, molds, and gas-turbine engine aircraft. These nickel alloys are endowed with high-temperature strength, high creep, and oxidation resistance. These two alloys can be used depending on the applications, but the production of objects with a complex shape is expensive with conventional manufacturing technologies. Therefore, the ability to produce complex components without using molds makes LPBF process particularly interesting. The microstructure created during LPBF process are out-of-equilibrium, and it is necessary to perform some heat treatments in order to homogenize the microstructural features. Depending to application it would be necessary to carry out a simple stress relieving to reduce residual stress induced by thermal gradients during LPBF process. As for other applications, annealing or solution treatment to allow the grain recrystallization and growth, thus improving the creep resistance, is typically requested [18–21].

4.2 Inconel

Inconel 625 is a nickel-chromium alloy designed as solid-solution-strengthened. The heat treatments favor the formation of metastable Y” phase that further improves the mechanical properties. Inconel 625 thanks to higher concentration of Cr and Mo with respect to Inconel 718 has higher corrosion resistance.

Inconel 718 is an age-hardenable nickel-chromium alloy mainly due to the presence of aluminum, titanium, and niobium that leads to precipitation of gamma prime Y’ $Ni_3(Al,Ti)$ phase and metastable gamma double prime Y” Ni_3Nb phase [18]. Inconel by LPBF is more difficult to be machined than the same materials produced by extruding or rolling processes. During milling process of Inconel by LPBF, the cutting speed and chip load are lower due the presence of hard precipitated particles. In general, the Inconel produce by LPBF exhibited relatively good wear performance. Such microstructures indicated that the presence of severe adhesive wear in turn resulted a relatively higher wear rate. The clustered Y dendrites gave rise to the fluctuations of COF. The formed protective adherent tribolayer on worn surfaces made considerable contributions to the further improved wear performance of LPBF-produced parts. The combined influence of elevated microhardness and the formation of adherent tribolayer contributed to the improvement of wear performance [20].

Different studies, in particular about Inconel 718, show that addition of tungsten carbide (WC) or titanium carbide (TiC) particles significantly increased the hardness, friction resistance, and wear performance. The composite acquired a considerably low COF. The existence of a gradient interface has a very important role in improving the wear performance of LPBF-processed WC/Inconel 718 and TiC/Inconel 718 composites [22].

5. Titanium

5.1 Introduction

Titanium and its alloys have good mechanical properties, good corrosion resistance, and excellent biocompatibility. These alloys are the most interesting metallic biomaterials for orthopedic and dental implants. Until few years ago, titanium processing via AM technologies was given little consideration by the medical industry due to the high cost of production. However, in recent years, AM metal technologies are becoming popular in biomedical field because of the ability to build metals with customized porous architectures and shape. The titanium alloy Ti_6Al_4V (the most popular titanium alloy) has been widely used in various industrial applications due to its mechanical and physical properties. Beyond the biomedical field, Ti_6Al_4V has been commonly employed in producing aircraft engine airframe parts owing to its high strength to mass ratio and good performance at high temperature (up to 400–500°C) [23–24].

5.2 Ti_6Al_4V

Ti_6Al_4V has very good mechanical properties, but it has also been reported to exhibit poor tribology properties, such as a high COF and low wear resistance. The poor tribological property of Ti_6Al_4V is attributable to its low resistance to plastic shearing, low work hardening, and the low protection afforded by surface oxidation. No significant differences are present between TI_6Al_4V produced by the different processing technologies. Generally on Ti_6Al_4V produced by LPBF, less oxidized areas are found during the wear tests [25].

During the LPBF process, the high cooling rate of laser melting leads to higher amount of α and α' harder phases on Ti_6Al_4V alloy than the traditional process. The presence of harder microstructural constituents on Ti_6Al_4V produced by LPBF leads to a higher wear resistance. The heat-treatment Ti_6Al_4V generates a protective tribolayer containing oxygen without plastic deformation in the bulk material, which has the lowest wear rate [26].

Investigation of reinforced Ti_6Al_4V with TiB_2 shows that nano-sized TiB whiskers are formed by the in situ reaction between Ti and TiB_2. The interface between matrix and TiB is a very strong interface bonding. During the wear test, this avoids the possibility of easy detachment of TiB whiskers. This reduces the wear rate significantly but not the COF, because the detached particles are few and it is not present enough third part that reduces significantly the friction [27].

6. Stainless steel (316L)

The 316L austenitic stainless steel has numerous application in different fields for its high resistance at oxidation and corrosion. The most popular applications are in marine, nuclear, oil and gas, and biomedical industry. 316L austenitic stainless steel which comprises iron alloyed with chromium of mass fraction up to 18%, nickel up to 14%, molybdenum up to 3% , manganese down 2%, silicon down 0.75%, copper down 0.5% and carbon down 0.03% along with minor elements [28].

During wear test on 316L stainless steel produced by LPBF, the passive layer made by chromium and nickel oxidation is removed and leaves iron exposed to the air, which easily gets oxidized especially at high temperature. Regarding the wear mechanisms, the worn surfaces of 316L stainless steel exhibited plastic deformation due to adhesive wear as well as grooves aligned along the sliding direction due to the abrasive wear. The wear rate and the friction of 316L stainless steel by LPBF were lower than the 316L traditionally processed; the LPBF-processed steel has a very fine austenite grains, the size of which was much smaller than in the traditional-processed 316L stainless steel. These fine grains in the 316L stainless steel by LPBF increase the wear resistance, and the surface is subjected to slight plastic deformation [29–30].

Investigation of the wear resistance of reinforced 316L stainless steel (with TiB_2 or TiC) shows that the wear resistance increases with the increasing TiB_2 content due to combined effects of grain refinement and grain-boundary strengthening [31].

7. Lubrication condition and heat treatment

Metallic alloys by LPBF have generally pores and cracks that influence the wear under lubricated condition. Few studies are available in literature under boundary lubrication regime.

In those studies [26, 30], when a lubricating film is not yet formed, the metal alloys by LPBF have better wear performance than metal alloys by traditional processes.

Surface pores may positively influence the formation of the lubricating film.

The effect of lubricant is critical in reducing friction and wear. The choice of oil needs to be carefully considered before applying LPBF process to hydraulic components.

In general, heat treatment (used to reduce the stress in material after LPBF process) reduces the wear resistance of metallic alloys. The wear resistance is reduced because the heat treatment changes the microstructure of metallic alloys by LPBF and lost the very fine microstructure. The most sensibility materials at heat treatment are aluminum alloys [15, 32]. The only metallic alloy that increases the wear resistance and reduces COF after heat treatments is Ti_6Al_4V because the oxidation of surface (if the heat treatment is realized in the presence of oxygen) produces a protective tribo-oxide layer [26].

8. Conclusions

In conclusion, metallic alloys by LPBF generally have higher wear resistance and less COF than metallic alloys produced by traditional processes under dry condition and boundary lubrication mainly due to the fine grains and high hardness.

The LPBF processing parameters are fundamental for wear rate since a fully densified part usually has high wear resistance and COF.

The existence of pores reduces the bonding between molten pools, resulting in cracks. These cracks can further cause material shell off which greatly increases wear.

In general, the metallic alloys produced by LPBF are more difficult to machine than the same metallic alloys produced by traditional processes. For this, it is important to reduce at the minimum the post-process machining.

The presence of ceramic particle reinforcements in MMCs causes generally a reduction of COF; this effect is due to the detachment from the metallic matrix of ceramic particles that can act as a third body. The interfacial bond between the matrix and the reinforcements has a fundamental role in wear process; a strong interfacial bond guaranties a low wear rate; a weak interfacial bond causes a low COF and sometimes high wear rate.

The heat treatment in general reduces the wear resistance and increases the COF.

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