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Fatigue Design with Additive Manufactured Metals: Issues to Consider and Perspective for Future Research

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Abstract

Additive manufacturing (AM) is a state of the art technology enabling fabrication of complex geometries, in addition to providing other advantages as compared to the traditional subtractive manufacturing methods. However, a wide variety of factors significantly influence fatigue behavior and structural performance of components made of AM metals. In addition to the fabrication process parameters, these include the effects of build direction, surface roughness, residual stresses, and heat treatment, and multiaxial stress states. At the microstructural level, defects such as pores and lack of fusion particles, as well as other microstructural features affect the behavior. In this paper, first a brief review of the aforementioned factors affecting the fatigue behavior will be presented. Then some experimental multiaxial fatigue data for selective laser melting (SLM), which is a powder bed fusion (PBF) metal AM process, of a common Ti alloy (Ti-6Al-4V) with applications in many industries are presented and discussed. The effects of surface finish, heat treatment, and stress state will be evaluated, as well as failure mechanisms in different life regimes and the role of defects. Finally, some additional factors that must be considered before wide acceptance of the AM technology in critical load bearing applications will be addressed.

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Keywords: Additive manufacturing, Multiaxial fatigue, Microstructure, Heat treatment, Residual stresses, Build orientation, Surface roughness

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1. Introduction

Nomenclature

$2N_f$	Reversals to failure
N_f	Cycles to failure
γ_a	Shear strain amplitude at surface
γ_{mid}	Shear strain amplitude at mid-section
$\bar{\sigma}_a$	von Mises equivalent stress amplitude
$\bar{\sigma}_{1a}$	Maximum principal stress amplitude
ε_a	Strain amplitude
$\bar{\varepsilon}_a$	von Mises effective strain amplitude
τ_a	Shear stress amplitude at surface
τ_{mid}	Shear stress amplitude at mid-section

Additive Manufacturing (AM) is a state of the art process which enables fabrication of complex geometries and provides several advantages over the traditional subtractive manufacturing methods. Among the advantages of AM process is the possibility of fabricating complicated geometries which are difficult or impossible to build using traditional manufacturing. In contrast to subtractive manufacturing, in which a part is made by removing the material from a block, in AM the part is built with a close to final shape geometry with little or no need for material removal, therefore, there is much less material waste. On site fabrication is amongst the other advantages of AM technique.

AM metallic parts are commonly fabricated via Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) processes. In PBF, a metal powder is melted selectively via laser or electron beam over the previous layer, while in DED, both energy source which could be laser or electron beam, and the material which is powder or wire infuse simultaneously. For more information about the fabrication process of AM parts the reader is referred to review articles in the literature, for example to [1, 2]. Several process parameters such as laser power, scanning speed and strategy, and layer thickness are amongst the important parameters which could directly influence the material microstructure and, therefore, behavior.

Similar to most other components in different industries, AM parts typically undergo cyclic loadings through their service life. Therefore, understanding their fatigue behaviour is essential to be able to widely adopt the technique in different industries while preventing fatigue failures. Moreover, multiaxial stresses are common for many components and structures. Even under uniaxial loading conditions, the stress state might be multiaxial, which could be due to the geometry complexity, notches, and residual stresses [3, 4].

This paper is not intended to be a review paper, but rather, an overview sort of paper, in which several important issues related to AM techniques are discussed. Although additive manufacturing is becoming more popular in many industries, it has been shown that a wide variety of factors could significantly influence their fatigue behaviour and structural performance of the components made by this technique. In this paper, first a brief review of several important factors including fabrication process parameters, build orientation, surface roughness, residual stresses, and heat treatment is presented. Then, some experimental multiaxial fatigue data for a common Ti alloy (Ti-6Al-4V) made via Selective Laser Melting (SLM), which is a PBF process will be presented. Finally, a summary and some perspective for future research is provided.

2. Important factors to consider in fatigue design with AM

Similar to many other mechanical components, most of the components made of this technique undergo cyclic loading throughout their service life, therefore, fatigue failure is a major concern. While AM offers several advantages, predicting the fatigue behavior of the parts made of this technique is still challenging. This is due to the many synergistic factors affecting the fatigue behavior. These include microstructural aspects such as grain and defects types and size, build direction effects, surface roughness, residual stresses, and heat treatment. In this section, a brief overview of these factors is presented.

2.1. Microstructure

A major concern in AM parts is the variation in the microstructure and the produced defects which are induced by and dependent on the different fabrication process parameters. These include parameters such as laser power, scan speed, hatch spacing, and heat conductivity of the processing machine. Microstructural characterization of AM parts is also strongly influenced by the thermal history of the part during the fabrication process including heating/cooling rate, temperature gradient, and cyclic reheating [5]. In addition to their influence on the microstructural texture, grain size and morphology, variation of these parameters affect the amount, type, and distribution of the internal defects. The microstructure of the AM parts, however, is mainly governed by the cooling rate, and the defect generation does not generally influence the microstructure evolution [6].

It has been shown that the most common responsible flaws for fatigue crack initiations in AM parts are pores due to entrapped gas, which are generally spherical, and voids which are generally irregular shaped and are due to the lack of fusion. In addition, for fully dense parts, for example in HIPed condition, single α-phase grains or clusters of α-phase are found to be responsible for crack initiation. Representative photos of such defects are shown in Fig. 1.

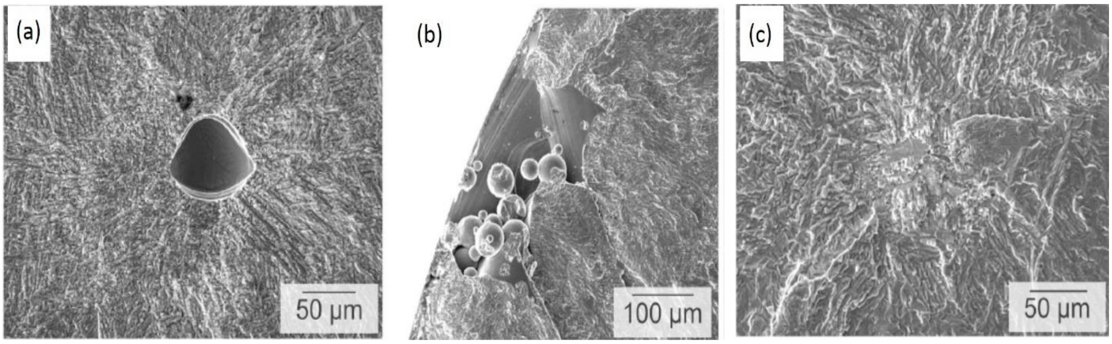

Fig. 1. Different representative defect types in AM Ti-6Al-4V: (a) Nearly spherical pore due to entrapped gas, (b) void due to un-melted particles, and (c) α-phase grains defect [7].

Variation of the processing parameters can significantly influence the porosity generation [8]. Kasperovich et al. [9] carried out analysis of the porosity formation on PBF manufactured Ti-6Al-4V samples with changing the process parameters such as scanning speed, hatch spacing, laser power, and focus distance, while all other parameters were kept constant. They found that while all of these variables could influence the porosity formation, the scan velocity and laser power play the most dominant roles in the porosity generation, as shown in Fig. 2.

Additional studies in the literature have been conducted in order to investigate the correlations of these factors and to optimize them, for example in [6, 10, 11]. Additionally, it has been shown that at low energy density levels, large elongated irregular shape voids develop due to incomplete powder melting, while at high energy density levels, generally smaller and circular/spherical entrapped gas type defects are evident [4, 6, 9]. The former defects have a more detrimental effect on the fatigue life, which is due to the higher stress concentration factor at the edge of these defects. Generally, larger pores are associated with shorter fatigue lives, for example, as shown in Fig. 3 for Electron Beam Melted (EBM) Ti-6Al-4V samples. Also, the relatively large subsurface internal pore in this plot with longer life indicates less detrimental effect of the internal pores, as compared to the surface defects. Therefore, in AM metals, both the stress amplitude level and defect size and location are key influencing factors in controlling the fatigue life.

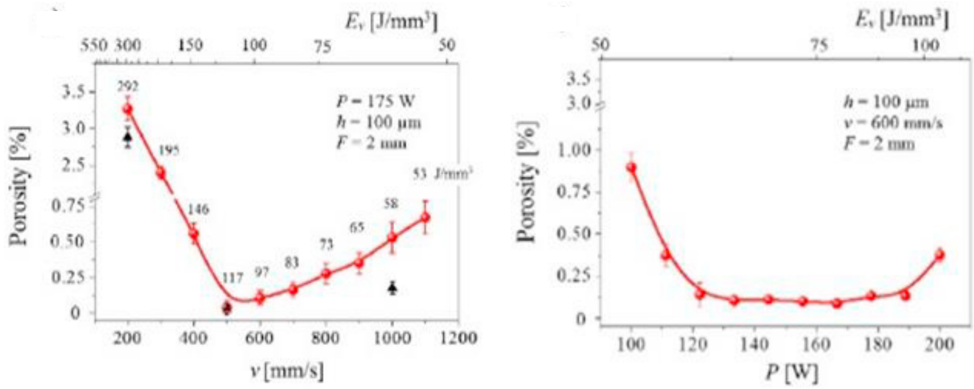

Fig. 2. Influence of the PBF process parameters on the amount of porosity for different parameter variations on Ti-6Al-4V samples. (a) Scanning velocity, and (b) laser power [9].

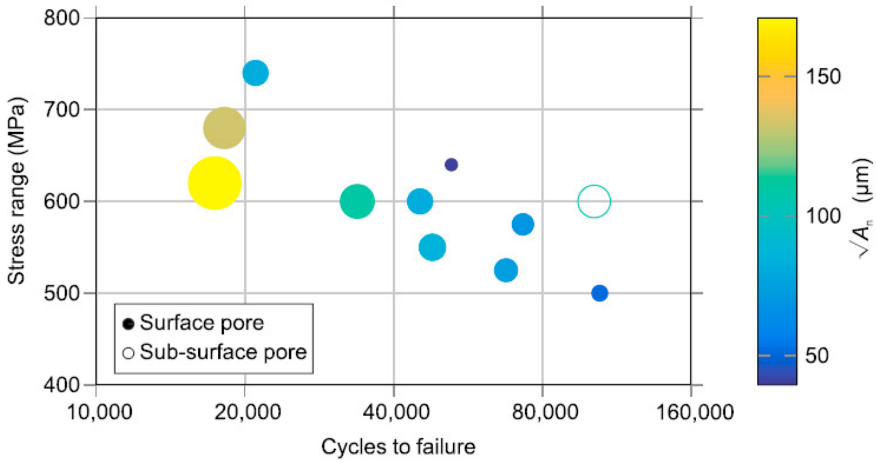

Fig. 3. Effect of pore size on fatigue life. The size and color of the markers indicate the size of the pore (A_n) measured from SEM images of the fracture surface of EBM Ti-6Al-4V samples [12].

2.2. Build orientation

Build orientation of AM parts can have a significant influence on the anisotropy of their mechanical behavior under either monotonic or cyclic loading. Yadollahi et al. [13] showed that the part's aspect ratio relative to the building orientation could play an important role in the thermal history and, therefore, influence the microstructural and mechanical properties of the material. Thermal history difference via different building orientations could affect the direction and shape of the defects [5]. Moreover, several weak layer interfaces could be generated due to the microstructural discontinuities as a result of the change in grain orientations after each layer [14]. Generally, the effect of thermal history during the fabrication process should be considered as an important factor of anisotropic behavior of the AM parts [5].

Several studies confirm the building orientation anisotropy of AM parts, i.e. in [13, 15-21], while some studies show no significant effect of building orientation on the mechanical performance, for example in [22]. Yadollahi et al. [13] showed that the AM PBF horizontally built 17-4 PH stainless steel specimens show significantly higher elongation to failure as compared to the vertically built specimens. This was attributed to the difference in formation of defects mostly between build layers. For the vertically built specimens these defects were perpendicular to the load direction, providing an easier path for defect growth and coalescence under loading. As shown in Fig. 4, the horizontal specimens resulted in longer fatigue lives in both the as-built and heat treated conditions, as compare to the vertical specimens. This difference was attributed to the level of porosity, residual stresses, and the orientation of deposited layers with respect to the applied load direction.

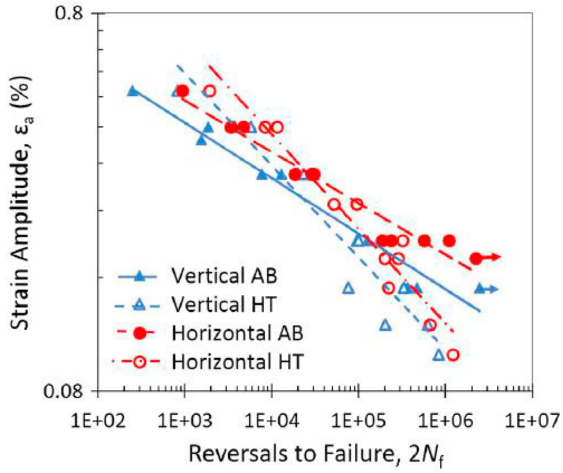

Fig. 4. Strain-life fatigue data for AM PBF 17-4 stainless steel in different build directions and with or without heat treatment [13].

However, another study by Qiu et al. [19] shows higher ductility for the AM PBF vertically built Ti-6Al-4V specimens as compared to the horizontal specimens. It was discussed that the anisotropy in ductility is mainly due to the columnar grain orientation with respect to the applied load direction. Additionally, lower amount of porosity of vertically built specimens was attributed to the thermal history of the specimens during the fabrication process which could retain the heat for a longer time and cause a better melt of two adjacent layers.

2.3. Surface roughness

One of the major factors that needs to be considered in investigating the fatigue behavior of AM parts is the rough surface of the fabricated parts. The rough surface of AM parts is attributed to the stair stepping effect due to the curvature of the surface and the deposited layer thickness, partially melted particles, and the presence of material defects [23]. The rough surface and micro cracks on the surface could be the potential points for the crack initiation and, therefore, lead to early fracture under cyclic loading. Several investigations have been reported in the literature on the importance of the surface finish for different materials, for instance in [4, 17, 22, 24-28].

A mentioned earlier, one of the substantial benefits of the AM technique is the capability of fabricating complex geometries. While this is a promising advantage as compared to the conventional manufacturing techniques, machining of these complex geometries for improved surface finish subsequent to AM would be difficult, if not impossible. Moreover, due to the wide variety of applications, some AM components might be used in the as-built surface condition without any further post surface finishing. Therefore, it is important to evaluate the surface finish effect on fatigue behavior of AM components.

Several reports have been published in the literature on evaluating the importance of the surface finish in increasing the ductility and improving the fatigue life. Fatemi et al. [26] reported that machining could improve the ductility of the Ti-6Al-4V specimens processed by PBF, significantly. For example, for the monotonic shear stress-strain curves shown in Fig. 5(a), annealed Ti-6Al-4V AM specimens under identical build condition are shown, with the only difference being the surface finish. As can be seen, the shear ductility of the specimen with machined and polished surface is higher than that of the specimen with the as-built surface. They also observed longer fatigue lives by about a factor of 3 for tests on the machined annealed condition, as compared to the as-built annealed specimens, see Fig. 5(b). As discussed earlier, machining removes the stress concentration effect of the rough surface and, therefore, the longer life for the machined surface condition is not surprising. However, in contrast to conventional metals, the stress-life curves are nearly parallel, rather than converging at high stress levels and diverging with increased fatigue life.

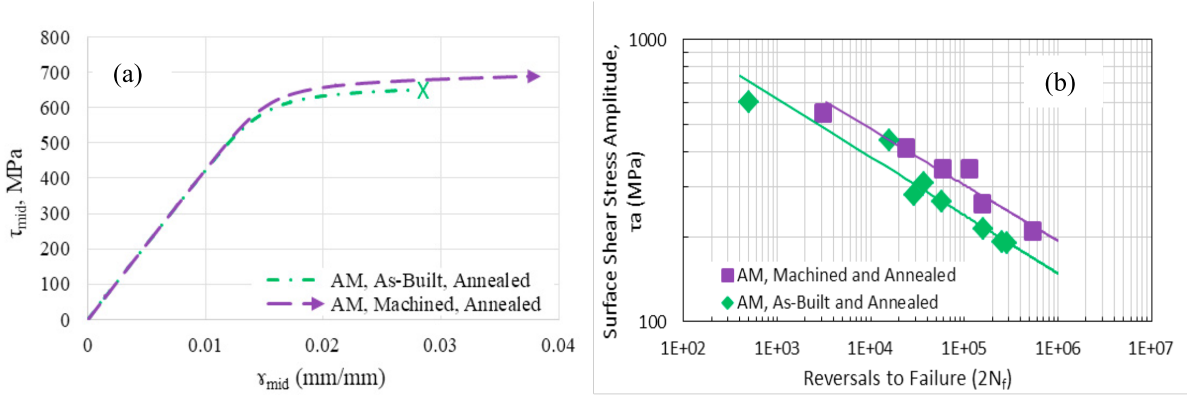

Fig. 5. Monotonic shear stress-strain curves (a) and shear stress amplitude vs. reversals to failure for fully-reversed torsional fatigue tests (b) of AM Ti-6Al-4V with machined and as-built surface finish conditions [26].

Although the majority of studies indicate the importance of the surface machining on improving the monotonic and fatigue behavior of the AM specimens, a few studies have reported less or no effect of machining [17, 25]. This is due to the presence of internal defects which are left and/or moved to the surface or near the surface after the machining process. Therefore, it has been suggested that when Hot Isostatic Pressing (HIP) heat treatment is considered, it should be done prior to machining the specimens to be able to significantly shrink/close the internal defects and to prevent the movement of the subsurface defects to the outer surface after machining [4]. This is due to the fact that the HIP process is not able to effectively close the surface defects.

2.4. Residual stresses and heat treatment

Excessive thermal gradients, high energy density, and most importantly fast solidification during the AM processes cause residual stresses. Tensile residual stresses are detrimental to fatigue behavior, but it is difficult, if not impossible, to avoid during them the fabrication process. Therefore, it is desirable to decrease/eliminate tensile residual stresses at critical locations during the manufacturing process by using appropriate process parameters, appropriate build orientations, or relax them with applying proper post heat treatment. If significant residual stresses remain, it is necessary to take them into account in proper fatigue analysis of the fabricated parts.

A relatively large number of studies about the characterization of residual stresses and heat treatment methods are available in the literature, i.e. in [8, 13, 17, 25, 29-33]. Ali et al. [33] used a modified pre-heating platform which was integrated to a PBF system to be able to increase the preheating temperature up to 800°C. They studied several temperatures ranging from 100°C to 770°C and were able to decrease the residual stress of Ti-6Al-4V specimens from 214 MPa at 100°C pre-heated chamber to 1 MPa at 570°C. Enhancement in fatigue lives via different heat treatments was reported in [25, 26, 30], while no effect of annealing and heat treatment was observed in [8, 29, 32].

Leuders et al. [31] studied the fatigue behavior of PBF Ti-6Al-4V and 316L alloys under different heat treatment conditions. As shown in Fig. 6, the fatigue response of the materials to different heat treatments is very different. Fatigue behavior of the Ti-6Al-4V alloy is positively affected by most of the heat treatment processes used, while inferior results are observed after heat treatment of 316L specimens. Inferior fatigue behavior of the 1050℃ heat treated Ti-6Al-4V alloy is related to the two phase microstructure and overlap of the micrometer-sized defects with microstructural notches. It has been discussed that the fatigue behavior of 316L alloy is strongly affected by its monotonic strength. The 316L alloy is characterized by a high ductility in all conditions and the HIP process is only recommended in HCF regime. This is because the yield and ultimate strengths of the material significantly decrease due to the temperature-time profile of the heat treatment process. The difference between the two HIP post treatments observed in the figure is due to different microstructure, fine microstructure of HIP 920℃ resulting in high monotonic strength, as compared to the two phase microstructure of HIP 1050℃ resulting in lower ultimate tensile strength. Similar observations have been published in [34] regarding the effectiveness of the HIP process on different AM alloys, including Ti-6Al-4V and 316L.

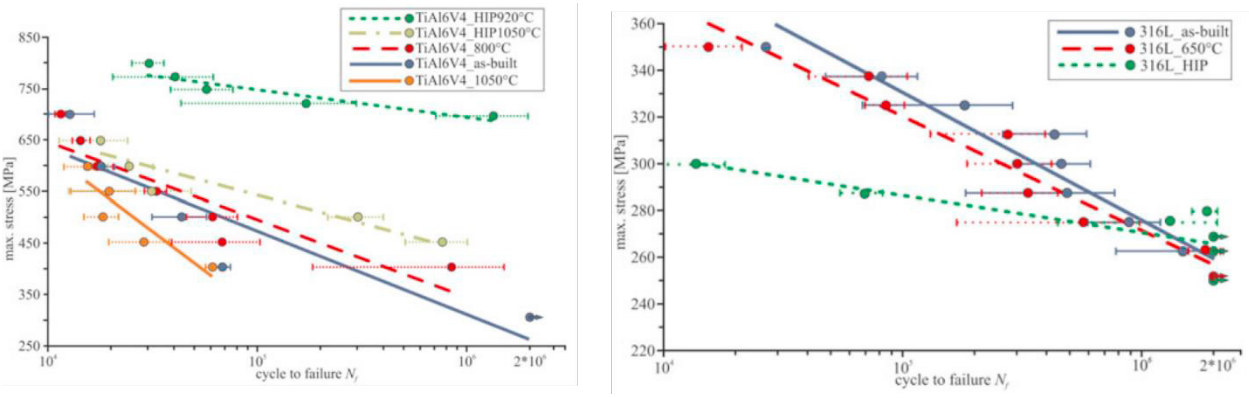

Fig. 6. S-N curves for PBF processed (a) Ti-6Al-4V, and (b) 316L under different heat treatment conditions [31].

However, it has been confirmed that the HIP treatment is generally an effective heat treatment process that can shrink/close internal defects such as gas pores and lack of fusion defects, reduce the amount of residual stresses and, therefore, improve the densification of the material and improve the mechanical behavior of AM metals [8, 34-37]. Similar to [35], Mower and Long [34] reported that there is no build direction effect after the HIP process, while Seifi et al. [38] have reported anisotropic fatigue behavior of Ti-6Al-4V alloy after this process.

3. Multiaxial fatigue characterization

Similar to many other structural parts, the AM fabricated parts employed in critical applications are typically subjected to multiaxial stress states. Multiaxial loads are common for many components, and even under uniaxial loadings the stress state could be multiaxial due to the complexity of the geometry or presence of multidirectional residual stresses. Capturing the correct damage mechanism under multiaxial stress states is necessary to use an appropriate damage quantification parameter for robust multiaxial fatigue life predictions [3]. To date, a very small number of studies have been performed on AM materials considering stress states other than uniaxial. The data included in this section were generated under axial, torsional, and combined axial-torsion loadings [4, 26].

Some results of the conducted torsional fatigue tests for L-PBF Ti-6Al-4V specimens are superimposed and shown in Fig. 7. All of the specimens were fabricated vertically using a gas-atomized Ti-6Al-4V grade 23 powder via a Renishaw AM 250 machine. Per built, 5 samples were printed on a preheated base plate to 170°C. For additional details related to the manufacturing process, specimen geometry, and experimental procedure, the reader is referred to [26]. Fatigue life comparisons of the torsional fatigue tests on as-built and as-built annealed, and machined and machined annealed specimens in Fig. 7 indicate that the annealing treatment process could significantly improve the fatigue behaviour. As mentioned previously, this could be attributed to the relaxation of the detrimental tensile residual stresses which are generated during the fabrication process. As can be observed, machining the annealed specimens could improve the fatigue life by more than a factor of 3. Stress concentration effect of the rough surface and un-melted particles on the surface act as crack initiation sites and cause multiple initiations and premature failure. Also, comparison of the as-built annealed and machined not annealed test results with those of the machined annealed condition indicates that the best results can only be obtained with applying both heat treatment and surface machining. Similar to the findings in [25] for PBF AM AlSi10Mg alloy, machining without heat treating does not improve the fatigue life significantly.

Comparison of the strain-life behaviour of the machined annealed AM specimens with the wrought material indicates that AM material results in shorter fatigue lives. This is not surprising, since the fatigue behaviour of the AM material is heavily affected by the presence of internal defects which act as micro-notches and cause stress concentrations. However, subsequent torsional fatigue data of HIPed AM specimens indicate the performance to be similar and even better than the wrought material. This is due to the effectiveness of this treatment process in eliminating or shrinking pores to a much smaller size, so that they no longer control the fatigue behaviour.

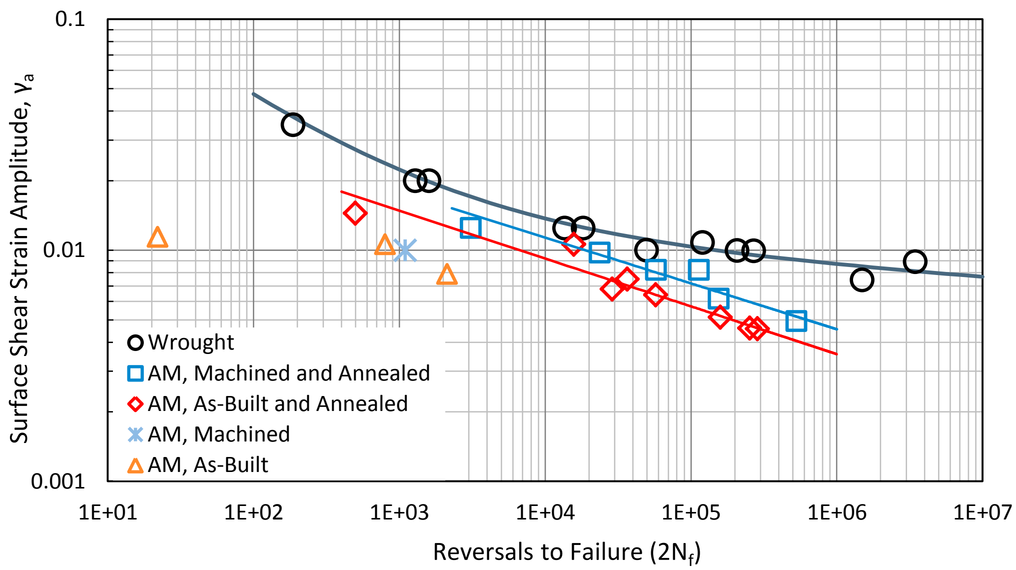

Fig. 7. Total shear strain amplitude vs. reversals to failure for fully-reversed torsional fatigue tests of wrought and AM Ti-6Al-4V with different heat treatment and surface finish conditions [26].

Monotonic and cyclic von Mises equivalent stress-strain curves of the wrought and AM Ti-6Al-4V materials under different loading conditions were superimposed in [4]. The wrought material was shown to experience cyclic softening under both axial and torsion loadings. Comparing the cyclic stress-strain behaviour of the AM material obtained from midlife hysteresis loops in fatigue tests with the corresponding monotonic torsion curve showed that while the AM material also experiences some softening when subjected to cyclic loading, the amount of softening is much less, as compared to that experienced by the wrought material. This was attributed to the lower ductility of the AM material and to the much shorter fatigue life, as compared to the wrought material (limiting the amount of softening with increasing cycles). However, it has been shown that the rate of softening for the wrought and AM materials are similar [26].

Some axial, torsion, and combined in-phase (IP) axial-torsion experimental fatigue data of the same AM Ti-6Al-4V alloy in the annealed condition with as-built and machined surface finish are presented in Fig. 8. Crack orientations of both as-built and machined surface conditions indicate that all failures are along the maximum principal stress plane. As discussed in [4] in detail, the presence of defects and the brittle behaviour of the AM Ti-6Al-4V alloy are the reasons for the observed tensile mode of failure. Therefore, a criterion such as the maximum principal stress criterion correlates the multiaxial fatigue test results much better, as compared to the commonly used von Mises equivalent stress criterion which is more suitable for ductile-behaving materials.

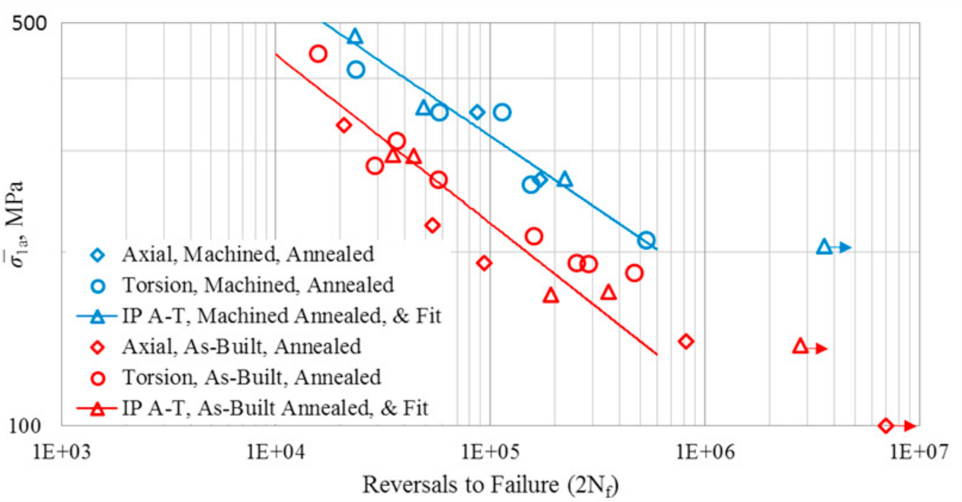

Fig. 8. Correlation of fatigue test results of PBF Ti-6Al-4V with different surface conditions based on maximum principal stress amplitude [4].

4. Summary and perspective for future research

Similar to most other components in different industries, additively manufactured parts typically undergo cyclic loadings through their service life. Therefore, understanding their fatigue behaviour is essential to their application in many industries in order to prevent fatigue failures. Many synergistic factors affect the fatigue behavior of AM metals. These include microstructural aspects such as grain and defects types and size, build direction effects, surface roughness, residual stresses, and heat treatment. The produced microstructure and defect characteristics vary by and are dependent on the fabrication process parameters as well as the thermal history of the part during the fabrication process. The fabrication process parameters include laser power, scan speed, hatch spacing, and heat conductivity of the processing machine. Thermal history includes heating/cooling rate, temperature gradient, and cyclic reheating. In addition to their influence on the microstructural texture, grain size and morphology, variation of these parameters affect the amount, type, and distribution of the internal defects. The most common defects for fatigue crack initiations in AM parts are pores due to entrapped gas, which are generally spherical, and voids which are generally irregular shaped and are due to the lack of fusion.

Several studies confirm the building orientation anisotropy of AM parts, while some studies show no significant effect of building orientation on the mechanical performance. Where a significant effect has been observed, it was attributed to the thermal history difference in different building orientations which in turn affects the direction and shape of the defects, as well as the ductility. With regards to the surface finish effect, while a promising advantage of AM as compared to the conventional manufacturing techniques is the ability to build complex geometry parts, subsequent machining of such geometries for improved surface finish would be difficult, if not impossible. Therefore, it is important to evaluate the surface finish effect on fatigue behavior of AM components. Although the majority of studies indicate the importance of surface machining in improving fatigue performance, a few studies have reported less or no effect of machining due to the presence of internal defects which are left and/or moved to the surface or near the surface after the machining process.

Excessive thermal gradients, high energy density, and most importantly fast solidification during the AM processes causes residual stresses. Tensile residual stresses are detrimental to fatigue behavior, but it is difficult, if not impossible, to avoid during them the fabrication process. Their effect may be eliminated or reduced by using appropriate process parameters, appropriate build orientations, or relaxing them with applying proper post heat treatment processes. Annealing treatment could significantly improve the fatigue performance, resulting from the relaxation of detrimental tensile residual stresses. HIP treatment is generally an effective heat treatment process that can shrink/close internal defects such as gas pores and lack of fusion defects, reduce the amount of residual stresses and, therefore, improve the densification of the material and improve the fatigue performance. Some studies suggest no build direction effect after the HIP process, while others report anisotropic fatigue behavior after this process.

Similar to many other structural parts, the AM fabricated parts employed in critical applications are typically subjected to multiaxial stress states. Capturing the correct damage mechanism under multiaxial stress states is necessary to use an appropriate damage quantification parameter for robust multiaxial fatigue life predictions. Crack orientations of axial, torsion, and combined axial-torsion fatigue tests of AM Ti-6Al-4V alloy with both as-built and machined surface conditions indicate failure along the maximum principal stress plane. The presence of defects and the lack of sufficient ductility are the reasons for the observed tensile mode of failure. Therefore, a criterion such as the maximum principal stress criterion correlates the multiaxial fatigue test results much better, as compared to the commonly used von Mises equivalent stress criterion which is more suitable for ductile-behaving materials.

A large amount of experimental data and research over the last few years have significantly advanced the understanding of additive manufacturing technology. However, from the material mechanical behavior and structural performance points of view, most of these studies were conducted under monotonic loading, which may have little or no relevance to their behavior or performance under cyclic loading and, therefore, fatigue design or analysis. As a result, to be able to reliably take advantage of the opportunities offered by AM in many fatigue critical structural applications, a broader and more in depth understanding of the effects of AM process parameters and the associated thermal history, as well as post manufacture treatments under cyclic loading is necessary. As mentioned earlier, these variables cause a variety of microstructures, defect populations, and residual stresses, all of which in turn affect the fatigue performance.

Most of the fatigue studies on AM materials are empirical in nature. As discussed previously, defects play a key role in controlling fatigue behavior of AM materials. Due to the large number of defect quantification parameters such as variations in shape, population density, size, location, etc, and their dependence on the many build parameters, it is not practical or efficient to attempt to quantify their effects by testing. Instead, developing analytical models appropriate for the material type and defect characteristics, which could include multi-scale and/or multi-physics models, may potentially be able to quantify the effects of defects on fatigue performance in a more efficient and robust manner. Testing would still be needed for model calibration or validation, but to a much smaller degree.

Using the geometric freedom offered by the AM technique, new specimen geometries can be used for fatigue testing which reduce or eliminate the limitations of conventional commonly used fatigue test specimens. For example, a limitation with conventional plate type test specimens for fully-reversed fatigue testing is buckling during the compression part of the loading cycle. As a result, most fatigue test data generated with this type of specimen are in tension-tension, therefore, imposing a mean stress. The buckling resistance can significantly be increased by using alternative geometries, such as the one proposed in [39]. Such geometries may be difficult, or even impossible, to make by the common subtractive manufacturing processes, but not any more difficult with AM processes. Other examples include tubular specimens suitable for multiaxial fatigue testing. Taking advantage of the geometric freedom, geometries can be designed with uniform or nearly uniform stress or strain distribution in the gage section and avoiding stress or strain gradient under shear loading.

Nearly all of the fatigue data for AM metals have been generated with simple geometries and under constant amplitude loading. However, in addition to the factors discussed in sections 2 and 3 (i.e. heat treatment, residual stresses, anisotropy, surface roughness, etc), other factors need to be considered for application to fatigue design and analysis of actual components. These include geometrical details such as stress concentrations similar to those in the actual component, loading conditions similar to service loading, and environments similar to those in service. Fatigue cracks generally initiate at stress concentrations. Notches and internal defects are, therefore, likely locations for crack initiation. It is also well known that in addition to the stress concentration, stress gradient at such concentrations also plays an important role in fatigue behavior. The combined effect of a notch in addition to defects such as porosity or voids on fatigue behavior, although also common to some castings, have not yet been quantified. With regards to the loading history, service load histories are typically variable amplitude in nature. Load sequence and interactions are important in such loadings. The effects of such loading for AM metals and processes in terms of cumulative fatigue damage evolution, particularly in the presence of multiaxial stresses, have not yet been studied. With regards to service environment, evaluation of common operating environments such as those where corrosion is present, or at elevated temperatures where creep-fatigue interactions becomes important, have not yet been explored for metals made of AM processes. Finally, developing qualification and certification standards are essential for application of AM metals in safety critical applications. Such standards cannot practically rely on large numbers of data sets as is common for conventional metals, due to relatively small batch sizes and long build times in AM. Therefore, novel evaluation techniques need to be developed for qualification and certification of AM components.

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