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Reviewed Paper

Comparison of Rotating-Bending and Axial Fatigue Behaviors of LB-PBF 316L Stainless Steel

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Abstract

Additive manufactured (AM) materials are prone to internal defects such as entrapped gas pores and lack of fusions along with having a rough surface. There are different types of fatigue tests that are used to characterize the effects of such defects on the structural integrity of AM parts. The present study aims to investigate the effect of stress gradient on the fatigue behavior of 316L stainless steel (SS), fabricated using a laser beam powder bed fusion (LB-PBF) process. Axial fatigue tests are performed on as-built (non-machined) LB-PBF 316LSS round specimens with uniform gage section, while rotating bending fatigue tests are conducted on hourglass specimens (i.e. reduced gage section). Fatigue tests revealed that the specimens subjected to the axial loading exhibited lower fatigue resistance compared to the specimens failed under rotating bending test. Such differences in the fatigue life was attributed to the variation in the stress distribution resulting from different loading types and its effect on the fatigue crack propagation. Fractography analysis conducted to determine the failure mechanism showed that all of the cracks initiated from the surface of the specimen irrespective to the loading conditions. Furthermore, fracture surface observed for LB-PBF 316L SS specimens resembled a typical fracture surface of notched specimens, which supports the fact that for the as-built specimens cracks initiates from the micro-notches as a result of layer wise fabrication in AM process.

Keywords: Stress gradient, Fatigue, 316L stainless steel, Surface roughness

Introduction

Layer wise fabrication technique used in additive manufacturing (AM) process has provided design freedom for fabricating parts with complex geometries as well as complete assemblies. As a result, AM technology is attracting interest from automotive and aerospace industries as a cost effective manufacturing process with an ability to fabricate lightweight parts to enhance fuel efficiency and reduce carbon foot print [1-3]. With an increased usage of AM techniques in various applications, it is necessary to establish standards to qualify and certify AM parts with an aim to ensure their reliability, especially under the realistic cyclic loading conditions [4]. Various standardization and federal agencies, such as American Society of Testing and Materials (ASTM) International, National Institute of Standards and Technology (NIST), Federal Aviation Administration (FAA), etc., are also actively involved in developing necessary guidelines to qualify and certify AM parts with optimal mechanical properties under various loading conditions.

Axial and rotating bending loadings are two of the most common loading types used for fatigue characterization of metallic materials. Furthermore, it has been recognized that the major differences in the fatigue behavior under axial and rotating bending tests arises from the differences in stress distribution experienced by the specimen. Normal stresses under axial loading is distributed uniformly throughout the gage volume of the specimen, while under rotating bending loading, maximum normal stress occurs at the surface and decreases linearly to zero at the center of the specimen [5, 6]. A correlation factor ranging between 0.75 and 0.9 has also been established to relate the fatigue limit of metallic parts subjected to axial and rotating bending loading [5]. In addition, this variation in stress distribution can affect the crack propagation behavior once the crack has been initiated [6]. Manson [6] also revealed that the nominal stress values used for rotating bending tests varies from the true stress due to the plastic deformation, which can have a significant effect on the fatigue life in low cycle fatigue regime.

Sakai et al. [7] compared the effect of surface defects and sub-surface defects (i.e. an inclusion) on the fatigue behavior of wrought high carbon-chromium steel specimens subjected to axial and rotating bending loading. Specimens subjected to rotating bending loading exhibited higher fatigue lives when compared to the specimens subjected to axial loading at identical value of stress amplitude. Such result was attributed to the fact that under axial loading condition, entire volume of the specimen's gage section experiences maximum stress, while under rotating bending loading, only the surface of the specimen experiences maximum stress. As a result, for the uniformly distributed defects, the number of critical defects becomes larger in the case of specimen under axial loading and consequently decreases the fatigue resistance. Furthermore, although higher fatigue lives were exhibited by the rotating bending specimens, the location of the defects (i.e. surface or sub-surface) was reported to be more influential for rotating bending loading compared to the axial loading condition [7].

The relationship between the fatigue behavior obtained from rotating bending and axial fatigue tests by understanding the effects of macroscopic and microscopic features for traditionally manufactured metallic materials are established. However, the effect of different types of defects inherent to additive manufacturing, such as surface roughness, lack of fusion (LoF), and gas entrapped pores [8, 9], on the type of loading is not yet understood. Furthermore, these defects in AM materials are not always uniformly distributed which could add more complexities to the fatigue analysis. Therefore, addressing this knowledge gap is necessary for understanding property-structure relationship and establishing the trustworthiness of fatigue and fracture critical AM parts in various industrial applications.

In this study, the synergistic effects of surface roughness and loading types on the fatigue behavior of LB-PBF 316L SS are investigated. The material selected in this study, 316L SS is bio-compatible and exhibits excellent corrosion and wear resistance. Hence, 316L SS are currently being used in marine applications, nuclear power plants, and internal fixation implants in biomedical applications [10-12]. Following the introduction in this study, the material and experimental procedures are presented. The experimental results are then discussed with accompanied fractography analysis. Finally, important conclusions are drawn.

Material and Experimental Procedures

316L SS powder produced by LPW Inc. with size distribution ranging from 15-45 µm was used to fabricate fatigue specimens utilizing a Renishaw AM 250, a laser beam powder bed fusion (LB-PBF) system, under argon purged environment. Manufacturer recommended process parameters (laser power of 200 W, hatch spacing of 0.11 mm, exposure time of 80 ms, and layer thickness of 50 µm) were used for the part fabrication. In this study, two sets of specimens, (I) cylindrical specimen with uniform gage section for axial fatigue test and (II) cylindrical specimen with reduced gage section (i.e. hourglass specimen) for rotating bending fatigue test, were designed according to ASTM Standard E-466 [13] and ISO 1143 [14], respectively. The specimen dimensions are shown in Fig. 1(a) and 1(b) for axial and rotating bending fatigue tests, respectively. It should be noted that these specimens were designed to have similar cross section as shown in this figure. Additionally, the fatigue stress concentration factor for the rotating bending specimens was also calculated to be very small (K_f = 1.009). The specimens were manufactured in their net shaped geometry in vertical direction (i.e. perpendicular to the build plate). All fatigue specimens were further annealed at 1900 °F for one hour in vacuum followed by air cooling, while no post fabrication machining was conducted.

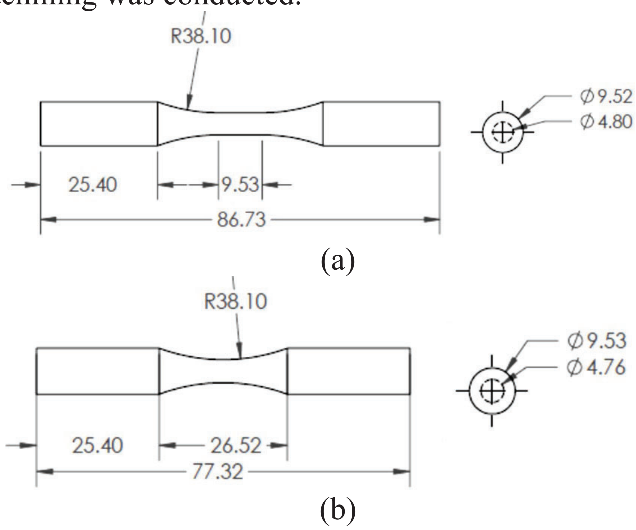


Figure 1. Specimen geometries and dimensions for (a) axial and (b) rotating bending fatigue tests. All dimensions are in mm.

To investigate the effect of stress gradient on the fatigue behavior of LB-PBF 316LSS in the presence of surface roughness, as-built specimens were subjected to axial and rotating bending fatigue loading. Rotating bending tests were conducted on a System Integrators RBF200 system under constant frequency, while MTS landmark servo-hydraulic system with 100 kN load cell was used to conduct uniaxial tests. All fatigue tests were conducted under fully-reversed (R_σ = -1) force-controlled mode with stress varying between 250 – 375 MPa. Detail fractography analysis on the specimens failed under both axial and rotating bending tests were further analyzed using Keyence VHX 6000 digital microscope to determine the factors responsible for crack initiation as well as failure mechanism arising from variation in fatigue loading.

Experimental Results and Discussions

Stress amplitude versus fatigue life data obtained for LB-PBF 316L SS specimens subjected to axial and rotating bending cyclic loadings are presented in Fig. 2. A significant effect of loading type on the fatigue behavior of LB-PBF 316L SS was observed, as specimens generally exhibited better fatigue resistance under rotating bending loading when compared to the axial loading condition. At higher stress amplitudes, the difference in fatigue life was seen to be more than an order of magnitude, while at lower stress amplitudes, the difference was within approximately a factor of three.

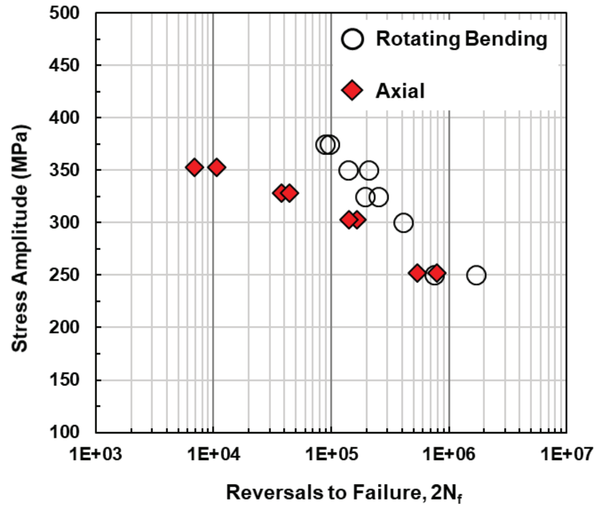
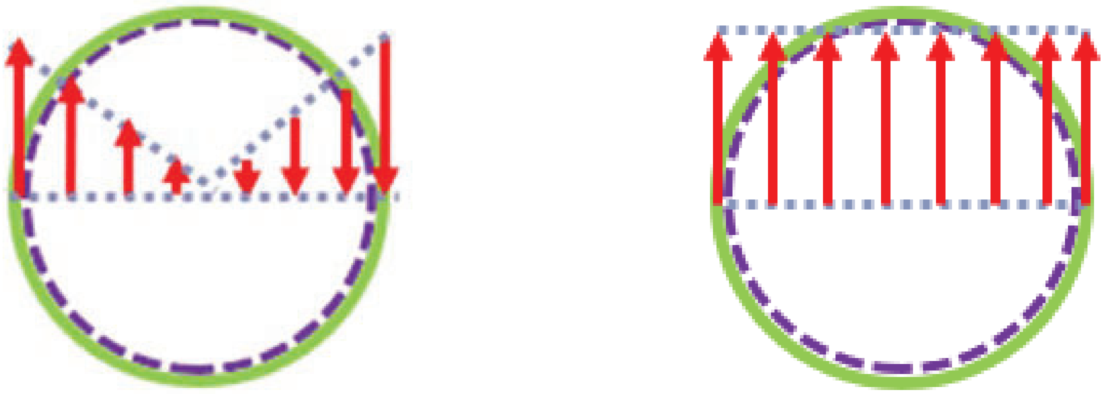


Figure 2. Stress amplitude versus fatigue life data obtained from rotating bending and axial loading under force-controlled mode.

Schematic representing the normal stress distribution on cylindrical specimens under rotating bending and axial loading conditions is shown in Fig. 3(a) and 3(b), respectively. Under rotating bending loading, the stresses are highest at the surface of the specimen, and gradually decrease and reach zero at its neutral axis, while under axial loading, the stress distribution remains constant throughout the entire gage section of the specimen. This stress gradient effect can influence the crack initiation and crack growth behavior [7]. In high cycle fatigue regime, the majority of the fatigue life is dominated by crack initiation stage. Since the cracks mainly initiate from the surface of AM specimens in the presence of surface roughness [15, 16], this may have resulted in smaller variation in the fatigue lives in lower stress amplitude levels as indicated in Fig. 2. It is also important to mention that, based on the specimen geometry, axial specimens with uniform gage section have higher gage volume when compared to the rotating bending specimens with reduced gage section. As a result, axial specimens have higher probability of having larger amount of crack initiating defects as compared to the rotating bending specimens, which consequently can also reduce the fatigue life.

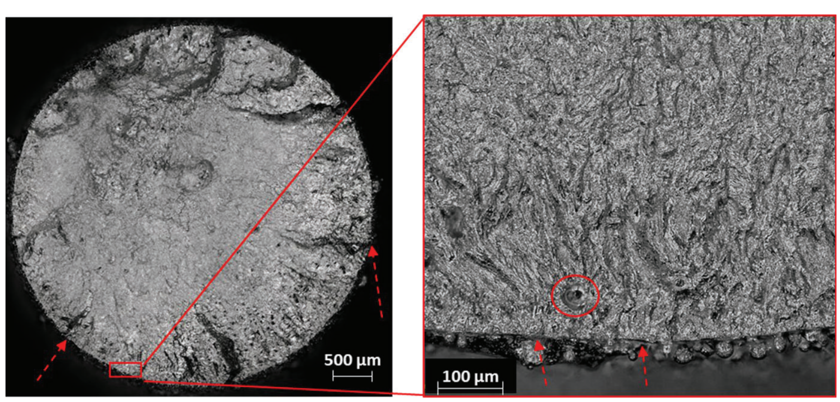
In low cycle fatigue regime (i.e. higher stress amplitude levels), the majority of fatigue lives is spent in crack growth regime. As a result, once the crack initiates in the specimen subjected high stress amplitudes, the crack starts to propagate inwards in the direction towards the center of the specimen. Since there is less stress within the internal region of the rotating bending specimen's cross section as compared to its surface as shown in Fig. 3(b), crack will grow in a slower rate. On the other hand, since the stress is uniform throughout the gage section of the specimen under axial loading, crack will grow at similar rate. This effect of stress gradient may be responsible for the larger variation in the fatigue lives obtained from rotating bending and axial loading conditions under identical stress levels at both high and low cycle fatigue regimes.



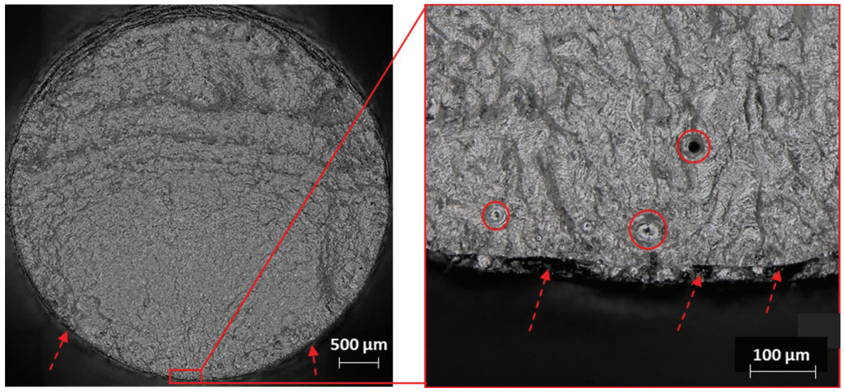
(a) (b)

Figure 3. Schematic showing distribution of stress under (a) rotating bending and (b) axial loading.

To further investigate the failure mechanisms of LB-PBF 316L SS under different loading conditions, fractography analysis was conducted on selected specimens subjected to rotating bending and axial loading at identical stress levels. Fracture surfaces obtained for specimens subjected to the stress amplitude of 350 MPa under rotating bending and axial fatigue loading are shown in Fig. 4(a), and 4(b), respectively. Irrespective to the loading condition, cracks were always observed to initiate from multiple location as a result of surface roughness in all specimens. Upon further magnification, fatigue cracks were seen to initiate from several micro notches located at the surface of the specimen as indicated by the red arrows in the zoomed in images. Furthermore, the fracture surfaces seen for LB-PBF 316L SS also resembled a typical failure mechanism observed in notched specimens shown in [5]. Therefore, in as-built surface condition, micro notches resulting from the layer wise fabrication process of AM technique may be the major factor driving the fatigue failure in AM parts.



(a)



(b)

Figure 4. Fracture surfaces showing differences in failure mechanism in as-built specimens (i.e. non-machined) subjected to (a) rotating bending and (b) axial loadings.

Conclusions

In this study, the effect of stress distribution within the volume of the specimens' gage section on the fatigue lives of LB-PBF 316L SS in as built (non-machined) surface condition was investigated. Based on the results obtained and discussions presented, the following conclusions were drawn:

1. Some influence of stress gradient was observed on the fatigue behavior of LB-PBF 316L SS. In general, higher fatigue resistance was observed for specimens subjected rotating bending loading compared to those subjected to axial loading.
2. Larger difference in the fatigue lives resulting from the variation of fatigue loading was seen at low cycle fatigue regime as compared to high cycle fatigue regime. This was attributed to the influence of stress gradient on the crack growth behavior, which governs the majority of fatigue lives at low cycle fatigue regime.
3. Fractography analysis revealed that the cracks always initiated from the micro-notches present at the surface of the specimen irrespective to loading condition. This result was also supported by the fracture surface that resembled those of notched specimen made of wrought counterpart.

Acknowledgements

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