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Influence of laser polishing on fatigue life of conventionally machined and laser powder bed fusion 316L stainless steel

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Abstract

One of the main factors keeping additive manufactured metal parts from being used in industry is the relatively low fatigue life of the as-printed parts when compared to their conventionally manufactured counterparts. In addition, certain areas on additively manufactured parts need finishing operations in order to make them functional. While laser polishing has demonstrated the ability to reduce the roughness of various metal surfaces, including additive manufactured ones, it is necessary to study the influence of this process to ensure the surface roughness improvements are not gained at the detriment of fatigue life. The objective of this work is to determine the influence of laser polishing on the fatigue life of both conventionally and additively manufactured metal parts. Fatigue samples were generated from 316L stainless steel using conventional machining and additive manufacturing through laser powder bed fusion. A single set of laser polishing parameters was used to determine the influence of laser polishing on samples manufactured from both methods. This work has shown that surface roughness of both machined and additive manufactured parts can be reduced without sacrificing fatigue life under certain polishing conditions. This demonstrates that laser polishing is a practical method for addressing additively manufactured surface roughness challenges while not negatively impacting fatigue performance.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Laser polishing is a contact-free and volume-neutral alternative to traditional methods like mechanical or chemical polishing. In the case of laser polishing by remelting, the scanning laser generates a melt pool which will solidify into a smooth surface as surface tension and viscous damping work to reduce initial surface features by redistributing the molten material [1]. Laser polishing has been shown to be an effective method for reducing surface roughness of metal surfaces. The ability to selectively reduce roughness on a surface has been applied to molding surfaces [2] as well as metal additive manufactured (AM) components such as medical implants [3]. Xu et al. have shown a reduction of arithmetical mean height, R_a, from 16.06 µm to 1.76 µm on AM TiAl parts [4]. Temmler et al. investigated laser polishing on conventionally machined AISI H11 tool steel and achieved R_a = 50 nm while also resulting in a decrease in surface hardness due to a reduction of carbon content in the melted surface layer [5]. Yung et al. was able to yield a reduction in surface roughness on selective laser melted tool steel using both pulsed and continuous wave laser polishing while increasing surface hardness [6]. Laser polishing of CoCr AM components with concave, convex, and slanted surfaces have been successfully laser polished while also yielding an increased surface hardness [7]. The role of laser power, spot size, and scan speed was investigated by Marimuthu et al. and surface roughness was found to be highly dependent on melt pool width and velocity [8]. Souza et al. performed laser polishing on AM 316L stainless steel reduced roughness while maintaining surface microhardness and a slight decrease in contact angle (increased wettability) of the polished surface [9]. Wang et al. showed that laser polishing can lead to a higher corrosion resistance and increased surface and near-surface micro-hardness in stainless steel AM parts [10].

In addition to modifying the surface roughness, laser polishing has also been found to change the microstructure and surface mechanical properties following processing. The rapid solidification that occurs during laser polishing can result in finer, equiaxed grains when applied to additive components with an initial columnar microstructure [11]. Tian et al. found that laser polishing of Ti6Al4V can result in residual tensile stress which can cause solidification cracking to occur [12]. Therefore, an adapted scan strategy taking the thermal cycle and stress conditions into account must be employed to reduce the solidification crack susceptibility. The residual stress that is a result of laser polishing is of interest as it has the ability to affect fatigue life depending on if the stresses are compressive or tensile and their magnitudes. Other process artifacts include solidification rippling and the generation of spatially periodic features which correspond to the melt pool overlap as consecutive line passes are used for areal polishing [13,14].

The fatigue life of laser polished parts was investigated in this work because the process has been found to modify multiple properties of a surface which have been associated with fatigue life: e.g., surface roughness, residual stress, microstructure. Surface roughness in the form of mean arithmetical height, max peak-to-valley depth, and RMS mean height (Sa, Sz, and Sq) has been shown to be inversely related to the fatigue life of conventionally manufactured metal parts [15]. Aviles et al. found that laser polishing on conventionally machined AISI 1045 steel results in an increase of fatigue life when the initial roughness before polishing is above a threshold [16]. Residual tensile stresses have been shown to result in reduced fatigue life of conventionally machined parts [17]. Metal AM components in their as-built geometry have been shown to have significantly reduced fatigue lives when compared to their conventionally machined counterparts, which has been attributed to residual stresses and surface-connected defects [18]. In addition, the fatigue life of metal AM components has been found to be inversely related to the samples surface roughness for both strain-controlled and force-controlled fatigue testing methods [19]. Heat treatment of metal AM 12CrNi2 low alloy steels has been found to improve fatigue life due to a reduction of residual stresses caused by the additive process [20].

Table 1: Summary of prior work in the study of the influence of laser polishing on fatigue life of metal components

Material	Process	Effect on Fatigue Life	Reference
Ti-6Al-4V	LPBF	Significant Reduction	Li et al. [21]
Ti-6Al-4V	LPBF	High cycle fatigue life increased	Lee et al. [25]
AISI 1045	Conventional	High cycle fatigue life increased	Aviles et al. [16]
Ti-6Al-4V	LPBF	High cycle fatigue life increased	Liang et al. [22]
Inconel 625	LPBF	No effect on fatigue life	Witkin et al. [24]
Ti-6Al-4V	LPBF	Significant reduction of fatigue life	Kahlin et al. [23]

The research on laser polishing of metal AM components has reported a wide range of results: from a significant decrease in fatigue life to a mild increase. Table 1 contains a summary of prior work studying the influence of laser polishing on fatigue life of metal components. Li et al. performed laser polishing on laser powder bed fusion (LPBF) Ti6Al4V, which resulted in a significant reduction in fatigue life from the order of 10^7 cycles to 10^4 cycles to failure due to the formation of a martensite layer and residual tensile stresses [21]. Liang et al. observed a slight increase of fatigue life after laser polishing LPBF Ti6Al4V alloy and performing tests with a fatigue stress ratio of 0.1 [22]. Laser polishing was found to result in a significant reduction of fatigue life of thermal stress relieved LPBF Ti6Al4V while only slightly reducing the fatigue life of electron beam powder bed fusion Ti6Al4V that had been stress relieved with hot isostatic pressure treatment [23]. Witkin et al. performed continuous wave laser polishing on Inconel 625 samples and has shown no significant change in fatigue life [24]. All studies on metal AM components have shown an overall of reduction in the roughness, Sa or Ra. This indicates that roughness is not the only major contributing factor to the fatigue life of metal AM components and the resulting fatigue life of AM parts, whether laser polished or not, is largely due to other properties including but not limited to microstructure, internal porosity, or residual stress. The effect of residual stress on laser polished powder bed fusion

Ti6Al4V samples was found to be significant by Lee et al., in which the fatigue strength was improved after thermal stress relief that was performed after laser polishing [25].

This work serves as an initial study of the influence of laser polishing on both machined and additively manufactured 316L stainless steel parts. 316L is a commonly used austenitic stainless steel alloy and was chosen to reduce the effect of the generation or removal of the martensite phase. Furthermore, 316L belongs to the most used alloys in the field of AM [26] and therefore further knowledge about the impact of laser polishing on the functional properties of this alloy is of great scientific and industrial value. The influence of laser polishing on additive and machined samples is investigated by comparing the fatigue test results over a range of stress conditions for a single laser polishing condition for samples created from wrought and laser powder bed fusion manufacturing methods. The as-built and laser polished conventionally machined samples will be referred to as M-AB and M-LP; the as-built and laser polished AM samples will be referred to similarly as AM-AB and AM-LP. Laser polishing has previously been shown to result in a reduced surface roughness and altered stress state in metal components, thus the process is hypothesized to have a positive influence on the fatigue life.

Nomenclature

AM	Additive Manufactured
M	Conventionally Machined
AB	As-Built
LP	Laser Polished
LPBF	Laser Powder Bed Fusion

2. Materials and Methods

The fatigue samples used in this work were designed according to the criteria set forth in ASTM E466 [27] and are described schematically in Fig. 1. The conventionally machined cylindrical samples were generated by turning on a computer numerically controlled lathe and the AM parts were produced on a laser powder bed fusion machine (EOS M290, Krailing, Germany) in the horizontal build direction. A laser power of 195 W, scanning speed of 1083 mm/s, hatch spacing of 90 µm, and layer height of 20 µm were used in the build process of the AM samples. All AM samples were produced in a single build and were removed from the build plate using electrical discharge machining (EDM). The AM samples were not heat treated prior to fatigue testing or laser polishing due to one of the objectives of this work being to observe the effect of laser polishing on as-built AM parts.

Both conventionally machined and AM samples were produced using 316L stainless steel rod and gas atomized powder, respectively. 316L is a corrosion resistant alloy that is widely used in industry and is a common material for metal additive manufacturing. Typical applications of 316L are where corrosion resistance is important, e.g., heat exchangers or chemical industry. The 316L gas atomized powder was supplied by EOS and had a particle size distribution of 20 to 65 µm. The AM samples were printed in the horizontal build direction and thus had support structure that had to be removed from the side facing the build plate. The support structures were removed manually, resulting in a rough surface where the support attached to the fatigue samples. The roughness at these locations was further reduced through mechanical polishing. All samples were placed in an ultrasonic bath for cleaning before laser polishing. In total, 22 AM samples were tested, of which 11 were tested in as-built and 11 in laser-polished condition. In addition, 18 machined samples were tested, of which 9 were tested in the laser-polished condition.

For laser polishing an Nd:YAG fiber laser with a TEM00 beam mode was used (JK 400, Rugby, UK). The 1070 nm wavelength approximately gaussian beam was sent through a beam expander that output into a two axis, XY-scanhead (Raylase Superscan III-15, Weßling, Germany). The incident beam diameter at the material surface was 120 µm during laser polishing. The laser was operated in continuous wave mode with a power of 34 W. The beam was scanned across the surface at a process speed of 100 mm/s. This set of polishing parameters was chosen because it can significantly reduce the initial roughness of the AM specimens. Argon was used as a shielding gas and the oxygen content in a closed chamber was measured to be 65 ppm at the surface of the processed part. The schematic of this set up is show in Fig. 2.

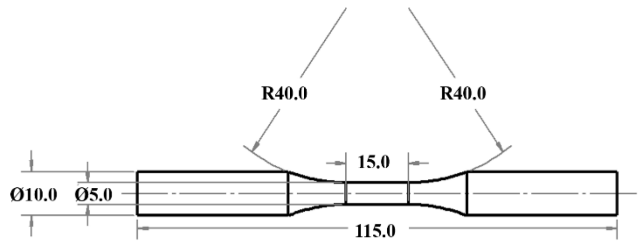

Figure 1: Schematic of cylindrical fatigue sample geometry

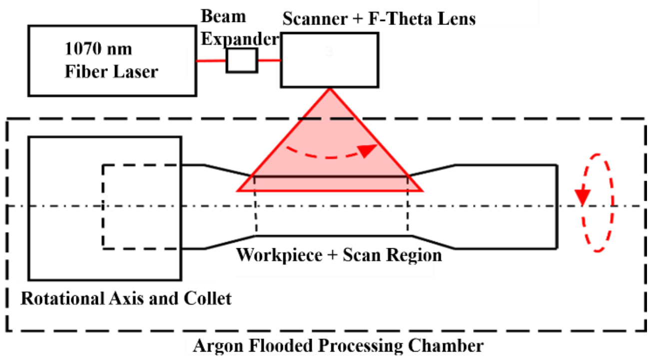

Figure 2: Schematic of laser polishing set up for polishing cylindrical samples

The scanning strategy used to polish the fatigue samples consisted of 8 discrete scan fields incremented around the samples' circumference. Each scan field consisted of line passes parallel to the rotational axis of the fatigue sample with an overlap between consecutive passes equal to 60% of the beam diameter. A dual pass polishing strategy described in Fig. 3 was used to reduce the effects of the overlapping scan fields. This scan strategy was used in order to minimize distortion by distributing the input laser energy over time and space. Other goals of the scanning strategy were to effectively distribute heat input in space and time as well as reduce the effects of process artifacts at the start and stop of a single line pass by starting/stopping the line at a point on the sample beyond the gauge section where the diameter starts to increase. The heat input was spread out in time by waiting 60 seconds between the starts of consecutive scan fields.

The analysis of the fatigue samples included the measurement of the initial and laser polished surface roughness using confocal laser microscopy. The mean arithmetical height, Sa, was calculated by fitting a plane to the confocal laser microscopy data and averaging the height of all the data points in the scanned region. A fast Fourier transform was used to divide the surface data into its spatial wavelength components. The fracture surfaces were observed using focus variation microscopy. Cross sections of the laser polished samples were prepared by etching with a hydrochloric acid solution diluted

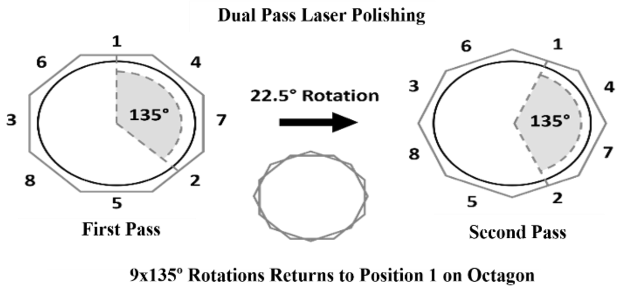

Figure 3: Dual pass scanning strategy using eight discrete scan fields.

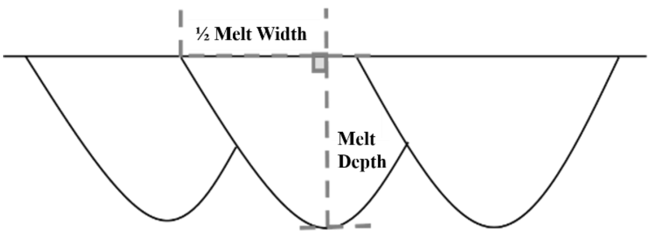

Figure 4: Method for measurement of overlapping melt pool width and depth

with ethanol that uses ferric chloride as a coloring agent to view the melt pool boundaries and measurement of melt pool depth and width were made using variable focus microscopy according to the method described in Fig. 4.

3. Results

3.1 Sample Geometry

The initial surface roughness as well as after laser polishing surface roughness are not the only differences between the AM and conventionally machined samples. The samples conventionally machined from wrought rod are straighter than those produced by LPBF from gas atomized powder. The AM samples had a slight curvature in them due to the additive process. The horizontal built samples had the tendency to curve upwards away from the build plate once machined from the build plate due to residual stress within the samples. This effect is shown in Fig. 5. It was of interest to characterize the impact of laser polishing on the as-built AM samples with minimal post-processing, which made stress relieving of the plate untenable. This curvature instead was attempted to be remedied through initial builds that measured the generated curvature and offset the build samples by an equivalent curvature in the opposite direction. However, the offset was not enough to fully remove all of the remaining curvature. In addition, the AM samples were built with support structures that had to be removed by grinding. When clamping the AM samples in the grippers on the tensile tester the samples are straightened, imposing a tensile stress on the top side of the samples which is opposite of the surface that had the support structure removed by grinding. All AM samples were found to have their failure initiate at this area of imposed tensile stress.

Figure 5: Conventionally machined (top) and as-built LPBF fatigue samples before any post processing. Slight warpage of AM sample is realized in the direction away from the attached support structure.

3.2 Surface Roughness

An improvement in surface finish was realized through laser polishing for both conventionally machined and additive manufactured samples. Images of the polished region in Fig. 6 reveal a reduction in roughness with some mild oxidation at the surface. The samples were polished across the entire neck region and into the tapering section. This was to ensure that the sample fails in the laser polished region during fatigue testing. Confocal microscopy was used to image the surfaces before and after laser polishing, Fig. 7. No solidification cracking was observed on the laser polished surfaces of either sample.

Figure 6: Conventionally machined (top) and LPBF (bottom) fatigue specimens that have been laser polished.

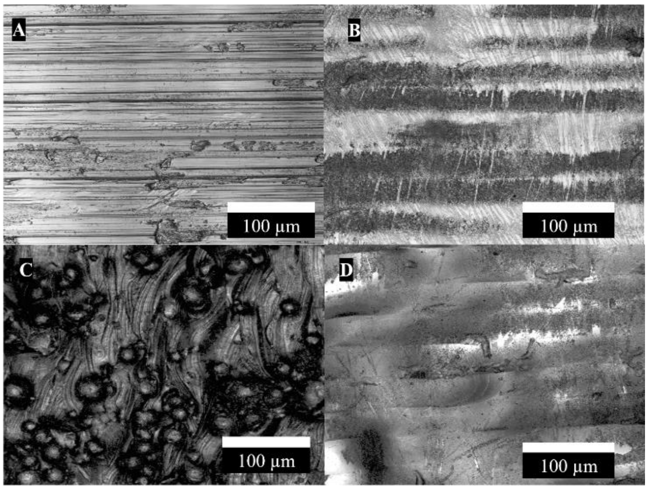

Figure 7: Confocal microscopy of conventionally machined (top) and LPBF (bottom) surfaces before (left) and after (right) laser polishing.

The mean arithmetical height, Ra, for the M-LP samples were reduced from 3.11 µm to 0.91 µm and the AM-LP samples roughness was reduced from 10.94 µm to 4.85 µm as a result of laser polishing. The contribution of different spatial wavelengths to the total roughness for machined and AM samples are plotted in Fig. 8 and Fig. 9, respectively. It can be observed that the laser polishing process was able to effectively reduce spatial wavelength across the entire roughness spectrum for the machined samples, yet the additive samples failed to achieve a significant reduction of its low wavelength features through laser polishing. The AM-AB samples have a larger initial surface roughness than those machined from a wrought rod and thus implies that the initial surface condition has an effect on the laser polishing process's ability to reduce roughness.

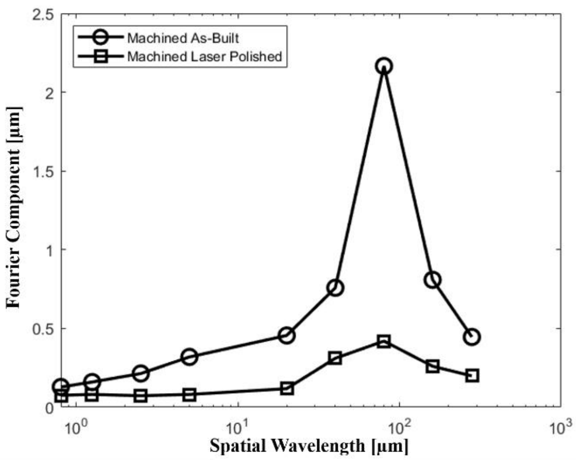

Figure 8: Semilogarithmic plot of spatial wavelength components for a M-AB and a M-LP sample.

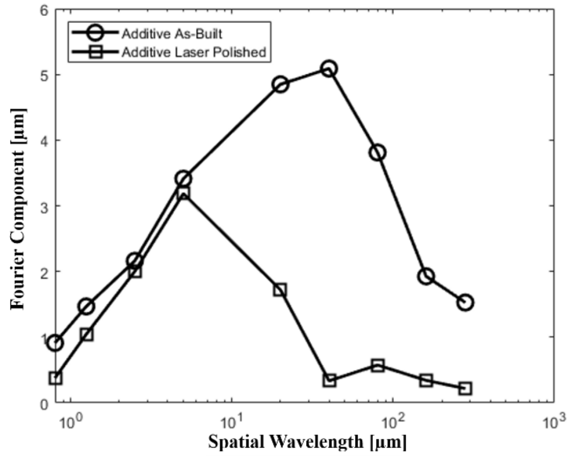

Figure 9: Semilogarithmic plot spatial wavelength components for an AM-AB and an AM-LP sample.

3.3 Melt Pool Geometry

Cross sections of machined and AM parts were etched to reveal melt pool boundaries, as seen in Fig. 10. For the AM samples, the etching method also reveals the melt pool size from the laser powder bed fusion process. Five measurements of melt pool width and depth were taken for the machined - laser polished and AM-LP samples. Their mean values and standard deviation are listed in Table 2. The M-LP samples were found to have a deeper and narrower melt pool when compared to the AM-LP samples.

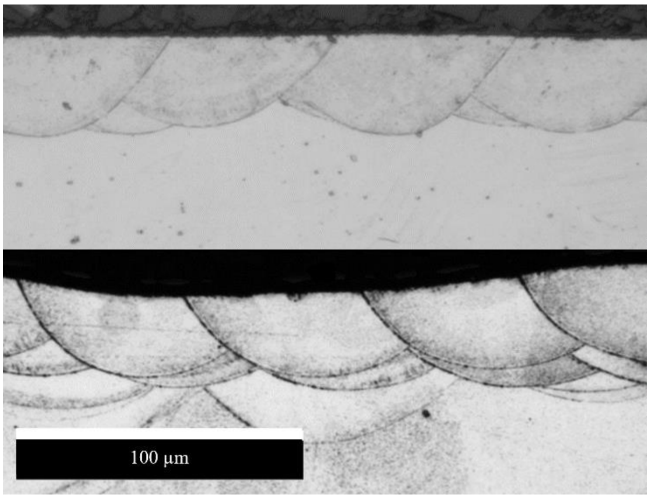

Figure 10: Cross section of melt pools for M-LP (top) and AM-LP (bottom)

Table 2: Mean and standard deviation of melt pool depth and width of AM and conventionally machined samples

Sample	Remelt Depth	Remelt Width
Additive Manufactured Laser Polished (AM-LP)	28.7 +/- 2.1 µm	78.1 +/- 6.2 µm
Machined from Stock Laser Polished (M-LP)	33.3 +/- 1.5 µm	72.3+/- 2.2 µm

3.4 Fatigue Life

The S-N curves are plotted on a semilogarithmic scale in Fig. 11. At least three samples of each condition were tested. The runout condition of two million cycles was achieved by both machined conditions of M-AB and M-LP. All three samples for both M-AB and M-LP reached the runout criteria for the lowest stress condition of 300 MPa. This indicates that the yield strength of the 316L stainless machined samples was greater than 300 MPa for both as-built and laser polished samples. A significantly lower fatigue life was observed in the additive manufactured samples when compared to their machined counter parts. For the lowest stress condition of 150 MPa, the AM-LP appear to have a higher fatigue life when compared to the AM-AB. For the other two stress conditions, no difference is observed.

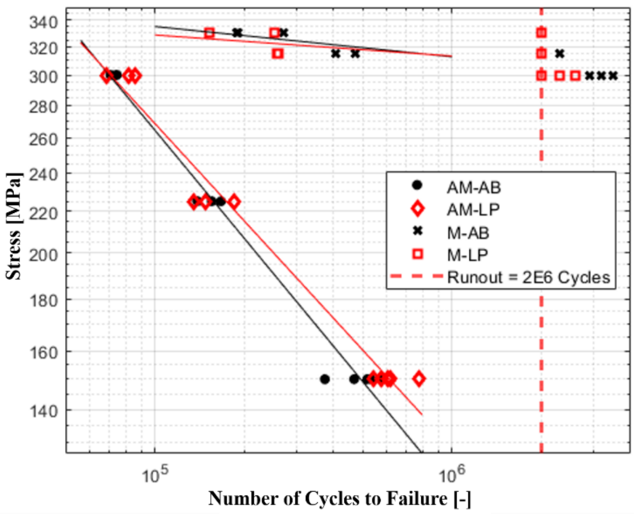

Figure 11: Log-log plot of S-N data for M-AB, M-LP, AM-AB, and AM-LP

3.5 Fracture Surfaces

Fracture surfaces from M-AB and M-LP samples tested at 315 MPa and AM-AB and AM-LP samples tested at 150 MPa are shown in Fig. 12. The mode of failure appears to vary between AM and conventionally machined parts. The machined samples have many small fracture lines whereas the additive sample images reveal larger and more distinct fracture lines. The additive samples have a smaller ductile region when compared to the machined samples. This is revealed by the failure region of the AM samples maintaining their circular cross section when compared to the narrow ductile region of the conventionally machined samples.

The ductile region is indicated by the necking that occurs near the support structure surface, the opposite side of crack initiation which occurred at the top surface. The crack initiation occurring at the top surface may be a result of induced tensile stresses from straightening of the AM samples during gripping. Another reason for crack initiation may be a result of the microstructure varying from top to bottom of the AM part.

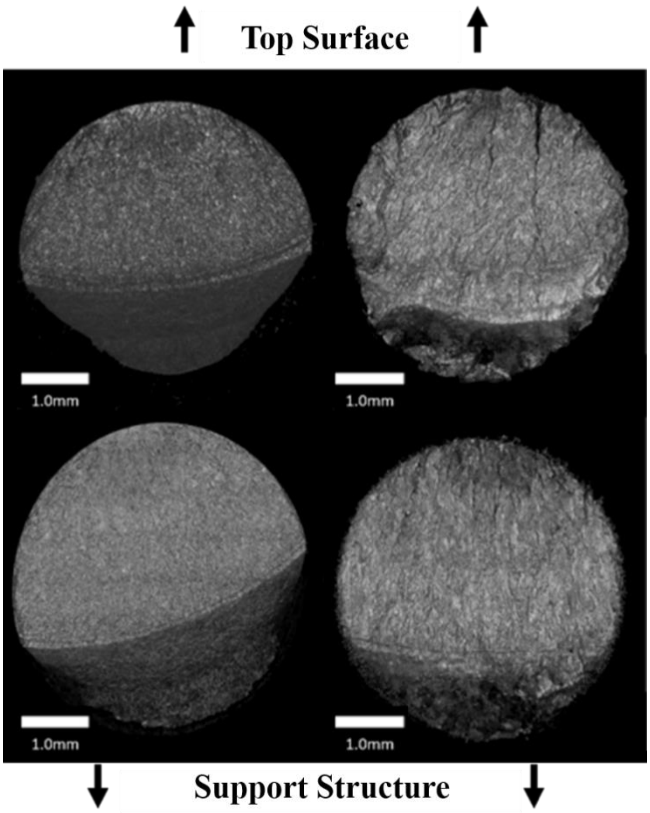

Figure 12: Fracture surfaces of M-AB (Top Left), AM-AB (Top Right), M-LP (Bottom Left), and AM-LP (Bottom Right)

4. Discussion

The surface roughness of both conventionally machined and AM samples was shown to be reduced for the laser polishing parameter set used in this work. A single set of laser polishing parameters was used and it is assumed that the roughness of either sample could be reduced further with a more comprehensive study over a range of parameters. The ideal parameter set is expected to differ between the machined and additive samples.

The S-N plots in Fig. 11 do not show a significant change in fatigue life for between as-built and their laser polished counter parts for conventionally machined samples over the range of stress amplitudes tested. The AM samples appear to have an increased fatigue life for only the lowest stress condition of 150 MPa. High cycle fatigue is more sensitive to surface condition than low cycle fatigue. Laser polishing can only manipulate a shallow surface layer on a sample and thus would be expected to have a greater influence on high cycle fatigue, whereas low cycle fatigue is most influenced by the bulk properties and defects of the material [28].

The AM components were found to fail earlier than their conventionally machined counter parts. This has been seen in prior literature but it should be noted that part of this reduction in fatigue life may be a result of the tensile stresses induced by the gripping and straightening of the slightly curved AM components. The failure on all of the AM components was initiated at this region of induced tensile stress and was indicated by the ductile failure region occurring on the side opposite of the induced tensile stresses.

This work has shown that surface roughness is not the only contributing factor to the fatigue life of AM parts. A reduction of surface roughness by 56% of the AM parts resulted in similar fatigue lives. Further work is needed to determine the role of residual stress and microstructure on the fatigue life of AM-AB and AM-LP components. The conventionally machined samples had an increase in runouts for the two highest stress conditions of the M-LP when compared to the M-AB samples. This indicates that machined samples may stand to benefit from laser polishing in terms of reduced surface roughness and increased fatigue life but more testing is required to support this claim.

5. Conclusion

It has been shown that standard scan fields can be used to laser polish cylindrical parts and result in a reduction in surface roughness. The fatigue life has been shown to not be reduced due to laser polishing for the single set of polishing parameters chosen in this work for both additive and machine 316L stainless steel. This is advantageous as laser polishing could be used to generate smooth parts without a reduction in the fatigue life and useful lifetime in real-world applications. Thus, the basis for laser polishing as an efficient post-processing method in the process chain of the widely used AM 316L, where fatigue strength is of relevance, was created and may thus be a prerequisite for further applications. Future investigations will study the effect of laser polishing parameters on the fatigue life as well as the influence on samples that have been additively manufactured, machined, and then laser polished.

Acknowledgement

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