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Influence of defects and as-built surface roughness on fatigue properties of additively manufactured Alloy 718

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ABSTRACT

Electron beam melting (EBM) and Selective Laser Melting (SLM) are powder bed based additive manufacturing (AM) processes. These, relatively new, processes offer advantages such as near net shaping, manufacturing complex geometries with a design space that was previously not accessible with conventional manufacturing processes, part consolidation to reduce number of assemblies, shorter time to market etc. The aerospace and gas turbine industries have shown interest in the EBM and the SLM processes to enable topology-optimized designs, parts with lattice structures and part consolidation. However, to realize such advantages, factors affecting the mechanical properties must be well understood – especially the fatigue properties. In the context of fatigue performance, apart from the effect of different phases in the material, the effect of defects in terms of both the amount and distribution and the effect of "rough" as-built surface must be studied in detail. Fatigue properties of Alloy 718, a Ni-Fe based superalloy widely used in the aerospace engines is investigated in this study. Four point bending fatigue tests have been performed at 20 Hz in room temperature at different stress ranges to compare the performance of the EBM and the SLM material to the wrought material. The experiment aims to assess the differences in fatigue properties between the two powder bed AM processes as well as assess the effect of two post-treatment methods namely – machining and hot isostatic pressing (HIP). Fractography and metallography have been performed to explain the observed properties. Both HIPing and machining improve the fatigue performance; however, a large scatter is observed for machined specimens. Fatigue properties of SLM material approach that of wrought material while in EBM material defects severely affect the fatigue life.

1. Introduction

Additive manufacturing (AM), which is a relatively new manufacturing technology, offers the possibility of manufacturing complex geometries, part integration and has even relatively eased the processing of some difficult to process materials. Some commercial products, particularly aerospace engine components, have already capitalized these possibilities offered by AM such as the fuel nozzle in the LEAP engine (complex design) [1], injection head of Ariane propulsion module (part integration) [2] and titanium aluminide (TiAl) low-pressure turbine (LPT) blades (difficult to process material) [3]. Aerospace industry is, however, known to be conservative and even though AM has gained high interest, extensive research into characterization of material properties, non-destructive inspection, process control etc. would be necessary to mature the AM technology to produce *critical high-value* components [4].

In powder bed AM, parts are built in a layer-by-layer fashion based on digitally sliced CAD data. The sequence of build operations are as follows:

1. spreading of powder, which has a certain size distribution, as a layer of predefined thickness,
2. melting the geometry on the powder layer corresponding to the slice data,
3. lowering the build table corresponding to the layer thickness and repetition of the sequence until the entire part height is built.

Though the basic idea of building is similar, the two processes have some differences as well. The heat source in the EBM process is an electron beam while it is a laser beam in the SLM process. The EBM process is carried out in a controlled vacuum environment at a high bed temperature and the powder layers are pre-sintered before the melting begins; in SLM, however, the powder bed is maintained at a lower temperature and the build chamber is filled with argon gas. The powder

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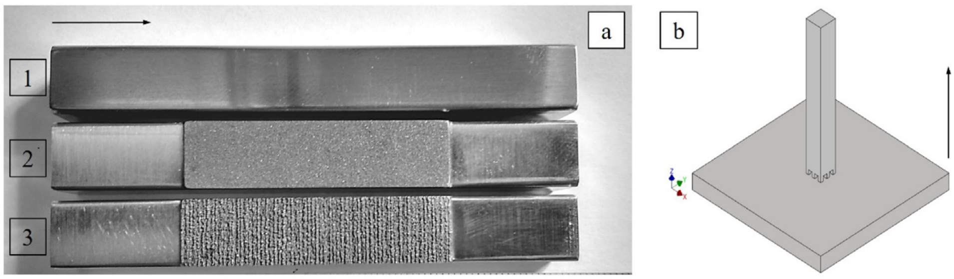

Fig. 1. (a) Photograph of the bending fatigue specimens in different surface conditions. 1: machined specimen, 2: as-built SLM specimen, 3: as-built EBM specimen. (b) Schematic image of one of the bars on a build plate. Arrows in the images indicate the build direction.

utilized in the SLM process is finer compared to the EBM process. While the EBM process produces parts with less residual stress in the as-built condition, the SLM process has relatively better roughness on the as-built surface.

One of the major advantages offered by powder bed AM processes is the complexity of geometries that can be produced, which could be expensive or sometimes impossible to manufacture by conventional methods. However, the as-built surface is rough and could negatively affect the fatigue properties. Machining or other methods of surface finishing of complex shapes could be difficult, expensive or impossible; but scaling down the complexity to ease such post-processing would undermine the geometric capabilities of the technology. Therefore, it is important to investigate the effect of the as-built rough surface on the mechanical properties. For characterization of the roughness, numerous techniques such as metallography, µCT, contact and non-contact roughness measurement methods have been investigated; in general, it is observed that the stylus profilometry is not suitable and that the areal methods are better suited for the purpose [5,6].

There are numerous process parameters that control the energy input for melting the powder such as beam power, spot size, distance between adjacent melt lines, beam path etc. A variety of strategies to control beam path during melting of a layer are available; these, so called, *scan strategies* also influence the microstructure [7], residual stress distribution [8] and the defect distribution [9] in the built parts. Hot isostatic pressing (HIP) has been evaluated to minimize defects from the AM process; however, remnant pores after HIP [10] and re-growth of pores during subsequent heat treatment of that were formerly closed by HIP [11,12] have been reported.

The effect of as-built surfaces and defects on fatigue properties have been investigated by a number of investigators for the AM built aerospace alloy Ti-64 [13–17]; effect of surface roughness on fatigue properties [15], effect of the surface roughness in presence of geometric notches [13] and effect of surface finishing methods on fatigue [14,17] have been investigated. An approach to use micro computed tomography (µCT) to characterize the as-built surface and use stress concentration factors to quantify the effect of surface roughness has also been attempted [16]. Such studies for Alloy 718, however, are quite limited [18]; in fact, there are only a few investigations related to fatigue of Alloy 718 produced by powder bed AM processes [19–21]. Fatigue properties of SLM built material has been investigated by conducting low cycle fatigue tests at room temperature [20] and by high cycle fatigue tests at 650 °C [21]. Similarly, low cycle fatigues testing at 650 °C has been performed on EBM built material.

Fatigue has contributed to failure of 55% of components in aerospace and is expected to remain a major concern for metallic parts [4]. In the context of application of metal AM parts in aerospace, understanding the effect of defect distribution and the as-built surface roughness on fatigue properties is crucial. The aim of this work, therefore, is to study the effect of defects and the as-built surface on high cycle fatigue properties of EBM and SLM built Alloy 718 material at room temperature. For the sake of brevity, the effect of microstructural features will be reported separately and the discussion in this paper is limited to the defects and the as-built surface.

2. Materials and methods

2.1. Test specimens

Test specimens were built in Alloy 718 using both EBM and SLM methods. EBM specimens were built in an Arcam A2X machine with powder having a size range of 40–105 µm. The standard Arcam parameters for building Alloy 718 and 75 µm layer thickness were utilized. SLM specimens were built in an EOS M290 machine with powder, which had an average size 40 µm, and nominal size less than 65 µm; standard EOS parameters for Alloy 718 and 40 µm layer thickness were used. The respective equipment manufacturer supplied the powder for each of the processes.

Following the build completion and powder recovery by recommended protocols, specimens were cut off from the base plates. No stress relief treatment was performed before cutting off the specimens. One batch of specimens from both EBM and SLM were HIP:ed in a Quintus QIH21 HIP furnace at 1200 °C and 1200 bar for 4 h followed by uniform rapid quenching (URQ). All the specimens, including the ones that were not HIP:ed, were heat treated in accordance to AMS 5664 in a vacuum furnace: solutioning treatment at 1066 °C for 1 h followed by a two-step ageing at 760 °C for 10 h, cooling to 649 °C at 55 °C/hour and held at 649 °C for 8 h.

The specimens were machined to a dimension of 10 mm by 10 mm square cross section and 80 mm length and the radii rounded off to 0.75 mm. The as-built specimens had 40 mm, in the mid-section, left without machining on one of the four sides. The as-built surfaces were perpendicular to the building direction for both EBM and SLM. All the machined surfaces were finished to R_a of 0.2 µm by low stress grinding. Specimens with different surface conditions are shown in Fig. 1. The types of specimens w.r.t. processes, heat treatments and surface conditions utilized in this project are summarized in Table 1. Due to constraints in building all the SLM specimens in a single build, 20 SLM specimens were taken from one build and 4 specimens from another build; all EBM specimens were from a single build.

Table 1
Specimens in different combination of test factors utilized in the project.

Process	Heat treatment	Surface	No of specimens
EBM	HIP + HT	Machined	9
EBM	HIP + HT	As-built	9
EBM	HT	Machined	9
EBM	HT	As-built	9
SLM	HIP + HT	Machined	6
SLM	HIP + HT	As-built	6
SLM	HT	Machined	6
SLM	HT	As-built	6