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Relating porosity to fatigue failure in additively manufactured alloy 718

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ABSTRACT

Additive manufacturing (AM) has the potential to revolutionize the way parts are designed and manufactured; however, AM also produces defects that influence the performance of the components. In order to ensure the quality of the manufactured parts, the processing-structure-property-performance (PSPP) relationship must be understood. In this study, the porosity created during the AM process is investigated, and its influence on performance is quantified with respect to the PSPP framework. Test specimens were fabricated with different processing pedigrees, and the porosity populations within each specimen was characterized. The fatigue life of the specimen was predicted based on the size and location of porosity using a fatigue crack growth approach. Results show that the fatigue life can be successfully predicted, when the appropriate crack growth behavior is used. The insight gained in this study will inform future AM fatigue studies and will lay the groundwork for design and qualification of fracture-critical AM components.

1. Introduction

The versatility of AM processes allows for re-evaluation of current practices to produce cutting edge, weight-reducing designs while reducing costs and material waste. Although the benefits of AM make it attractive to the defense and aerospace industries for maintenance, sustainment, and innovation both in deployed and domestic environments [1], there are many complex facets that need to be addressed before AM may be considered a viable manufacturing process for fracture-critical components. Critical structures in turbine engines experience cyclic stresses because of aero-driven vibration, blade rubs, and rotordynamic phenomena. Therefore, qualification techniques and rejection criteria must be developed to fully characterize failure-inducing material defects in AM components before they may be leveraged in fracture-critical applications. Additionally, the model for the relationship between processing, structure, properties and performance (PSPP) must be developed to efficiently facilitate best practices for consistent AM components.

Many studies have shown that material properties of AM materials differ significantly from wrought materials [2], and AM components may exhibit notable scatter due to the large number of variables that influence the PSPP outcomes [3]. It is well known that the processing of an AM material from raw powder to final heat treatment dictates the material performance in a given application [4,5]. The thermal history of an AM component has bearing on a wide range of material characteristics including microstructure [6–8], residual stress [9], and porosity [10,11]. Porosity is known to dictate fatigue performance in many traditional materials. In casting, micro-porosity and shrinkage porosity were shown to act as stress concentrators which lead to crack initiation and failure [12,13], and quantification of porosity distributions was shown to provide sufficient information to predict component life using statistical methods [14,15]. Similarities in porosity observed in both casting and AM materials indicate that historical methods may be used to characterize the porosity content in AM components.

Primary processing parameters (PPP) such as, but not limited to, beam power, raster speed, and hatch spacing have been varied to explore the mechanism for developing porosity in AM. It has been shown that different types of porosity are developed by manipulating these PPPs, and that controlling the quantity, size, and morphology of porosity populations can be achieved [10]. This work utilizes four PPPs (power, speed, hatch spacing, and layer thickness) and multiple scan strategies that are known to influence porosity content, and explores the PPP space to further develop the understanding of the PSPP framework in relation to fatigue life of AM components. The parameters are varied to obtain various porosity distributions and the porosity is subsequently related to the fatigue life.

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Nomenclature

PSPP	Processing, Structure, Properties, Performance
PPP	Primary Processing Parameter
CL	Concept Laser
CM	Continuous Meander Scan Strategy
SM	Stripped Meander Scan Strategy
IM	Island Meander Scan Strategy
EDM	Electron Discharge Machine
C	Crack growth constant
n	Crack growth constant
Y	Stress intensity shape factor
a_1	Initial crack length
a_2	Final crack length
a_c	Critical crack length
$\Delta\sigma$	Peak to peak stress amplitude
R	Load Ratio

2. Materials and methods

This paper brings together data from two different experiments that will provide further insight into the PSPP model for AM materials from different material and processing pedigrees. In the first experiment, three scanning strategies (SS) were used, and in the second experiment, three PPP settings were used to explore the effect of processing changes on the formation of porosity. In both of these experiments, the internal porosity was measured using computed tomography (CT), and predictions were made based on these observations and the application of crack growth theory. The CT measurements were obtained using a North Star Imaging X-View X-50 machine. A summary of the experimental design is provided in Table 1 where A,B, and C denote the three SS and PPP settings for their respective experiment.

2.1. Experiment 1: Scan strategies

The components produced for the SS study were manufactured using a Concept Laser™ (CL) M2 Cusing laser powder bed fusion machine. Alloy 718 powder was used to construct five rectangular bars on a 316 L stainless steel plate. Three different scan strategies were used including Continuous Meander (CM), Striped Meander (SM), and Island Meander (IM).

In CM, the beam scans across the entire part in a continuous raster while in SM, a strip of width 5 mm creates multiple raster patterns across the width of the part. In IM, 5 mm squares are melted at random across the entire component cross-section. For each powder layer, CM and IM undergo a 1 mm layer shift and a 90 degree layer rotation. CL's layer exposure technique also incorporates a skin and core strategy where the skin and core regions are exposed differently. The skin is exposed every layer under one PPP setting, and the core is exposed every other layer under a different PPP setting. The core material controls the fatigue performance of the component because the skin material is machined off, but it must be noted that the 50 µm noted in Table 1 is actually two 25 µm layers of powder that have been deposited on top of each other and subsequently exposed.

For this experiment, the core beam settings, power, speed, hatch spacing, and laser spot size, were held constant for each component as shown in Table 1. The components were stress relieved on the plate according to ASTM F3055 [16], wire electron discharge machined (EDM) from the plate, and solution annealed and aged according to AMS 2774 [17]. Each component was machined into a round fatigue bar within the ASTM E466 standard [18], low stress ground to final dimensions, and electro-polished to a mirror finish. The machining removed the entire skin region in the gage section and left the core material for testing. The gage section of each specimen underwent CT measurements with a 14 µm/voxel resolution, and the ImageJ (v. 1.5 H) software package [19] was used to process these images and to measure the observed pores.

2.2. Experiment 2: Primary processing parameters

The second experiment was performed using an EOS M290 laser powder bed fusion machine. Alloy 718 powder was used to construct eight rectangular bars on a 316 L stainless steel plate. This experiment was to develop a relationship between PPPs (power, speed, hatch), porosity content, and resulting fatigue life of AM components. Three different PPP combinations (see Table 1) were specified. For this experiment the stripes scan strategy was used for all bars and the beam settings were modified. The porosity in the gage section was measured using CT, and the images were analyzed via ImageJ using the same procedure as the Scan Strategy Experiment.

2.3. Raw material and processing

Two different powder pedigrees were used for the two experiments. The powder used in the scan strategy study had been reused approximately 10 times at the time of the build while the powder used in the PPP study had been lightly reused (< 5 times). The powder morphology for both batches was observed in a NanoScience Phenom Pro scanning electron microscope. Irregularly shaped powder particles with multiple satellites were observed in both powder batches (Fig. 1). Diligent sieving procedures and enclosed powder hoppers ensured that large powder particles were removed and the contamination level was kept low for both batches.

Post process chemistry analyses were performed for five samples from both experiments, and the chemical composition for each of those specimens was determined using wet chemical analysis (Table 2). A representative specimen for PPP-A was not available for chemical testing at the time of the procedure, so this measurement was omitted from consideration. The chemistry of the components for each experiment were found to be within the specifications for alloy 718. Due to the consistency of the chemical composition for each of the tested components, it is assumed that the PPP-A's chemistry is consistent with the other components.

Table 1
Overview of experiment.

Machine	Concept laser M2 cusing			EOS M290		
Setting name	SS-A	SS-B	SS-C	PPP-A	PPP-B	PPP-C
Power	370 W			285 W		
Velocity	700 mm/s			1000 mm/s	1150 mm/s	1400 mm/s
Hatch Spacing	0.13 mm			0.120 mm	0.110 mm	0.055 mm
Layer Thickness	0.050 mm			0.020 mm		
Scan Strategy	Continuous	CL Stripped	Island	EOS Striped		

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