EFFECT OF BUILD ORIENTATION ON FATIGUE PERFORMANCE OF TI-6AL-4V PARTS FABRICATED VIA LASER-BASED POWDER BED FUSION

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Abstract

The effects of build orientation on the fatigue behavior of additively-manufactured Ti-6Al-4V using a Laser-Based Power Bed Fusion (L-PBF) process is investigated. Ti-6Al-4V rods were manufactured in vertical, horizontal, and 45° angle orientations. The specimens were then machined and polished along the gage section in order to reduce the effects of surface roughness on fatigue behavior. Fully-reversed strain-controlled uniaxial fatigue tests were performed at various strain amplitudes with frequencies adjusted to maintain an average constant strain rate throughout testing. Results indicate slight variation in fatigue behavior of specimens fabricated in the different orientations investigated. Fractography was conducted using scanning electron microscopy after mechanical testing in order to investigate the crack initiation sites and determine the defect responsible for the failure. The experimental program utilized and results obtained will be presented and discussed.

Keywords: Fatigue, Fractography, Build Orientation, Additive Manufacturing, Ti-6Al-4V

Introduction

Additive manufacturing (AM) is a promising avenue of part fabrication due to the ability to fabricate parts in a layer by layer fashion and to create geometries difficult or impossible to achieve by traditional subtractive methods. There are two broad categories of laser-based additive manufacturing: Laser-powder bed fusion (L-PBF) and direct laser deposition (DLD) [1]. L-PBF processes, such as selective laser melting (SLM), involve the deposition of thin layers of metallic powder over a build substrate, with a laser moving in a predetermined pattern in order to create a layer. After this occurs, the substrate is incremented down, and the process repeats until the part is fully formed.

Layer orientation has been shown to significantly affect the fatigue properties of additively-manufactured materials [2]. Fatigue testing of L-PBF stainless steel 316L by Shrestha et al. [3] showed that specimens fabricated in a diagonal orientation displayed lower fatigue lives than those fabricated in the vertical direction, which in turn exhibited lower fatigue lives than horizontally fabricated specimens. Previous study by Yadollahi et al. [4] has shown that the layer orientation of 17-4 PH steel parts produced using L-PBF can have an effect on the tensile and mechanical properties of the part. It was found that specimens printed horizontally had better fatigue properties and more elongation to failure than vertically built specimens did. The relative orientation of defects with respect to the loading direction lead to variation in the size of the projection of the void onto the plane perpendicular to the applied load. As the size of these projections increased, the resultant stress concentration also increased, resulting in lower fatigue strength of the specimens [4].

Results from Edwards and Ramulu have shown that this is true in Ti-6Al-4V as well, with specimens machined horizontally from L-PBF fabricated Ti-6Al-4V displaying longer fatigue lives than the vertically machined specimens [5]. In another study of Ti-6Al-4V fabricated via SLM [6], specimens printed vertically had better fatigue performance than cast and annealed Ti-6Al-4V. The SLM Ti-6Al-4V also possessed higher yield stress and ultimate tensile strength as compared to published values in the ASM Handbook. This improved fatigue performance was attributed to the presence of fine lamellar structures and acicular microstructure in the SLM Ti-6Al-4V [6]. Other studies attributed the difference in fatigue properties between different build orientations to orientation of prior-β boundaries [7]. Porosity is also a major contributing factor to the fatigue strength of L-PBF [8-10], with porosity drastically reducing high cycle fatigue life [8] and porosity caused by insufficient energy input (i.e. lack of fusion) during SLM fabrication having a much greater impact on mechanical behavior than porosity caused by super-optimum energy input [9]. Therefore, the relative orientation of pores with respect to the loading direction may cause anisotropy in mechanical and fatigue performance of additively-manufactured parts.

In this study, the effects of the build orientation on the fatigue properties of L-PBF Ti-6Al-4V is investigated. Using an EOS M290, rod stock was fabricated in three batches of different orientations: horizontal, vertical, and 45° with respect to the build plate. This rod stock was then machined into fatigue specimens and subjected to fatigue testing, with fractographic analysis following failure. Finally, conclusions were drawn based upon these results.

Experimental Setup

For the testing conducted in this study, 30 total specimens were fabricated. Three batches of ten L-PBF rods were fabricated with a batch each in the vertical, horizontal, and 45° orientation (i.e. diagonal). All specimens were fabricated using an EOS M290 machine, gas atomized Ti-6Al-4V powder supplied by LPW Technology Inc. (particle size 15 µm - 45 µm), and the default performance Ti-6Al-4V process parameters provided by the equipment manufacturer. Default support structures of 3 mm were used for each specimen in order to facilitate easy removal from the building substrate.

After fabrication, the specimens were subjected to an annealing process consisting of a one-hour soak at 700°C in an argon atmosphere, followed by cooling to room temperature via free convection with the hope of removing any residual stresses from the fabrication process. After annealing, the specimens were removed from the substrate and machined into round fatigue specimens with straight gage sections of 15 mm length and 3.75 mm diameter, compliant with ASTM standard E606 [11]. Once the machining was completed, the surfaces were polished with progressively finer grits of sandpaper in order to reduce the surface roughness in the gage section.

The specimens were then subjected to fully-reversed, strain-controlled uniaxial fatigue testing, ranging from 0.004 to 0.01 mm/mm, conducted using an MTS Landmark servohydraulic test system with 100 kN load cells. Test frequencies were adjusted to maintain an average constant strain rate among all tests. An MTS Extensometer was used in order to measure and control the strain applied to the specimens. Acrylic was applied to the gage section in order to prevent slippage of the extensometer and prevent scratching of the specimen surface. Fracture surfaces of failed specimens were investigated via field emission gun scanning electron microscope (FEG-SEM) in order to determine the crack initiation sites and crack growth behavior, as well as to document any porosity or lack of fusion areas on these fracture surfaces.

Experimental Results and Discussion

Fatigue Behavior

Strain-life curves derived from the fatigue data collected during the strain-controlled testing of the L-PBF Ti-6Al-4V specimens are presented in Figure 1. As can be seen from the figure, the specimens possessed similar average fatigue lives regardless of build orientation. Therefore, the build orientation appears to have not had a significant impact on the fatigue responses of the specimens fabricated using EOS M290. While this is in disagreement with the study by Edwards and Ramulu, in which it was found that build orientation did have a noticeable effect on the fatigue performance of SLM Ti-6Al-4V [5], the samples used in their study contained much more porosity than those fabricated and tested in this study. This difference in porosity could account for the difference in findings, as the porosity contained within SLM specimens has been shown to affect fatigue life [4, 8-10].

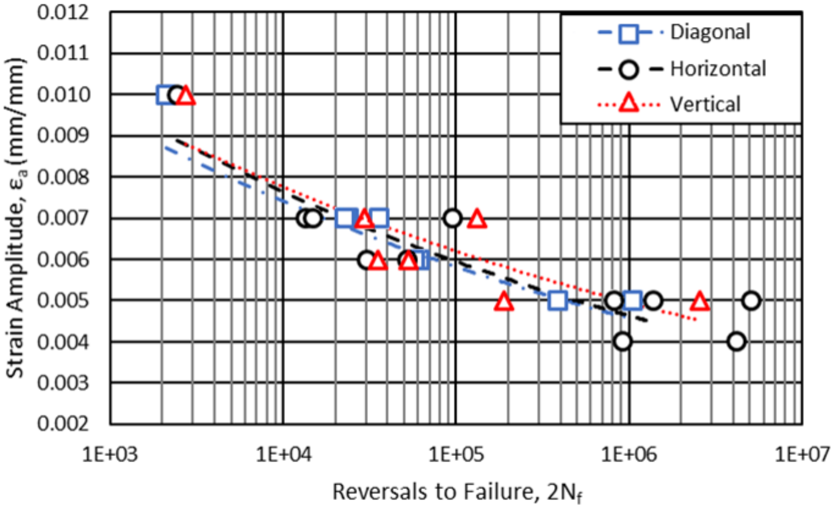

Figure 1. Comparison of strain-life fatigue behavior for diagonal, horizontal, and vertical L-PBF Ti-6Al-4V specimens.

The lower levels of porosity contained within the specimens in this study led to less pore orientation effect, resulting in a lessening of the impact build orientation can possibly have on fatigue life. While there were no runout tests, specimens in lower strain amplitudes did exhibit fatigue lives of greater than 2,000,000 reversals. There is generally less scatter in the low cycle regime as opposed to the high cycle regime for all orientations; this is due to the greater effect of porosity in the high cycle regime [12]. The diagonal specimens had the least amount of scatter of the tested specimens.

Fractography

After the fatigue testing was completed, fractography was conducted on the fracture surfaces. Very little porosity was found during the fractographic investigation, with the porosity that was seen on the fracture surfaces serving as the crack initiation site. Inspection of the fracture surfaces showed that the cracks generally initiated at either pores or lack of fusion areas. Pores had smooth surfaces, usually with either spherical or ovoid geometries. Lack of fusion areas ranged in size from small to large enough to be visible without the aid of a microscope, and had a smooth surface on one side of the fracture surface and a rough, powder covered surface on the sibling fracture surface. These smooth and rough surfaces of the lack of fusion area were on the top and bottom, respectively, during the fabrication process.

Figure 2 shows a representative fracture surface and crack initiation site for the vertical specimens. These surfaces exhibited crack initiation at a subsurface pore and evidence of crack propagation, with clear final fracture and ductile shear in the overload area. While the horizontal specimen fracture surfaces displayed similar properties, as seen in Figure 3, the fracture surface was smoother than that of the vertical specimens. This could be due to the pore that served as the crack initiation site in the horizontal specimen; it was larger than the pore seen in Figure 2 (83 µm versus 12 µm), it was also more uniformly shaped and much further away from the surface of the specimen. This could have lessened the severity of the pore's influence, allowing for longer crack propagation in horizontal specimens. Fracture surfaces of the diagonal specimens, shown in Figure 4, exhibited much less crack propagation and rougher fracture surfaces as compared to the vertical and horizontal specimens.

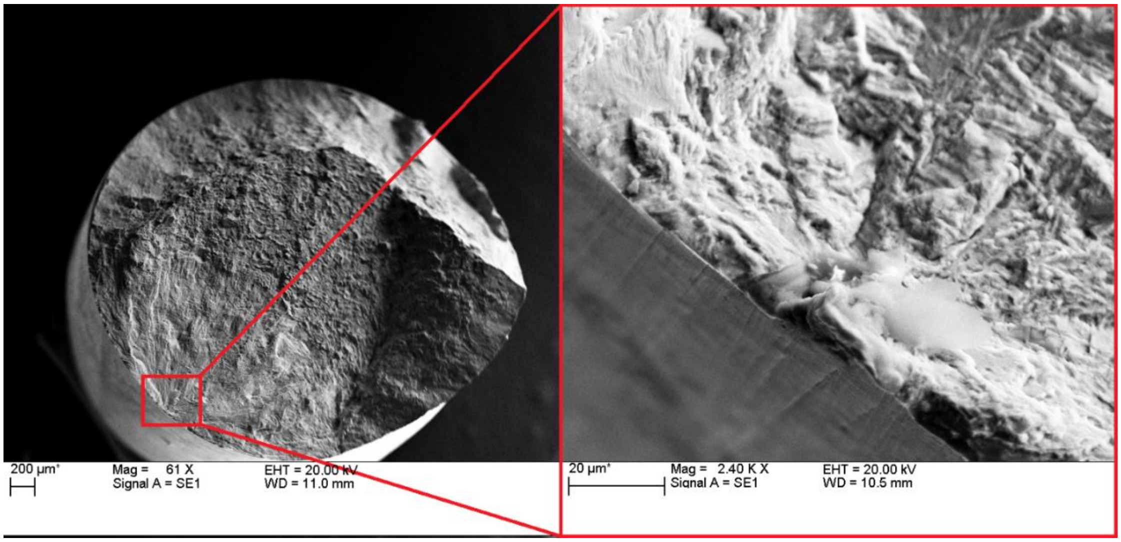

Figure 2. Overview and crack initiation site of a vertical L-PBF Ti-6Al-4V specimen.

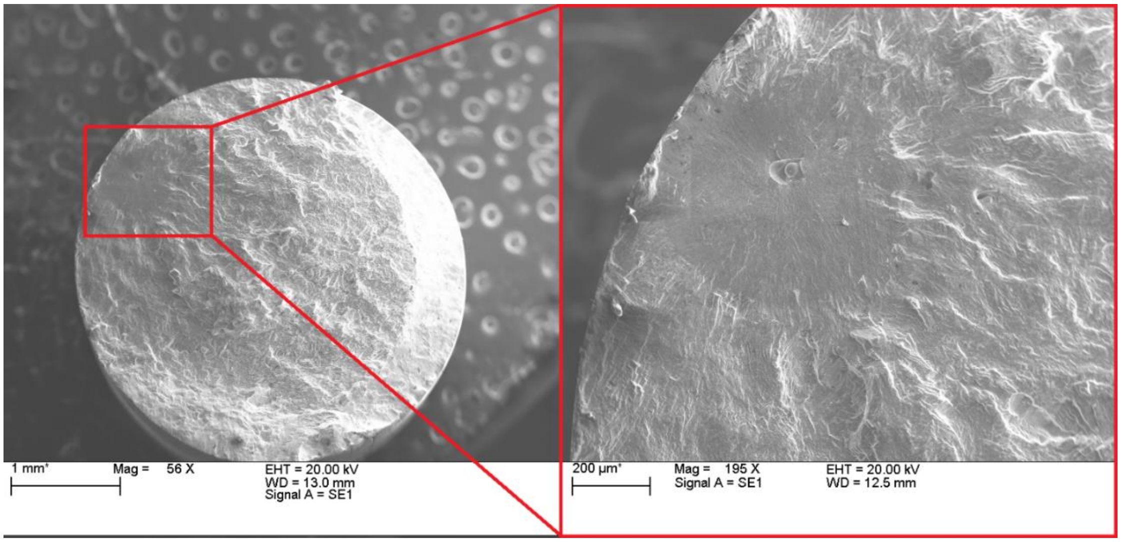

Figure 3. Overview and crack initiation site of a horizontal L-PBF Ti-6Al-4V specimen.

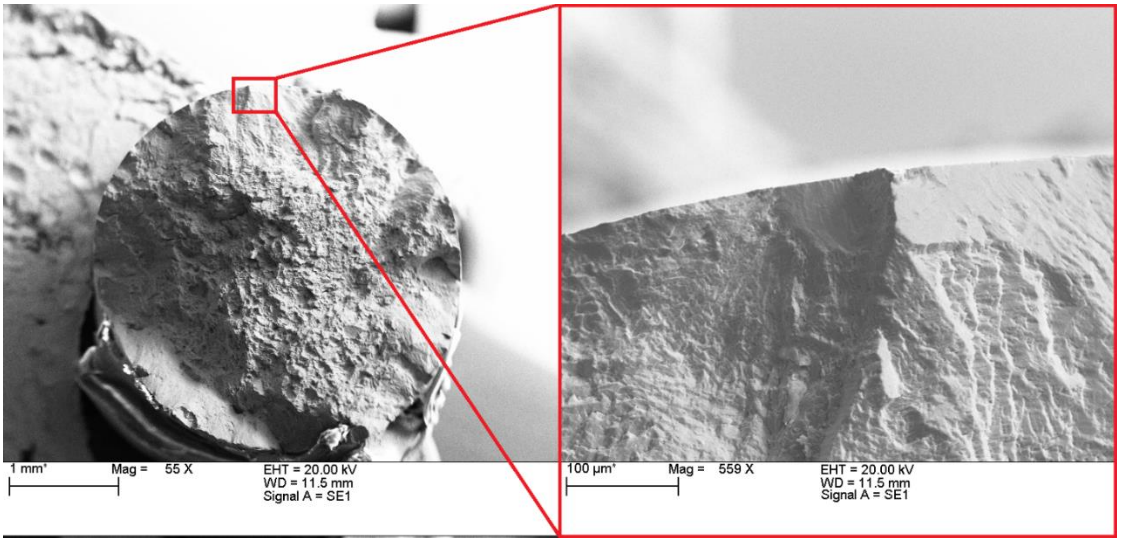

Figure 4. Overview and crack initiation site of a diagonal L-PBF Ti-6Al-4V specimen.

Conclusions

The goal of this study was to quantify the effects of build orientation on the fatigue performance of L-PBF produced Ti-6Al-4V. In order to accomplish this, fully-reversed, strain-controlled fatigue testing was conducted on specimens machined from rod stock printed in the vertical, horizontal, and 45° angle (i.e. diagonal) orientations using an EOS M290 machine. After testing, fractography was conducted on the resultant fracture surfaces. The following conclusions can be made based upon the results:

1. Layer orientation did not have a significant effect on the fatigue response of the L-PBF Ti-6Al-4V, with all specimens displaying nearly identical fatigue properties. This could be due to the low levels of porosity observed in these specimens.

2. There were no runout tests. While specimens tested at lower strain amplitudes did exhibit fatigue lives greater than 2,000,000 reversals, the tests did fail eventually.
3. Cracks were observed to initiate at pores or lack of fusion areas just below the surface in all specimens.
4. While there was little difference in the fatigue behavior of the specimens and crack initiation sites, the fracture surfaces were radically different, with varying levels of roughness and crack propagation.

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