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Direct metal laser melting of Inconel 718: Process impact on grain formation and orientation

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ABSTRACT

Line scan specimens of Direct Metal Laser Sintering (DMLS) processed Inconel 718 were fabricated under a wide range of process parameters in order to correlate the laser energy density (LED) input with the resulting microstructure. High quality specimens at LED values between 0.14 and 1.50 J/mm were prepared for Electron Backscatter Diffraction (EBSD) microscopy. Cross sections of samples perpendicular to the build direction showed a highly oriented crystallographic texture in the ⟨001⟩ direction. LED value directly affects the heat flow direction which was found to have a pronounced effect on the preferred orientation of the grains. Also, the results show that crystallographic texture along the build direction not only depends on manufacturing parameters, but most importantly is a function of heat flow direction and former layer's grain orientation. Furthermore, morphology of grains in the bead area depends on the geometry of bead. Narrow beads with low LED value have columnar grains along the build direction. However, wide beads with high LED values have grains converging to the top middle of the beads. The higher LED experiments show characteristics similar to high energy processes, such as electron beam welding as excessive voids and porosity similar to key-hole effect observed in electron beam welding was found in substrate and melt pool region.

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1. Introduction

Metal additive manufacturing (AM) is quickly becoming a viable alternative to subtractive manufacturing as complex printed parts can be fabricated in a fraction of the time. Direct Metal Laser Sintering (DMLS) is one of the processes that utilizes powder bed technology to form near net shaped parts. The process operates by spreading a thin layer of gas atomized (GA) or plasma rotation electrode preparation (PREP) metal powders over a build plate and directing a high powered Ytterbium fiber laser to locations specified by a sliced CAD file [1]. A few different options for in-layer scanning patterns exist including stripes, islands, and chessboard patterns which all have been tested by a number of different research groups [2–4]. After successful completion of the first layer, the build plate drops down for a specified layer thickness and the process repeats until the part is completed. The part is then allowed to cool and eventually removed from the build chamber to be cleaned off and heat treated, if necessary. The DMLS machine has the capability of running a variety of different materials in either argon or nitrogen filled chamber including different types of steel, cobalt chrome, titanium, nickel alloy, and even aluminum [1].

Inconel 718 is a widely utilized nickel super alloy that makes up between 55 and 70% of all nickel super alloys used in the jet engine industry [5]. This material exhibits high strength and corrosion resistance at temperatures up to 700 °C [6]. It high strength resulting from both solid solution strengthening and precipitation hardening makes it a difficult material to machine. Due to its low thermal conductivity and high hardness [7], tools wear out quickly when Inconel 718 is machined. However, these are some of the features that make the material so desirable in high temperature applications. Finding an alternative to subtractively manufacture high strength, high temperature materials is therefore an important topic of research in which AM is already becoming a practical option.

While AM shows promise in this field, issues and defects still exist in as-built parts which limit their use in certain applications. Although fully dense parts with material properties comparable or superior to that of wrought Inconel have been produced using this technique by a number of different studies [8–10], unpredictable

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microstructures resulting from changing process parameters are common. The AM process in general allows a machine operator to control a variety of different process parameters, although how these changes will affect the part are still not fully understood.

Various studies have discussed the microstructural variations due of altering process parameters. Jia Q. et al., for example, found that as the amount of laser energy density is increased in selective laser melted (SLM) Inconel 718, a change from coarsened columnar dendrites to much more slender and uniformly distributed columnar dendrites are seen [7]. Gong X. et al. observed that even in a single build, microstructure will vary in different distances from base-plate due to different cooling rates. This study showed that lower layers exhibit smaller columnar grains due to higher cooling rate. Initial lower layers are in direct contact with the build plate which is at a lower temperature, causing higher cooling rates than layers that are further away from build plate [11]. Amato K. et al. compared as-built SLM processed cylinders to similar components post processed by hot isostatic press (HIP). This study found a significantly higher Vickers hardness in the HIPed parts. The as-built parts showed that grains oriented in the ⟨100⟩ direction parallel to the build direction [10]. Other post processing treatments were tested by Trosch T. et al., who saw that after heat treating and aging, SLM Inconel 718 showed a much finer grain size by a factor of 10 than that of forged or cast [12]. Investigation on microstructure of areas produced by low and high LED (the ratio of beam power to scan speed, $LED = \frac{Power}{Scan\ Speed}\left[\frac{J}{mm}\right]$) showed that high laser power leads to columnar grains in the range of millimeters length scale in depth. Because, the thickness of each layers is less than a millimeter (about 100 μm), existence of columnar grains in a mm range shows that there is re-melting of previous layers [13,14]. In general, tendency to have preferred grain orientation decreases from higher layers to the lower one [13]. The fastest growth direction for a FCC crystal (γphase) which is the crystal structure for Inconel 718 is the ⟨1 0 0⟩ direction [13]. Hence, grain's growth is expected to be along ⟨1 0 0⟩ crystallographic directions. The columnar growth observed in power bed process is not limited to this material. Previous studies on electron beam melted Ti6Al4V parts have also shown similar microstructural features and columnar texture [15,16].

Strong texture will dramatically affect mechanical properties of the final part. One major effect is introduction of anisotropy in mechanical properties [17]. It has been shown that AM parts experience large anisotropic behavior parallel and perpendicular to the direction of build [13,17].

Anisotropic behavior has two underlying microstructural reasons; morphological anisotropy and textural anisotropy. Morphological anisotropy is defined by variation in grain size in different orientations for example, elongated grains. Textural anisotropy, however, is caused by preferred grain orientation.

AM process will result in both of these types. Morphological anisotropy can be removed by a post-built heat treatment process. However, the textural anisotropy cannot be easily removed. In other words, it is difficult to change the preferred crystal orientation after formation. Anisotropic behavior is not necessarily an undesired property. In some cases where a design requires better properties in one orientation, AM anisotropy can be utilized to achieve desirable microstructure.

While a great deal of studies have focused on the effects of process variation on bulk material microstructures on larger scale components, effect of process variation in a single laser pass has received little attention. The research presented in this paper delves into the effect of changing process parameters for a wide range of LED values on grain sizes and orientations within the melt pool and bead regions.

2. Experimental methods

An experiment is designed in which 24 square samples of Inconel 718 with base dimensions of 25.4 mm × 25.4 mm x 4.0 mm were fabricated. Ten scan lines with dimensions of 24.9 mm × 0.09 mm x 0.04 mm as length, width and height respectively were then fabricated onto the surface of each base while systematically altering process parameters. Beam power and scan speed, two of the most influential process parameters, that affect LED value were systematically altered to see their effects on line quality and microstructure. Once fabricated, the specimens were cut into six sections perpendicular to the direction of the scan lines using a gold wire electrical discharge machine (EDM). Fig. 1 shows the dimensions and cross sections after the cutting process. The beads and their melt regions are the areas of interest.

The scanning strategy employed in the fabrication of the base of these parts is seen in Fig. 2. The first track moves from X to -X starting from the back right corner, the second track then moves from −X to X, and the third track moves from X to −X until the base block is completed. All bases were manufactured using a beam power of 285 W, a scan speed of 960 mm/s, a beam diameter of 75 μm, a beam offset of 0.015 mm with a hatch spacing of 0.11 mm in order to achieve consistent base microstructures and good foundations. After the 4 mm thick base is built, the laser scans 10 evenly spaced lines across the top of the surface perpendicular to the base scan directions while changing process parameters on each specimen. This allows for an easy way to distinguish the melt area of the line scans within the already fabricated substrate. The 10 scan lines on the surface of the material were scanned twice with a recoat in between as a result of having set the layer thickness of the build to 20 μm and designing the scan line thicknesses as 40 μm.

A systematic Design of Experiment was conducted according to Table 1; where speed and power were systematically varied. Evaluation of effect of process variability on the final line and melt pool dimensions and defect density are provide in Ref. [14]. The experiment looked into the effect of changing these process parameters on overall line quality and melt pool geometries. Lowest beam powers were unable to provide enough energy to maintain a continuous line. Certain combinations of high beam powers and high scan speeds were unable to keep the line width consistent [14].

3. Material preparation for EBSD

Only experiment runs that showed promise in fabricating defect free accurate samples were selected for EBSD analysis. Selected specimens over a range of LED values are shown in Table 2.

Since microstructural formation is heavily affected by the heat conduction rate and direction and because the geometry of the build affects heat conduction greatly, it is important to take geometry into account. Location of the scan is a geometric parameter that affects heat conduction. The scan lines that are at the center of the build have more uniform heat conduction in all directions, while the scan lines on the side have higher heat conduction in solid region versus powder regions on the sides. This is illustrated in Fig. 3. Therefore, for EBSD analysis, two areas of bead cross-section were taken into consideration; one from four lines in the middle and the other one from one of the three lines at the sides of the sample.

Samples were initially mounted using conductive mold. However, initial use of conductive mount material showed excessive charge build up at the edges of the beads. This was mainly caused

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