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INFLUENCE OF LASER PARAMETERS ON THE L-PBF PROCESSING OF INCONEL SUPERALLOYS: A BRIEF REVIEW

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Abstract. *Inconel superalloys are critical materials for the manufacturing of heat-resistant components of turbine systems, which demand a combination of properties difficult to be attained by other materials. The poor workability of Inconel superalloys, however, restrain the broadness of its applications due to costs and dimensional precision requirements. Thus, the additive manufacturing of these superalloys by Laser Powder Bed Fusion (L-PBF) has been the object of research of various publications in the last couple decades, given the capabilities of additive manufacturing techniques for the production of near net shape components even when produced in difficult to work materials. Among such studies, various authors aim to optimize L-PBF manufacturing parameters in view of the search for processing windows, which permit the production of materials with properties similar or superior to those produced by conventional manufacturing techniques. However, few studies analyze the impact and effects of altering laser-only parameters, given that the use of standard commercial systems often make it difficult to make the changes needed in its optical system for such analysis. Therefore, this brief review aims to show the effects of laser-only parameters such as laser power, focus distance, energy profile and pulsed beam on the L-PBF processing of Inconel superalloys.*

Keywords: *Laser Powder Bed Fusion, Selected Laser Melting, Laser focal shift, Energy Distribution, Pulsed Laser Powder Bed Fusion*

1. INTRODUCTION

1.1 Laser Powder Bed Fusion

Additive Manufacturing (AM) is a relatively new branch of fabrication processes, being developed from rapid prototyping technologies in the 1980s (Kruth et al. 2005). It consists in the generation of solid components by the layer-by-layer joining of precursor material through energy transferred from an energy source. The final geometry of such components is previously defined by a computer-aided design (CAD) model, being produced through various production systems in virtually all classes of materials (Bourell et al. 2017).

Laser Powder Bed Fusion (L-PBF), also known as Selective Laser Melting (SLM), Direct Laser Metal Sintering (DMLS) and Laser Beam Melting (LBM) is one of the main methods of additive manufacturing of metal components, achieving good geometrical precision and densification of the produced components (Frazier 2014). The system consists in a cycle of transference of energy by a laser source to specific regions of a powder bed in which the component is produced, followed by raking of additional powder to the powder bed as to compose a subsequent layer. Each powder layer composes a slice of the component to be produced, and the laser melts the regions of such layer according to the associated cross-section of the slice.

The properties and final quality of components produced by L-PBF, however, are strongly dependent upon various extrinsic and intrinsic variables. Among these variables, processing parameters are routinely varied as to aim for the optimization of material properties, such as density or mechanical strength. Processing parameters often controlled and varied are laser power, scan speed, hatch distance and overlap, scanning strategy and layer thickness.

1.2 Inconel Superalloys

One of the most used materials in engineering applications at high temperatures, Ni-Cr superalloys are used repeatedly in gas turbine blades for industrial, aerospace and nuclear applications (Clarke, Oechsner, and Padture 2012). These work conditions present high rates of corrosion, oxidation and microstructural degradation due to fatigue and creep processes, in addition to requiring materials with the capacity to maintain their properties in long time scales (usually 100,000 cycles in turbines for civil aviation) (Reed 2006:187–91). In order to resist such a medium and achieve such performance, Ni-Cr superalloys have a composition with various alloying elements and a highly complex microstructure on a nanometer scale, characterized by several reinforcement phases.

Within the various superalloy classes, Inconel superalloys have been the object of various L-PBF studies, comprehending the majority of publications dealing with the L-PBF processing of superalloys. Among Inconel alloys, Inconel 718 and Inconel 625 (henceforth referred as IN718 and IN625), comprise, due to their weldability, reasonable price and wide use in conventional industrial contexts, the vast majority of such publications. Nonetheless, recent studies aim to broaden the literature by including different types of Inconel alloys, such as IN738LC and IN939.

As with studies examining the L-PBF processing of other materials, however, the influence of laser-specific parameters in the characteristics of Inconel components produced by L-PBF is poorly described in the literature, which usually only focus on the influence of laser power in the produced components. This is due to the fact that the majority of published studies conduct experiments in commercial processing systems whose optical characteristics are difficult to alter. Therefore, this study aims to collect, classify and analyze recent studies focusing on the influence of laser-only parameters in the processing, microstructure and properties of Inconel superalloys produced by L-PBF.

2. METHODS

2.1 Search strategy

The selection of studies was conducted in the Scopus database (Elsevier, Netherlands) by informing the following query: "(TITLE-ABS-KEY ("laser powder bed fusion") OR TITLE-ABS-KEY (LPBF) OR TITLE-ABS-KEY (L-PBF) OR TITLE-ABS-KEY (PBF-LB) OR TITLE-ABS-KEY ("selective laser melting") OR TITLE-ABS-KEY (SLM) OR TITLE-ABS-KEY ("direct metal laser sintering") OR TITLE-ABS-KEY (DMLS) OR TITLE-ABS-KEY ("laser beam melting") OR TITLE-ABS-KEY (LBM)) AND (TITLE-ABS-KEY (Inconel) OR TITLE-ABS-KEY (IN718) OR TITLE-ABS-KEY (IN625) OR TITLE-ABS-KEY ("Alloy 718") OR TITLE-ABS-KEY ("Alloy 625")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO(LANGUAGE, "English"))", which resulted in 541 research articles as of March 2nd 2021. These studies were thusly searched as to comprehend both the additive manufacturing processing by L-PBF and the various denominations of Inconel superalloys throughout the literature. The full set of identified studies was then assessed for eligibility, such that 30 full texts were regarded as eligible for the scope of this study.

2.2 Study characteristics

All eligible studies employed L-PBF systems equipped with ytterbium fiber lasers, to the exception of a pair that presented solid neodymium-doped yttrium aluminum garnets (Nd:YAG) as active medium (Mumtaz and Hopkinson 2010a, 2010b). The proportion between manufacturers of each employed system are presented in "Figure 1", in which "EOS" stands for Electro Optical Systems GmbH, "GE" stands for General Electric Company, "SLM Solutions" stands for SLM Solutions Group AG, "Renishaw" stands for Renishaw plc, and "IPG" stands for IPG Photonics Corporation.

3. EFFECT OF SELECTED LASER PARAMETERS

3.1 Laser Power

Among all laser-only parameters, laser power is the one with most representativeness throughout the reviewed literature, given the ease of its alteration during L-PBF parametrization studies. Together with scan speed, layer thickness and hatch parameters such as hatch distance and hatch strategy, it is one of the main parameters usually optimized in the literature.

When processing a powder precursor by L-PBF, laser power represents the maximum energy available to heat the powder bed, such that melting in a controlled and homogeneous fashion is desired to produce dense bulk components. Thus, studies often associate high laser powers to a better densification of the as-built components due to the intuition that more power produces an easier melting and, therefore, denser components (Guo et al. 2020; Kumar et al. 2019; Perevoshchikova et al. 2017; Scime and Beuth 2019). However, studies have shown that the increase of this parameter to very high powers can bring about the formation of porosity in as-built materials due to the development of keyhole pores and strong convective flows in the L-PBF melt pools (Scime and Beuth 2019; Shi et al. 2016; Zhang et al. 2018). Moreover, such conditions also favor remelting, microstructural coarsening and segregation (Sadowski et al. 2016; Shi et al. 2016; Yang et al. 2020), as represented in "Figure 2". Therefore, once these mechanisms are considered, maximum density and optimized microstructures of components are expected in intermediate laser power values, which present a simultaneous good melting of powder particles and not enough energy for keyhole formation and substantial remelting (Balbaa et al. 2020; Calandri et al. 2019; Letenneur, Kreitcberg, and Brailovski 2019; Marchese et al. 2017; Ni et al. 2017; Scime and Beuth 2019; Wang et al. 2019; Zhang et al. 2018).

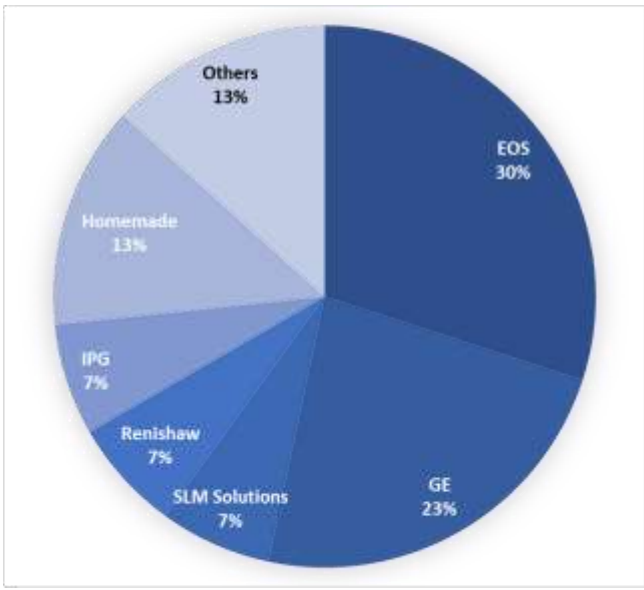

Figure 1. Manufacturers of L-PBF systems employed in the reviewed literature.

On the other hand, various studies also show that high laser powers tend to increase the L-PBF melt pool dimensions (Balbaa et al. 2020; Grange et al. 2020; Li, Guo, and Zhao 2017; Sadowski et al. 2016; Scime and Beuth 2019; Shi et al. 2016; Zhang et al. 2018), which can be inferred by the higher localized energy available for melting as granted by high laser powers. When L-PBF is applied in difficult to weld alloys such as IN738LC, this phenomenon has been associated with higher microcracking incidence (Grange et al. 2020; Perevoshchikova et al. 2017), what can be accounted to increased temperature gradients after laser melting, which, in turn, induce residual stress in the solidified material and, ultimately, cooling cracks (Shi et al. 2016; Yi et al. 2019).

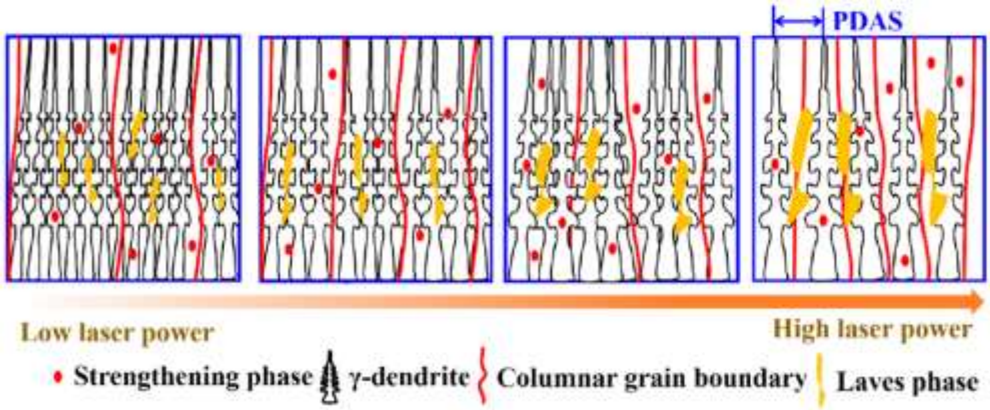

Figure 2. Schematic influence of laser power on the microstructural coarsening of Inconel superalloys (Yang et al. 2020).

3.2 Focal shift

The processing of Inconel superalloys by L-PBF in out-of-focus conditions leads to consequences to process and material characteristics that can be modelled according to the fact that, when out of focus, a laser beam presents a bigger spot size and a consequent reduced area power density when compared to focused processing, which reflects in less energy being available to melt a specific area of the powder bed. Therefore, melt pools produced by the unfocused laser raster tend to be shallower and wider ("Figure 3"), as present in the results of some studies (McLouth et al. 2018, 2020).

Additionally, defocused conditions have been reported to increase density in as-built components, such that minimum porosity was detected when processing materials at about one Rayleigh distance from the focal plane (G. Bean et al. 2018; G. E. Bean et al. 2018). These dense microstructures have been shown to present an increased anisotropy due to strong crystallographic texture, as well as larger dendrite arm spacing and increased segregation due to microstructural coarsening (McLouth et al. 2018, 2020).

These effects can be explained by a high degree of overlapping caused by focal shift under constant hatch distances, which, in turn, provides the microstructure with energy necessary for increased diffusion and solid-state transformations. It has been thus reported that, due to the intergranular resistance provided by these changes, microstructures produced under defocused conditions are able to achieve better creep resistances than isotropic microstructures in specific crystallographic directions (McLouth et al. 2020).

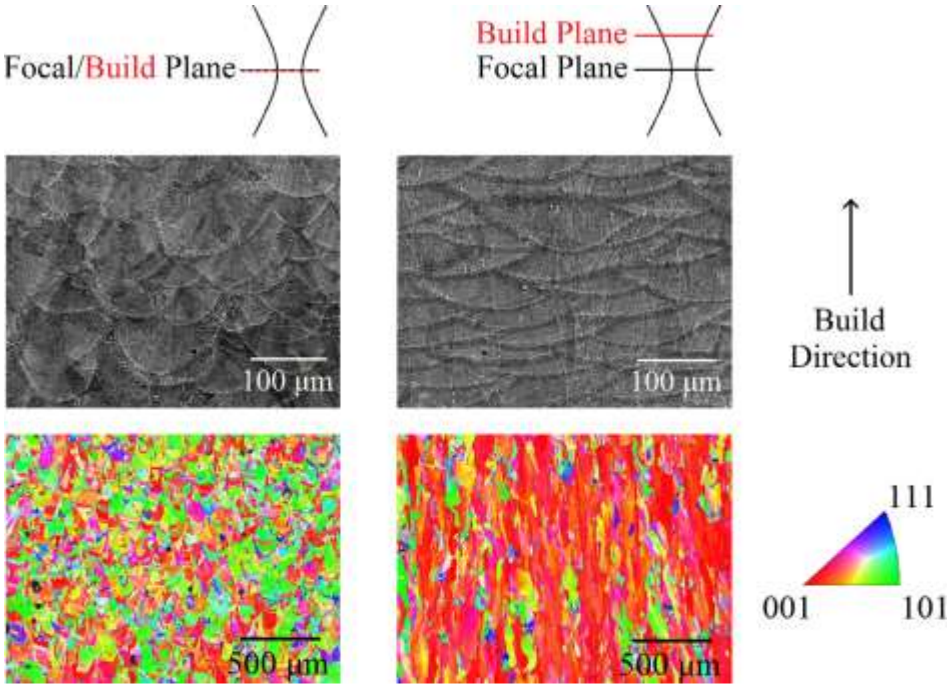

Figure 3. Influence of focus height on microstructure of IN718 (McLouth et al. 2018).

3.3 Energy Profile

By altering the spatial distribution of energy within the laser beam itself, it is also possible to tailor how the powder bed will be heathen on each given point of the laser path. In most studies, however, near-Gaussian energy profiles are employed, such that power density is rapidly reduced when departing from the beam axis. Therefore, by altering parameters from this standard energy profile, studies have focused on the influence of alternative geometries on various material characteristics.

Although the standard beam is usually considered to follow a Gaussian profile, authors have shown that experimental results regarding bead geometry may be better modelled when considering higher beam eccentricity in comparison to the ideal profile, which is especially visible for high powered lasers (Ahsan and Ladani 2020). This is quantitatively described by beam quality factors [M^2] higher than 1, which bring about a less concentrated energy distribution than Gaussian beams.

This effect can be also achieved by employing beam expanders to increase beam diameter. The broader energy distribution of the beam profile under these conditions, which could increase built rates, has been shown to produce shallower melt pools and, consequently, inhibit keyhole formation. Thus, a reduced rate of material vaporization and spattering have been reported, which produce a more uniform surface for as-built components. On the other hand, the final microstructure under these conditions seems to present a higher degree of columnar grains, which tend to increase material anisotropy (Sow et al. 2020).

The incidence of columnar grains, however, could be drastically increased by the employment of high-power flat-top energy profiles, which can be produced by the introduction of beam shapers within the optical system, as can be verified in "Figure 4". Moreover, substantial crystallographic orientation is also produced, which exacerbates the preferential parallelism between <100> and the build direction while increasing overall anisotropy (Wang and Shi 2020). An opposite effect can be produced by shaping the beam geometry according to a doughnut, i.e., a radial TEM_{01} beam distribution. While this configuration also tends to shallow melt pools and reduce keyhole incidence, it seems to retain the same grain morphology produced by standard near-Gaussian beams. Additionally, reduced hot cracking has also been reported, despite the tendency of higher porosity (Cloots, Uggowitzer, and Wegener 2016).

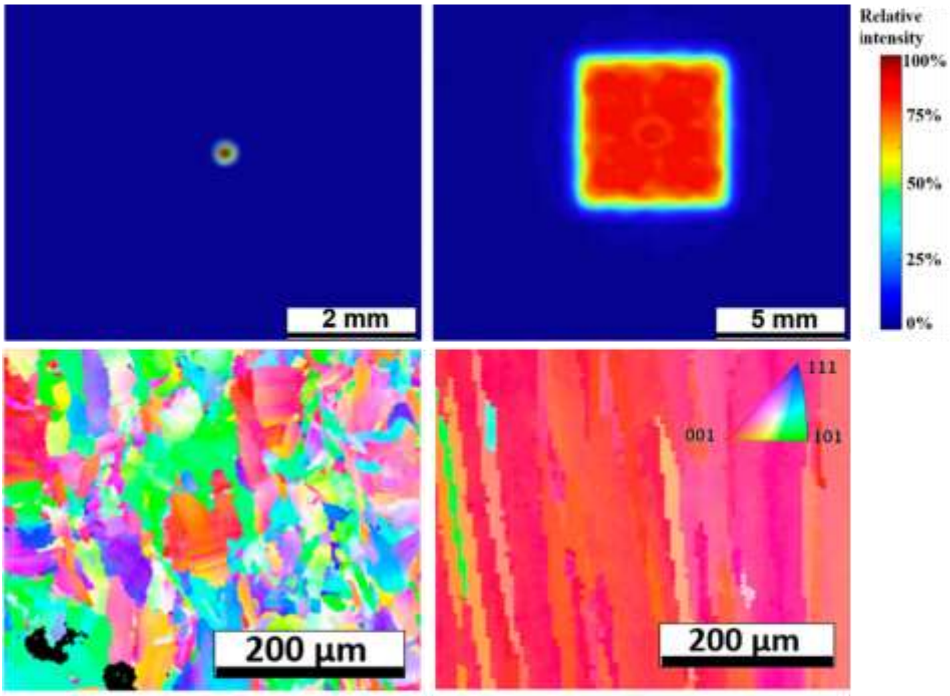

Figure 4. Influence of beam energy profile on microstructure of IN718. Gaussian beam with associated isotropic grain structure (left) and flat-top beam with columnar grains presenting expressive crystallographic texture (right) (Wang and Shi 2020).

3.4 Pulsed Laser Powder Bed Fusion

Although the majority of the literature dealing with the L-PBF processing of Inconel superalloys employs systems equipped with continuous lasers, selected studies aim to analyze the effects of the emerging technique of Pulsed Laser Powder Bed Fusion (P-LPBF) on the same materials. Due to the time between energy pulses, P-LPBF tends to generate higher localized cooling rates, such that significantly less energy is transferred to regions adjacent to the molten surface. Thus, not only do melt pools tend to be shallower and cleaner, but the solidification microstructure is usually refined (Tian, Muñiz-Lerma, and Brochu 2017) and isotropic (Georgilas, Khan, and Kartal 2020). This is especially interesting for the production of IN718, once high solidification rates hinder the formation of the brittle Laves phase in coarse geometries and, thus, avoid the solidification cracking phenomenon associated with the phase (Tian et al. 2017). Thus, due to these microstructural modifications, studies report that pulsed lasers are able to produce stronger and stiffer superalloys than continuous systems while maintaining ductility, presenting improvements up to 50 GPa, 180 MPa and 170 MPa for the elastic modulus, yield strength and ultimate tensile strength of IN718 respectively (Georgilas et al. 2020).

The processing of these superalloys by pulsed laser systems, however, depends upon the control of pulse parameters, which, due to the scarcity of publications within this field, is poor on the literature. These include pulse energy, point density, exposure time and pulse ramps.

Within the reviewed literature, increased pulse energy has been reported to reduce single track roughness, what could be also achieved by reducing point distance. Accordingly, long pulse durations seem to increase the roughness of the top of single tracks while decreasing the roughness on its sides (Mumtaz and Hopkinson 2010a). Regarding density, authors reported that the incidence of lack of fusion porosity is increased by increasing both exposure time and point distances, while metallurgical porosity seems to be unaffected (Karimi et al. 2018). Another study, however, arrived at the conclusion that there is an optimum value of both exposure time and pulse energy for maximum density, what indicates a conjugated effect of both parameters (Georgilas et al. 2020).

Moreover, subsequent pulses with no interval in-between (so called “ramps”) have been shown to also affect the quality of components after processing. “Ramps down” (a high energy pulse followed by a low energy one) have been reported to reduce the roughness at the top of single tracks, what can be rationalized by the remelting in lower energy of spatter residues produced by the previous high energy pulse. Accordingly, “ramps up” (a low energy pulse followed by a high energy one) seem to significantly reduce spattering, as the high energy pulse only affects an already heated region of the material (Mumtaz and Hopkinson 2010a). These pulse ramps, despite its advantages, have been however shown to decrease the quality of edges in as-built geometries, whose dimensions can be better controlled by restricting exposure time (Mumtaz and Hopkinson 2010b).

4. CONCLUSIONS

Inconel superalloys are one of the main materials currently under study for a processing development by laser powder bed fusion, given its strategic industrial applications and suitability for additive manufacturing technologies. The L-PBF processing of these materials, however, is highly influenced by manufacturing parameters, which, in turn, control the resulting material properties and characteristics in built components. The manufacturing parameters associated to laser characteristics, despite its poor documentation on the literature, have been shown to significantly affect the final microstructure and properties of Inconel superalloys, what indicates a need for increased awareness to the capacity of such parameters to achieve material conditions difficult to attain by other parametrization routes. Among the reviewed parameters, the following specific conclusions could be devised:

- The high energy available for heating under high laser powers induces the growth of melt pool dimensions and microstructural coarsening as more material is molten under the same laser exposure. Optimum power levels exist for densification and defects minimization, which can be achieved by parametrization;
- The spatial distribution of the energy available from the laser power, however, can be altered by tackling focus conditions, beam diameter and geometry. Whereas these methods can regulate the laser beam intensity as to achieve lower energy density in high power conditions, the same energy is distributed in broader regions, such that a more distributed superficial melting occurs. Despite the differences between these methods, it is possible to observe similar tendencies regarding its effects on material microstructure;
- When inducing remelting of previous epitaxial layers or lines by broader energy distributions (unfocused, expanded or shaped beams), laser parameters can induce the formation of a higher degree of texture and columnar grains than those achieved by other parameters, which affects the performance of components;
- By better distributing the power of the laser beam and, therefore, reducing keyhole formation, melt pool instabilities and residual stresses, laser-only parameters are capable of reducing the incidence of defects such as porosity, cracking and excessive roughness;
- The use of pulsed lasers for laser powder bed fusion brings about a set of pulse-parameters to be optimized for material production, which are capable, due to more localized material heating by short pulses, of tailoring specific aspects of the Inconel microstructure which are problematic in conventional L-PBF.

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