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Mechanical behavior of post-processed Inconel 718 manufactured through the electron beam melting process☆

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ABSTRACT

The electron beam melting (EBM) process was used to fabricate Inconel 718. The microstructure and tensile properties were characterized in both the as-fabricated and post-processed state transverse (T-orientation) and longitudinal (L-orientation) to the build direction. Post-processing involved both a hot isostatic pressing (HIP) and solution treatment and aging (STA) to homogenize the microstructure. In the as-fabricated state, EBM Inconel 718 exhibits a spatially dependent microstructure that is a function of build height. Spanning the last few layers is a cored dendritic structure comprised of the products (carbides and Laves phase) predicted under equilibrium solidification conditions. With increasing distance from the build's top surface, the cored dendritic structure becomes increasingly homogeneous with complete dissolution of the secondary dendrite arms. Further, temporal phase kinetics are observed to lead to the dissolution of the strengthening γ'' and precipitation of networks of fine δ needles that span the grains. Microstructurally, post-processing resulted in dissolution of the δ networks and homogeneous precipitation of γ'' throughout the height of the build. In the as-fabricated state, the monotonic tensile behavior exhibits a height sensitivity within the T-orientation at both 20 and 650 °C. Along the L-orientation, the tensile behavior exhibits strength values comparable to the reference wrought material in the fully heat-treated state. After post-processing, the yield strength, ultimate strength, and elongation at failure for the EBM Inconel 718 were observed to have beneficially increased compared to the as-fabricated material. Further, as a result of post-processing the spatial variance of the ultimate yield strength and elongation at failure within the transverse direction decreased by 4 and 3× respectively.

1. Introduction

Inconel 718 is the most widely used nickel-base (Ni-base) superalloy by the aerospace community despite being first developed in the 1960s [12]. The usage of Inconel 718 can be directly attributed to the excellent mechanical properties and corrosion resistance at temperatures up to 650 °C [34]. The strength exhibited by Inconel 718 directly related to the precipitation and size of the strengthening γ''. However, due to the metastable nature of the primary strengthening phase (γ'') in the alloy and ability for undesirable phases to form, heat-treatment (HT) of Inconel 718 can be difficult [52]. Further, heat-treatment of Inconel 718 is generally optimized for the intended material/component environment or service conditions [2].

Due to Inconel 718's workhorse status, there exists much interest in fabricating high temperature service components through additive manufacturing (AM) processes due to the large degree of design flexibility offered by the technology. Inconel 718 has been processed by selective laser melting (SLM), electron beam melting (EBM), and laser engineering net shaping (LENS) [6–10]. However, due to AM being an emerging family of technologies, the degree to which AM processing conditions (high solidification rates, high thermal gradients) effect the materials is not widely understood. Further, relatively few studies have reported the effects of post-processing on AM fabricated Inconel 718 and the associated impacts on the microstructure and mechanical properties of the material [7,8,11,12].

In the present study, Inconel 718 is fabricated by EBM. Characterized is the microstructure and mechanical properties of the EBM Inconel 718 in the as-fabricated state and after undergoing a

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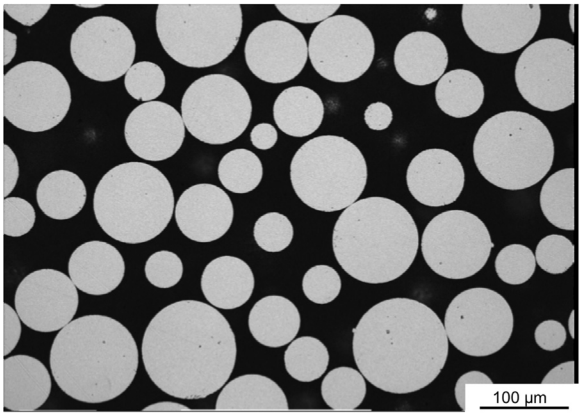

Fig. 1. SEM micrograph AP & C Inconel 718 powder used in this study.

combined hot isostatic pressure (HIP) and solution and aging treatment. Ultimately, the intent of this study is to provide further insight into the behavior of AM processed high temperature alloys and the manners through which their properties can be enhanced.

2. Experimental procedure and methods

The feedstock material was plasma wire atomized Inconel 718 manufactured by Advanced Powders and Coatings (Quebec, Canada). The powder feedstock was comprised of particles with a size distribution of 40–120 µm (−100 + 325 mesh). Further particles were highly spherical and contained minimal internal porosity as illustrated in Fig. 1. The nominal chemical composition is given in Table 1.

An Arcam A2X EBM machine was used to additively build a series of prismatic blocks (100×100×20 mm) and cylinders (⌀15 × 100 mm) with a diameter of 15 mm and height of 100 mm as shown in Fig. 2. The start plate used was a 150×150×10 mm, 304 L stainless steel start plate. The A2X was equipped with EBM Control V4.1 controls software. Within EBM Control, the prismatic geometries were loaded as a group rather than independent pieces while a raster scan pattern was used by the beam to melt. Within the Arcam software, beam velocity and current are a function of line scan length and speed function [13]. In the present work, a speed function of 63 was used. With the advance of each layer the control algorithm rotated the scan direction by 90°. The build began once a preheat temperature of 975 °C was achieved. The electron gun accelerating voltage was set to 60 kV. For the build, a layer thickness of 75 µm was used.

After completion of the build, half of the samples were given a two-step post-processing treatment comprised of hot isostatic pressing (HIP) and solution treatment and aging (STA). The material was HIP'd at a temperature of 1200 °C and 100 MPa for 240 min. The following STA was given to the EBM material: solutioning at 1066 °C for 60 min, followed by a double aging at 760 °C for 10 h, and subsequent cool-down and aging at 650 °C for 10 h. These STA conditions were chosen to be similar to those traditionally processed Inconel 718 are given [14].

Illustrated in Fig. 3 is the association of the terminology transverse orientation (T-orientation) and longitudinal orientation (L-orientation) in relation to the build direction. Specimens for monotonic tensile testing were machined from the prismatic blocks transverse to the build direction. From each block, five specimen blanks were removed

Table 1
Nominal chemical compositions of the Inconel 718 powder used in this work given as weight percent.

Cr	Fe	Nb	Mo	Ti	Cu	Al	C	Ni
18.5	18.5	5	3	1	0.15	0.5	0.05	Bal

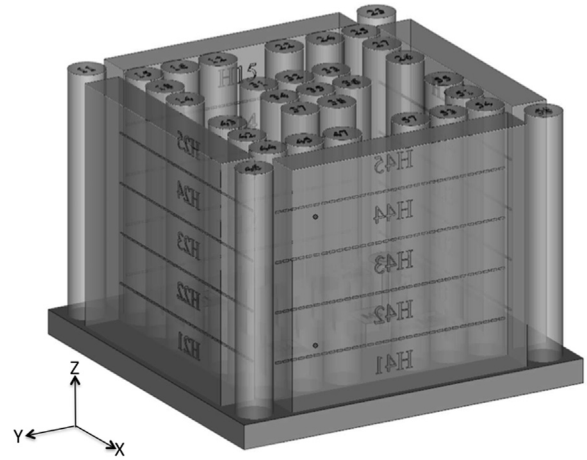

Fig. 2. Computer generated representation of build fabricated in this work.

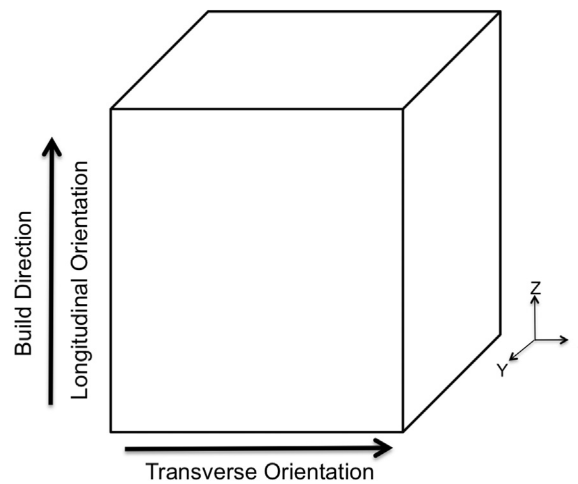

Fig. 3. Schematic depicting the orientation relationship between the build direction and the longitudinal and transverse material orientations.

with a center-to-center spacing of 15 mm. A single specimen was taken aligned longitudinal to the direction of the build from each of the cylinders. The specimens were machined into a cylindrical dogbone geometry with a gauge diameter of 5.6 mm and gage length of 42 mm. Monotonic tensile experiments were conducted according to ASTM E8-13a for room temperature testing and ASTM E21-09 for testing at 650 °C [15,16]. In all cases, the tensile experiments were done in open air conditions and at a strain rate of 0.005 $\frac{1}{min}$. High temperature tensile experiments were conducted using a Mayes elevated temperature extensometer (Model: R3/8 Block 2) on a Instron load frame equipped with a 250 kN load cell. Room temperature testing was conducted using an Instron 5582 load frame equipped with a 100 kN load cell and a Instron model 2620 extensometer.

Samples were sectioned using an Allied High Tech TECHCUT 5 and mounted in KonductoMet using a Buehler SimpliMet XPS1. The mounted samples were metallographically prepared using successively finer silica carbide grinding paper and given a final polish with 1 µm diamond on an Allied High Tech MetPrep 4. Chemical etching via submersion using a mixture of HCL, acetic acid, and HNO_3 (1:1:1) was used to reveal the microstructure. Microscopy was conducted using a Leica DM4000M optical microscope and a Hitachi S4800 field emission scanning electron microscope. Electron back scatter detection (EBSD) was done using a JEOL 6500 field emission scanning electron microscope equipped with a EDAX Hikari EBSD camera.