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Induced porosity in Super Alloy 718 through the laser additive manufacturing process: Microstructure and mechanical properties

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ABSTRACT

This paper addresses characterization of Super Alloy (Inconel) 718 manufactured through the powder bed fusion (PBF) process. Specimens were fabricated using five different sets of process parameters to induce a range of porosities within the samples. Scanning electron microscopy and micro-computed tomography methods were used to characterize microstructures of these specimens, and mechanical properties were measured using tension, compression, and impact tests. Energy absorption proved to be highly sensitive to density, and stress-strain curves from compression testing were found to behave much like open-cell foams in the presence of high porosity. The similarities with open-cell foams were confirmed with scanning electron microscopy images. Micro-computed tomography scans indicated that the induced porosity was continuous throughout the specimens.

1. Introduction

Additive manufacturing is a rapidly growing technology that can be used to fabricate complex parts in relatively short periods of time. Additive manufacturing technology is particularly useful in the fabrication of prototypes, where it is unreasonable to invest in high tooling costs associated with other manufacturing methods. Additive manufacturing also allows design flexibility and material freedom. This technique can directly create complex structures, including cellular materials, which are not possible with standard manufacturing methods. Furthermore, it enables design optimization which can lead to improved mechanical performance and weight reduction.

Additive manufacturing technology can be used with a wide-range of materials including polymers, metals, and ceramics. The most common methods of metal additive manufacturing are the direct energy deposition and powder bed fusion processes. The direct energy deposition process blows powder into the laser beam, whereas powder bed fusion (PBF) utilizes a bed of fine metallic powder. During the PBF process, a high-power laser scans across the powder surface, melting the particles into a coherent structure. Another layer of powder is then deposited on the solidified surface and the process is repeated.

The PBF process can produce parts with densities that are very close to theoretical density [1–3]. Parameters used in PBF, such as laser power, scanning rate, and hatch spacing influence the microstructure of final parts. These variations in microstructure have been shown to affect the mechanical and even magnetic properties of the final part [4]. PBF can be used with a variety of materials including Ti-6Al-4V, nickel-based, aluminum-based alloys, and Super Alloy 718 [5–9].

There are several process parameters that must be controlled in the PBF process, and key among these are laser power, scan speed, and hatch spacing (the distance between each pass the laser makes). Most mechanical testing literature focuses on components produced with these parameters adjusted for peak properties

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[10–12]. However, not all applications require such properties, and there is significant cost associated with using optimal parameters. As a result, it is highly desirable to determine whether components with sufficient mechanical properties can be manufactured with lower laser powers, higher scan speeds, and larger hatch spacing. Although such adjustments often induce artificial porosity, this can be a benefit as well. Many applications, especially in the transportation sector, require low weight components. By introducing artificial porosity, it may be possible to reduce bulk weight without altering the overall component design.

However, these benefits can only be fully realized if the resultant mechanical properties still meet design requirements. Altering the production parameters can have significant impact on the microstructure of the end product, and therefore influences the overall mechanical properties. Energy density of the laser beam, for instance, controls the amount of energy introduced during the solidification process. Variation of the energy density has been used to modify the density of several alloys, including Super Alloy 718 [13], but the energy density and cooling rate play a key role in the size of the grains in the final solidified part, often resulting in smaller grains compared to casted counterparts [14]. Additionally, energy intensity has shown to affect the degree of oxidation of the solidified material [15].

Along with affecting traditional microstructural features, such as grain size, the energy density can also affect microstructural features unique to additive manufacturing. The use of a lower energy density often results in balling phenomena, where ball-like structures form throughout the internal structure. These ball-like regions are then surrounded by porous regions, which can act as stress concentrators [16].

Likewise, hatch-spacing (the perpendicular distance between each pass of the laser) has a significant impact on the product. The final density and surface quality are especially dependent on this parameter [17]. Hatch spacing is also clearly visible in the microstructure of the final product [18]. Additionally, the scan speed of the laser can have a critical impact on the resultant microstructure. High scan speeds can induce liquation cracking [19] and reduce densification [20].

In this paper we investigate Super Alloy (Inconel) 718 manufactured via the Direct Metal Laser Sintering (DMLS) process. Inconel 718 has been widely used for applications requiring high temperature and corrosion resistance. The objective of this work was to study how the processing induced porosity affects mechanical properties of Inconel 718. Five different sets of process parameters were used to fabricate specimens. Microstructures of these specimens were characterized using scanning electron microscopy and micro-computed tomography methods. Mechanical properties were measured using tension, compression, and drop-weight impact tests.

In this study, porosities were introduced intentionally by adjusting processing parameters. The parameter choices are outside of the range recommended for additive manufacturing of fully dense materials. Such porous materials could be of technological interest. They could be used for structural parts involving regions under lower stresses than the rest of the structure, as porous networks for filtration, or porous bone implants to allow ingrowth of bone tissue into the implant, among other applications [21]. Secondly, the created materials and resulting porous microstructures can provide new insights into the nature of deposition related defects in additively manufactured materials.

2. Materials

The specimens fabricated in this study were composed of Super Alloy 718, a nickel-based super alloy. Specimens were manufactured at the Quad City Manufacturing Laboratory utilizing an EOS M270 DMLS system and powder of particle size 11–44 μm (Carpenter Powder Products, Bridgeville, PA). Five different sets of process parameters were selected to induce formation of porosity within specimens as summarized in Table 1. For all parameter sets, a 20 μm layer thickness was used and each subsequent layer was offset by 67°. Specimens were removed from the build plate by wire electric discharge machining (EDM).

Three different sample geometries were produced: traditional dog-bones for tension testing, right cylinders for compression testing, and un-notched rectangular prisms for impact testing. The samples with the highest density were approximately 98% as dense as Inconel 718 fabricated by traditional methods. Further discussion of sample density measurements is presented in Section 3.2.

3. Methods

All test specimens were submerged in a sonic bath to remove any powder particles that remained from the powder bed fusion process. Samples were individually immersed in an ethanol bath and were sonicated for an hour. The ethanol was replaced every 15 min to remove any remaining powder that had escaped the porous structure of the specimens. The bulk density of each specimen was determined by dividing the mass by the geometric volume (e.g. $Bulk\ Density = Mass/(Length \times Width \times Height)$ for rectangular prism samples). Different test specimens were then used for Scanning Electron Microscopy (SEM), Micro-Computed Tomography (micro-CT), uniaxial tension tests, uniaxial compression tests, and drop-weight impact tests.

3.1. Scanning electron microscopy

Samples selected for SEM imaging underwent no further preparation, and the imaging was performed using a JEOL JSM6060-LV scanning electron microscope. Unpolished surfaces of cylindrical test samples were imaged at magnifications of 90×, 190×, and 300×.

3.2. Micro-computed tomography

Specimens used for micro-computed tomography were cut to dimensions of approximately 5 × 5 × 5 mm^3 using a slow-speed diamond saw. After cutting specimens to the appropriate size, the test specimens were submerged in an ethanol bath for 1 h to remove remaining particles. Micro-CT was employed to image the internal structure of the test specimens. Scans were performed using an Xradia MicroXCT-200 at 4× magnification, providing a resolution of 3.3 μm. After the test specimens were centered on the instrument stage, scans of the samples were taken. A 150 kV, 10 W scan with a 2-s exposure time was obtained 0.5° about the sample. The resulting 721 images were post-processed using the Xradia MicroXCT Reconstructor software. The resulting files were then viewed using XM3DViewer.

MicroCT images were also used to quantify the porosity of the samples. First, the intermodes threshold method [22] provided in the Fiji distribution of ImageJ [23] was applied to convert each cross-section image from gray-scale to binary. The solid area fraction was then extracted from each image and averaged. These averages were taken to be representative of the solid volume fraction, which describes the porosity of the samples. The solid volume fractions were compared with the bulk density measurements to determine density of the solid components which compose the open-cell foam.