LASER POWDER BED FUSION OF ALUMINUM ALLOYS

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Abstract
The aim of this study is to analyze and to summarize the results of the processing of aluminum alloys, and in particular of the Al-Si-Mg alloys, by means of the Additive Manufacturing (AM) technique defined as Laser Powder Bed Fusion (L-PBF). This process is gaining interest worldwide thanks to the possibility of obtaining a freeform fabrication coupled with high mechanical strength and hardness related to a very fine microstructure. L-PBF is very complex from a physical point of view, due to the extremely rapid interaction between a concentrated laser source and micrometric metallic powders. This generate very fast melting and subsequent solidification on each layer and on the previously consolidated substrate. The effects of the main process variables on the microstructure and mechanical properties of the final parts are analyzed: from the starting powder properties, such as shape and powder size distribution, to the main process parameters, such as laser power, scanning speed and scanning strategy. Furthermore, some examples of applications for the AlSi10Mg alloy are illustrated.

Keywords: Additive Manufacturing, Laser Powder Bed Fusion, Aluminium Alloys

1 Introduction

Laser Powder Bed Fusion (L-PBF) process is the standard term according to ISO/ASTM 52900 used to define the Additive Manufacturing (AM) technique that allows to obtain full density free-form objects and components using a laser source to melt and consolidate thin layers of metallic powders spread onto a building platform by a recoating system [1,2]. The layer thickness depends on the size and distribution of the spherical powders employed, usually between 20 to 60 μm, and obviously on the machine used for the process. Regarding this, L-PBF is also known and present in literature with different commercial names depending on the machine manufacturer, such as direct metal laser sintering (DMLS) for EOS Gmbh, LaserCUSING for Concept Laser, Direct metal production (DMP) for Phenix (3D system), Selective Laser Melting (SLM) for SLM Solutions, Realizer, Matsuura and Renishaw [3,4]. The L-PBF is one of the most widespread AM technology for metallic materials, being already used with success in different industrial sectors such as biomedical, automotive, aerospace and jewelry [5, 6, 7].

However, this technology is not a "start and stop" simple process due to its complexity at every step. It could be stated that L-PBF process is set out of seven main steps, that are CAD model

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creation, .stl file generation, part orientation and support structures placement, slicing of the whole file, construction of the part, part removal from the building plate and post-processing. Therefore it is clear that a multidisciplinary approach, with competences in designing and software, in materials characterization and processing, is mandatory. A mistake in the early stages may compromise the success of the component production. It should be put attention in the 3D CAD model definition in order to meet the manufacturing constraints (e.g. minimum wall thickness, filled radii, etc.) [8], in finding a balance between number of facets and file size in the .stl file creation [9], in the identification of the correct part orientation on the building platform with the proper support structures [10]. The platform represents the metallic substrate used to give mechanical and thermal sustenance during the manufacturing of the parts.

Considering then the proper manufacturing step, it is fundamental to correlate the starting powders size and shape to the main process parameters, like laser power, scanning speed, layer thickness, hatching distance, and to the scanning strategy adopted [11]. This strategy differs depending on the L-PBF machine supplier, but in all cases the re-melting of the previous layers during the fusing of the current layer exposed allows its complete adherence to the rest of the part and a high final density. Once the build is completed, excess powder need to be removed, and the parts fabricated must be detached from the substrate. Usually this last operation is made after a stress relieving heat treatment, performed to release the thermal stresses that arise during the L-PBF process, which otherwise could lead to deformation of the parts and to loose dimensional tolerances [12, 13]. Finally, a post-process treatment like a grit blasting, also called micro-shot peening, is suggested to remove from the surface the sticky particles, which are not melt but only adhere to the surface, and to reduce the surface roughness of the parts [14].

Among the metallic alloy systems currently available for powder based AM techniques, the L-PBF of aluminum alloys has gained importance for the industry since the as-built parts have higher strength and hardness compared to the cast counterparts [3]. The Al-Si-Mg cast alloys are the most investigated, due to the high fluidity of the liquid phase that makes easier the preparation of pore-free samples and very good weldability, as reported in literature [15-17]. In this study, the main findings related to the processing of AlSi10Mg alloy through L-PBF is reviewed and summarized, and some examples of applications in different fields are also illustrated.

2 Materials, Methods and Results

2.1 Powders

The aluminum AlSi10Mg alloy investigated has a composition corresponding to A360 cast alloy, with 10% wt. of Si, near eutectic composition, and 0.3% wt. of Mg [18]. To evaluate the starting gas-atomized powders in terms of dimension and morphology, a Zeiss Supra40 Field Emission Scanning Electron Microscope (FESEM) was employed. As can be seen in **Fig. 1**, the aluminum powders are spherical and very fine: there are particles from 500 nm to 35 μm in diameter, with a mean size around 20 μm. The smallest spheres create many agglomerates. For this reason it is fundamental to sieve the powders before putting them in the L-PBF machine.

With such fine powders, the common systems adopted in powder metallurgy to evaluate the flowability, like through the Hall and Carney flowmeters, cannot be used. In fact we observed that the powders did not flow at all in such funnels. An alternative method could be the use of a Revolution Powder Analyzer (RPA) as a standard device, as suggested by Aumund-Kopp and co-workers [19]. Moreover, in handling and processing aluminum powders, a particular care

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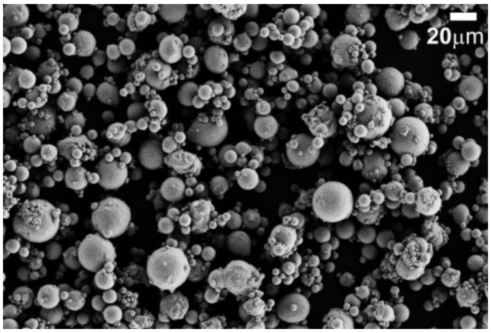
should be used to reduce the moisture adsorption, that otherwise could enhance the hydrogen porosity inside the samples, as observed by Weingarten et al. [20]. For this reason, it is suggest to perform a drying treatment before putting the powders inside the L-PBF machine.



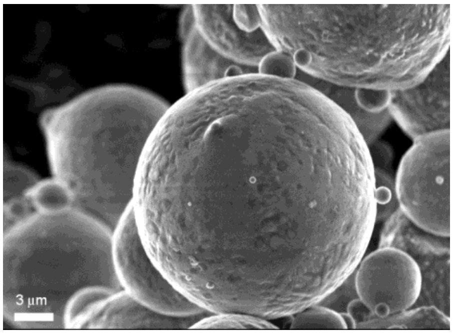


Fig. 1 FESEM images of AlSi10Mg powders employed

2.2 Process parameters and scan strategy

The L-PBF samples were built using a EOSINT M270 Dual Mode machine, equipped with a 200W Yb fiber laser. The choice of the main process parameters, like layer thickness (t), laser power (P), scanning speed (Ss), hatching distance (hd), is fundamental to obtain the lower porosity of the samples. The hatching lines create the laser stripes visible at naked eye during the process. In **Table 1** are summarized the parameters optimized starting from the above described AlSi10Mg powders. In all cases, the scanning strategy adopted is based on the laser exposure in stripes of 5 mm of the samples section and in their rotation of 67° between subsequent layers, which ensures to achieve the highest density [11].

Table 1 Parameters optimized for the fabrication of dense samples in AlSi10Mg alloy through an EOSINT M270 Dual Mode machine [21]

Material	**P [W]**	**t [µm]**	**S_s [mm/s]**	**h_d [mm]**
AlSi10Mg	195	30	800	0.17

With such parameters, cubic samples of 15mm per side were built for density measurements, microstructure observations by optical and electron microscopy (FESEM), and Vickers microhardness. The samples were polished down to 50 nm with colloidal silica suspension, and then etched with Keller's reagent for 12s. Tensile samples according to the standard ASTM E8 were also fabricated perpendicular and parallel to the building direction (or z-axis).

2.3 Microstructure and mechanical properties

As observed in literature in previous studies [2, 3, 17, 21-23] the L-PBF process is very complex from a physical point of view, due to the extremely rapid interaction between a concentrated laser source and micrometric metallic powders. This generates an extremely rapid melting and subsequent very fast solidification rate. This means an extension of solid solubility and refined microstructural features, like grains and precipitates, with respect to conventional solidification processes. L-PBF could be considered as a rapid solidification process, like gas atomization or melt spinning, but with the great difference of having a final 3D component, instead of powders or ribbons.

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In support of these statements, in **Fig. 2** are displayed macrographs of AlSi10Mg alloy samples by conventional casting and by L-PBF. The images are taken at the same magnification: in this way it is evident the grain size difference, being the L-PBF microstructure at least one order of magnitude finer than the cast one. The choice of the scanning strategy influences also the microstructural texture that could be created. In Figure 2c-d is clear the effect of subsequent laser tracks, generating the so-called melt pools. Due to the rotation of 67° between subsequent layers they are not perfectly superimposed, as it would happen with a scanning strategy all along x- or y- axes.

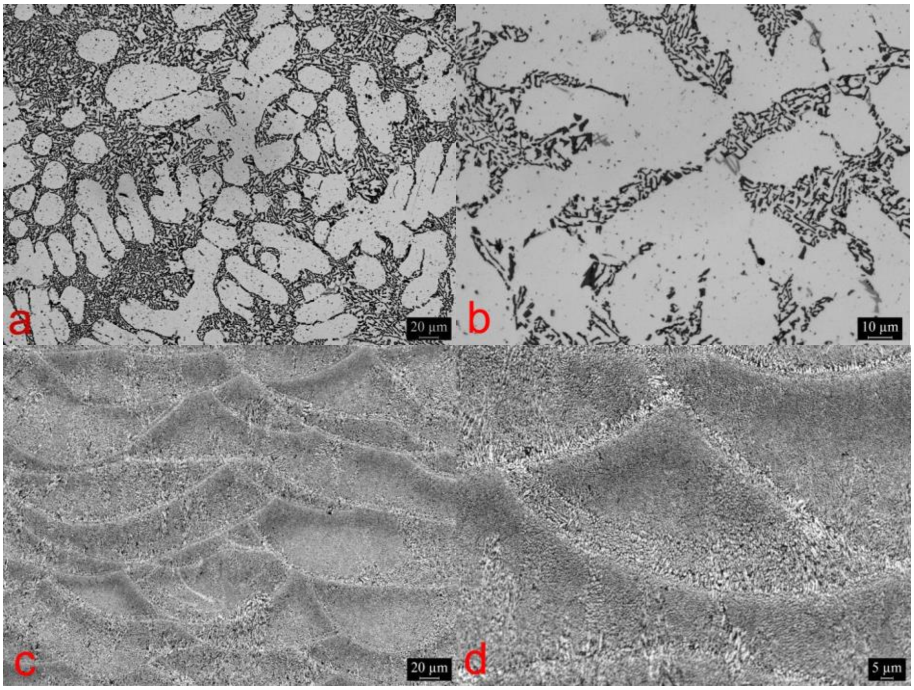

Fig. 2 Comparison among AlSi10Mg macrostructures obtained through: casting (a-b) and L-PBF process (c-d); the red arrow indicates the building direction, or *z-axis*

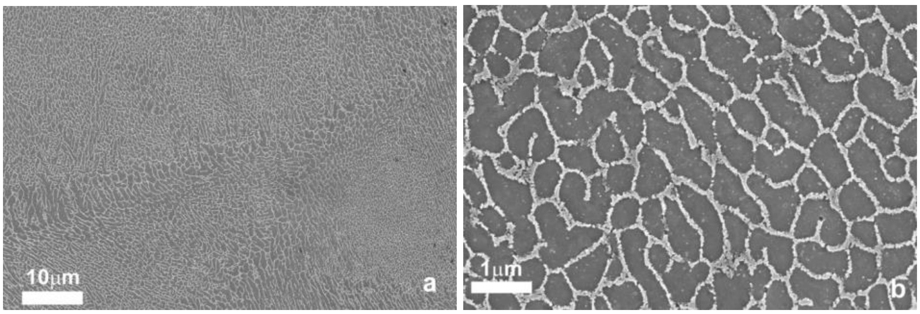

Fig. 3 FESEM images of AlSi10Mg microstructure by L-PBF process: (a) melt pool borders are visible; (b) a magnification of the melt pool center

To appreciate the very fine L-PBF microstructure, it is necessary to go to high magnifications and therefore to use electron microscopy. FESEM analyses of the as built L-PBF samples are

shown in **Fig. 3**. In the melt pool center, the cellular-dendritic solidification generates fine equiaxed grains, with the silicon in the form of a continuous segregation on the boundaries of the α-Al cells.
The consequence of such microstructure is a significant improvement in mechanical properties, like Ultimate Tensile Strength (UTS), Yield Strength (YS) and hardness, as reported in literature [3]. In particular, using the powders and the parameters described before, an increase of the YS of more than 30% with respect to the cast counterpart was observed [21]. Also the role of porosity represent the problem related to the mechanical properties. The investigation of the porosity behavior of aluminum alloys is reported in [24-27].

2.4 Post processing – design constraints

In order to create complex shapes and/or lightweight parts, it was necessary to know the threshold values for the building of certain geometries, such as overhanging structures, thin walls and small features [8-10]. An overhanging structure is a part of a component that is not supported during building, by solidified material or a substrate on the bottom side. The main function of the supports are to fix the part to building platform and conduct excess heat away from the part. The ideal situation is to design and to orientate in the L-PBF chamber parts that requires no supports at all. This is rarely possible, but minimize those means to save time and to reduce costs.
Another aspect that should be kept into account in designing for L-PBF is the powder removal from internal channels and small passages and features after the process. This is also related to the stress relieving treatment. If the heat treatment is performed at a high temperature, near the melting point of the alloy considered, the same treatment could agglomerate the loose powders in a sort of green body (like in sintering), making then impossible to remove them.
Furthermore, with the appropriate post process, like a micro-shot peening, in combination with the process parameters optimization, it is possible to enhance the surface roughness of the parts made by L-PBF [9], or to create a particular texture [10]. This treatment is in any case recommended, to remove the powders which are not melted but simply adhere the outer surface.

2.5 Applications

The multidisciplinary approach adopted in investigating the L-PBF process was fundamental to allow to use AlSI10Mg alloy in different applications, using a design driven to enhance the functionality. As examples, the following studies can be cited for the production of:

- a lattice anodic structure in a fully AM-based microbial fuel cell, exploiting low density and an increasing in the energy that can be produced [28];
- small heat sinks for electronic cooling, with a remarkably enhanced convective heat transfer coefficient, taking advantage of artificial roughness in fully turbulent regime [29];
- highly integrated hydraulic components with reduced weight and higher complexity when compared to traditionally manufactured for the IIT's recently developed Hydraulic Quadruped HyQ2Max [30];
- waveguide devices for microwave satellite telecommunications [31].

Conclusions

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There is the need to study and develop ad-hoc heat treatments, being the starting microstructure after L-PBF process something new with respect to the conventional metallurgical processes. The best properties are obtained in the as built conditions, but it is mandatory to remove the residual stresses in particular for complex shaped components, to avoid deformations and to do not loose tolerances. Moreover, considering aluminum alloys, the actual systems currently available are only those related to the Al-Si casting group, with the exception of the Scalmalloy, patented by Airbus APWorks. Therefore efforts should be devoted in developing new compositions suitable for this technology and able to take advantage of the high thermal gradients.

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