Performance enhancing drug usage: The influence of adverse health effects and public embarrassment

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An Overview of Very High Cycle Fatigue Behavior of Additively Manufactured Ti-6Al-4V

Palmer Frye[1]
Jutima Simsiriwong[1]
[1]*School of Engineering, College of Computing, Engineering & Construction*
University of North Florida
j.simsiriwong@unf.edu

Abstract

This paper presents a brief review on the current state of knowledge of the very high cycle fatigue (VHCF) behavior of metallic parts fabricated using Additive Manufacturing (AM) processes. It has been shown that AM has significant potential to replace traditional manufacturing methods that impose geometric limitations to designs. Powder-based metallic AM methods allow for precise layer-wise processing of complex net-shape parts without the use of special tooling or molds. Among various metals commonly used in AM processes, titanium (Ti) 6Al-4V alloy is currently of great interest especially in aerospace applications that contain parts with complex geometries (i.e., turbine blades in jet engines). To safely adapt AM Ti-6Al-4V parts in these applications, their mechanical properties and fatigue behavior must be understood. Various studies have identified AM process-induced defects (i.e., entrapped gas pores, lack of fusion defects between build layers, etc.) to be the main cause of fatigue failure of AM Ti-6Al-4V parts. However, there are limited studies relating to the effects of these defects on the behavior of AM metals in the VHCF regime (beyond 107 cycles). Knowledge of the VHCF behavior of AM Ti-6Al-4V is needed for the aforementioned applications due to the high loading frequencies and long service lives required for these parts.

1. Introduction

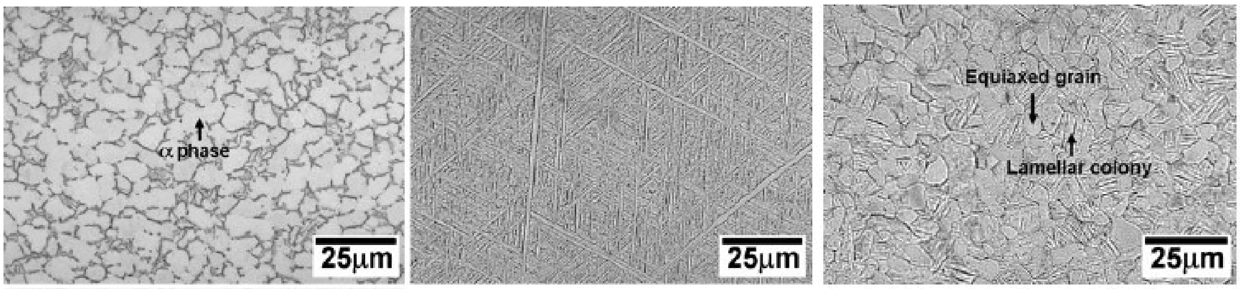
Metallic powder-based additive manufacturing (AM) methods, such as Laser Beam-Powder Bed Fusion (LB-PBF) and Direct Laser Deposition (DLD), can form high density metallic parts in a layer-wise fashion (Xu et al., 2015). Compared to traditional metal manufacturing processes, AM does not require special tooling or molds, which allows for affordable low volume production of functional parts. AM technologies simply require a computer aided design (CAD) model of a part and the metal powder that is to be used. It is expected that the aerospace industry could greatly benefit from metallic AM as it would allow for the production of part geometries that are too difficult or otherwise impossible to create using the traditional manufacturing processes. In particular, the ease of manufacturability of the turbine and compressor blades in jet engines would greatly increase (Gunther et al., 2017).

Titanium (Ti) 6Al-4V is an alloy that is commonly used in the aerospace industry and is also one of the many functionally graded materials available for use in metallic AM. Ti-6Al-4V has many favorable properties for aerospace applications, such as a higher strength to weight ratio as compared to ferrous materials, as well as corrosion and creep resistance (Murr et al., 2008, Heinz & Eifler, 2016). For AM of critical components to surpass those fabricated using traditional manufacturing methods, it is imperative that all material properties, especially fatigue behavior, are fully understood. Since structural fatigue failure accounts for up to 90% of all mechanical failures, extensive material testing and modeling are a necessary benchmark for engineers to properly design parts to withstand cyclic loading (Stephens & Fuchs, 2001). Low and high cycle fatigue (LCF and HCF) behavior studies have already been carried out for AM Ti-6Al-4V; however, critical engine components such as turbine or compressor blades in jet engines require the knowledge of very high cycle fatigue (VHCF) performance which accounts for fatigue lives greater than 107 cycles (Gunther et al., 2017). These critical parts are subjected to very high loading frequencies greater than 1 kHz and require a service life of greater than 109 cycles (Gunther et al., 2017).

Unlike the mechanical properties of conventionally processed metals, those of Ti-6Al-4V parts produced by powder based metallic AM are influenced by many factors, most importantly, process induced defects, residual stresses, and unique microstructures (du Plessis et al., 2018, Gunther et al., 2017, Seifi et al., 2016). Process induced defects in the form of lack of fusion voids from un-melted or un-fused powder particles or pores from entrapped gasses can be detrimental on the mechanical performance (Murr et al., 2008, Seifi et al., 2015, Tammas-Williams et al., 2014). Under cyclic loading, these defects act as stress risers and are common crack initiation sites (Leuders et al., 2012, Gunther et al., 2017). In addition to the high possibility of defects, the rapid heating and cooling associated with metal AM can introduce a variable distribution of residual stresses throughout parts which may have adverse effects on fatigue resistance (Gunther et al., 2017). Various researchers have investigated the effects of post build hot isostatic pressing (HIP), stress relief heat treatment, and manipulation of build parameters as ways to improve mechanical performance (Gunther et al., 2017, Ali et al., 2017). Still, a detailed understanding of these effects is lacking.

2. Effects of Microstructure

A material's microstructure can greatly influence its various mechanical properties (Stephens & Fuchs, 2001). For example, the yield strength of a material is directly related to the size and orientation of the grains within its microstructure. The boundaries between different grains serve as roadblocks for slip; therefore, larger grained metals are more ductile than their smaller grained counterparts (Meyers & Chawla, 2001). Grain size is also known to affect fatigue behavior of Ti-6Al-4V in a similar manner: as the grains become coarser, fatigue resistance decreases (Everaerts et al., 2016, Heinz & Eifler, 2016). Ti-6Al-4V is a two-phase alloy consisting of a hexagonal close-packed alpha phase and a body centered cubic beta phase. Varying thermo-mechanical processing methods plays a critical role in the formation of different microstructures and phase contents in commercially available titanium. The three most common microstructures of Ti-6Al-4V are equiaxed, lamellar, and bimodal (Park et al., 2011). The temperature at which titanium is processed determines the resulting microstructure. Titanium processed above the beta-transus temperature results in lamellar titanium shown in Figure 1b. Lamellar titanium microstructures contain a mixture of long grains of alpha and beta phase ordered in a neat, layered fashion (Meyers & Chawla, 2001). Titanium processed below the beta-transus results in equiaxed and bimodal microstructures, shown in Figures 1(a) and (1c). Equiaxed microstructures consist of primarily large alpha phase crystals, with small amounts of randomly sized and oriented beta crystals (Park et al., 2011). Bimodal microstructures are simply a combination of equiaxed and lamellar titanium microstructures. The material processing discussed in this paper results in microstructures that are somewhat unique due to the inconsistent thermal history of parts manufactured by powder-based AM methods (Galiando-Fernandez et al., 2018).



(a) (b) (c)

Figure 1. Common microstructures of commercially available wrought Ti-6Al-4V: (a) equiaxed, (b) lamellar, and (c) bimodal (Park et al., 2011)

The fabrication process of AM Ti-6Al-4V involves rapid heating and cooling of the metal, which induces a unique microstructure formation (Galiando-Fernandez et al., 2018). The electron backscatter diffraction (EBSD) maps in Figure 2 represent the typical microstructural configurations of Ti-6Al-4V fabricated using LB-PBF and DLD processes. The microstructures shown in Figure 2 are primarily alpha titanium with small amounts of beta titanium scattered between alpha grains. However, it is suggested that the rapid heating with a laser followed by rapid cooling causes a martensitic transformation of alpha titanium, whereas the microstructures of wrought Ti-6Al-4V in Figure 1 are formed through controlled beta-to-alpha heating and cooling (Xu et al., 2015). The EBSD mapping software used in Figure 2 is unable to distinguish between alpha titanium and martensitic alpha prime titanium. The LB-PBF strategy results in a lamellar microstructure of mostly fine columnar alpha-titanium with small amounts of beta-titanium, seen in Figure 2(a). Post build heat treatment of LB-PBF specimens causes a coarsening of the alpha grains, seen in Figure 2(b). These two batches of specimens were tested at both high and low frequencies. Figure 2(c) shows the microstructure of a test specimen that was produced by DLD and has a much finer grained microstructure than any of the test specimens produced by LB-PBF.

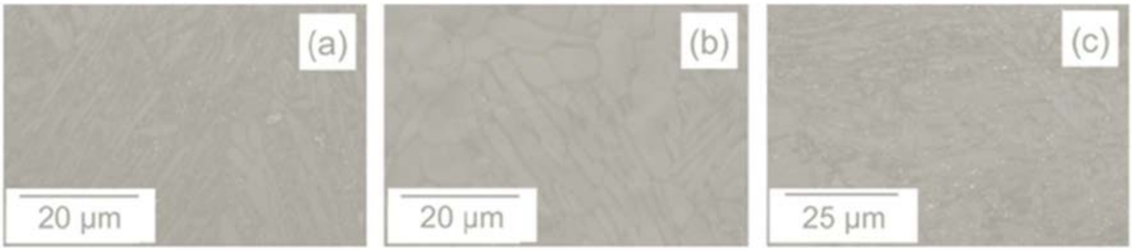


Figure 2. EBSD maps of various microstructures produced by additive manufacturing (a) as build LB-PBF (b) heat treated LB-PBF and (c) DLD (Leuders et al., 2012)

In the VHCF regime, AM Ti-6Al-4V experiences exclusively sub-surface fatigue failure (Gunther et al., 2017). The use of HIP as a post process means of decreasing porosity in AM metallic parts has been proven to improve fatigue performance (Masuo et al., 2017, Gunther et al., 2017). The HIP process leads to a drastic decrease in porosity, which makes test specimens more likely to experience fatigue failure as a result of sub-surface crack initiation at microstructural anomalies or interfaces between alpha and beta titanium (Gunther et al., 2017). In addition, entrapped gas pores have a detrimental effect on VHCF performance of AM titanium, which will be discussed in the next section. Gunther et al. (2017) determined that cracks in HIPed specimens tended to originate from smooth features or facets in the microstructure that are difficult to identify, as compared to non-HIPed specimens with much greater amounts of porosity. The two dominating crack initiation sites after

HIP processing are single alpha-phase facets or clusters of alpha-phase facets, respectively (Gunther et al., 2017). Pores in the microstructure were not fully removed from HIP, but no internal cracks were found to have propagated from pores. Fatigue loading can clearly identify the weakest link in microstructure (Gunther et al., 2017). The current results reveal that only a decrease of the size of the alpha-phase clusters could further improve the fatigue life of additively manufactured and HIPed Ti-6Al-4V (Gunther et al., 2017).

Microstructures of titanium parts built using laser AM can vary for many reasons: powder batches from material suppliers can contain inconsistent chemistries, different operating platforms, differing laser parameters, etc., which can all affect microstructural development in AM metallic parts. In addition to variable build parameters, post processing methods, such as heat treatment and machining, can result in parts with inconsistent mechanical performance. Therefore, developing a microstructure sensitive fatigue life model for AM metals seems to be a necessity as AM parts are increasingly adopted in various applications (Sterling et al., 2016).

3. Effects of Defects

Metallic parts that are produced using powder-based AM methods contain defects that are inherent to the process (Seifi et al., 2015). These defects include a lack of fusion of melted or partially melted metal powder between build layers, entrapped gas pores, voids, and poor as-built surface finishes (Seifi et al., 2015, du Plessis et al., 2018). All of these defects are not ideal for parts that experience cyclic loading, as they are likely sites for fatigue crack initiation (Wycisk et al., 2015). Most of these defects can be attributed to non-ideal process parameters and build conditions, such as incorrect laser energy, laser scan speed, humidity of the build chamber, and metal particle size distribution (du Plessis et al., 2018). It is important that the effects of each defect type on mechanical properties and fatigue performance are fully understood because of the random nature of defect formation in AM.

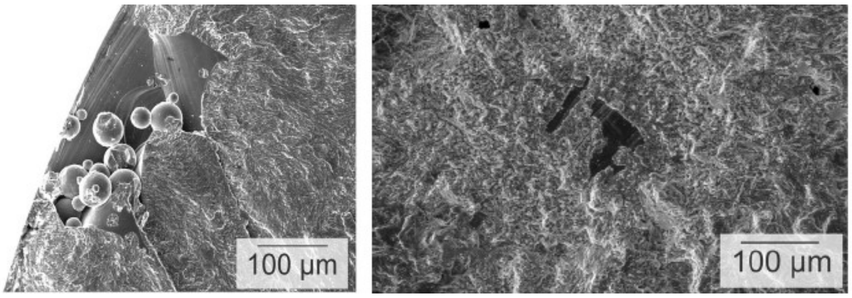
Often during the build process, metallic powder particles are not fully melted and bonded to previously deposit metal layers (Seifi et al., 2015). This type of defect is called lack of fusion (LOF) and can happen on both part surfaces and sub-surfaces between build layers. LOF defects are usually a result of insufficient overlap of successive melt pools between layers (du Plessis et al., 2018).

High amounts of entrapped gas pores and voids can also exist in AM metallic parts. It was suggested by Tillmann et al. (2017) that the rapid heating and cooling of metals used in LB-PBF does not allow enough time for outgas to occur, which results in pockets of entrapped gasses within parts. In some cases, empty spaces between metal powder particles are not filled during the melting and solidification of build layers, which leads to the presence of micro-voids. The Presence of voids and entrapped gasses reduces the relative density of parts and can cause localized reductions in the strength of the material (Pan et al., 2017). Researches such as Gunther et al. (2017) have implemented HIP as a means of closing the gaps between entrapped gas pores or micro-voids.

Lastly, AM parts may experience noticeable flaws on part surfaces, such as artificial notches, stair-stepping, and separation between build layers. These surface flaws act as stress concentrations, which can be detrimental to fatigue and mechanical properties (du Plessis et al., 2018). These defects are characteristic of parts built in a powder bed, as unmelted powder particles bond the part surfaces while the laser-melted metal solidifies. Post process machining and polishing of part surfaces are the only possible means of minimizing the detrimental effects of surface roughness on the fatigue behavior of AM parts. However, it is difficult to assess the exact effects of the as-built surface quality of AM metallic parts mechanical behavior. As-built AM specimens are rarely built to the same dimensional tolerances of test specimens that have been machined. As-built specimens are still expected to fail due to a large amount of pores and internal defects (Edwards et al., 2014).

Fatigue performance of AM Ti-6Al-4V is greatly influenced by the aforementioned process induced defects (Wycisk et al., 2015). In wrought titanium, crack initiation is mostly a function of the microstructure; phase interphases at part surfaces or at part sub-surfaces are likely crack initiation sites since wrought titanium is typically of much lower porosity than AM titanium (Crupi et al., 2016). In AM, the dominating factors influencing crack growth behavior are porosity and LOF defect population. The subsequent fatigue cracks that occur as a result of these defects have been found to initiate from both surface and sub-surface defects (Gunther et al., 2017, Leuders et al., 2012). Post build treatment by HIP removes many of the detrimental process induced defects and significantly improves fatigue performance (Wycisk et al., 2015). AM metallic parts that lack process inherent defects can experience fatigue failures similar to the wrought material, in which cracks are initiated by the weakest link in the microstructure (Gunther et al., 2017, Wycisk et al., 2015).

In the LCF and HCF regimes, AM Ti-6Al-4V experiences fatigue failure from surface and sub-surface fatigue cracks (Gunther et al., 2017). The internal defects that are most likely to initiate fatigue cracks are LOF defects (i.e. portions of partially melted or un-melted sections of metal powder). However, at higher stress amplitudes, fatigue failure is also likely to occur from sharp notches unmelted powder on part surfaces. An example of a surface fatigue failure site can be seen in Figure 3(a). It is clear from Figure 3(a) that the apparent discontinuity on the surface is the crack initiating defect. As fatigue life exceeds 107 cycles, AM Ti-6Al-4V experiences an apparent shift from surface to sub-surface fatigue failure. LOF defects such as those shown in Figure 3(a) are also likely to manifest beneath part surfaces. These defects lack uniformity in shape and size and are dispersed randomly throughout the microstructure. The fracture surface in Figure 3(b) is that of a specimen which failed as a result of a large, sub-surface LOF defect.



(a) **(b)**

Figure 3. LOF defects responsible for fatigue crack initiation in Ti-6Al-4V specimens with (a) $N_f = 1.56 \times 10^5$ cycles and (b) $N_f = 1.17 \times 10^7$ cycles (Gunther et al., 2017)

Entrapped gas pores and micro-voids in test samples had the most significant influence on fatigue performance (Gunther et al., 2017, Leuders et al., 2012). Gunther et al. (2017) compared two sets of specimens built under the same process parameters, however, one set of specimens was HIPed and the other set was only stress relieved. Figure 4 compares the stress-life performance between the two sets of specimens. Clearly, the HIP process significantly reduced the porosity of the specimens, and as a result drastically improved fatigue performance as compared to the non-HIPed specimens (Gunther et al., 2017). However, even the HIPed specimens contain some remnant porosity and voids, which shows that the HIP process only minimizes the presence of pores only. Micro-voids cannot be removed by any post processing techniques. This same result has also been observed in other studies (Masuo et al., 2017).

The cost and environmental effects associated with HIP may burden the benefits of AM. The presented studies have shown that HIP is the most effective post-process method to increase fatigue resistance of AM titanium parts. It would be more advantageous to the manufacturer if parts did not require HIP or any post build heat treatments to be used in cyclically loaded applications. Kasperovich and Haussman (2015) successfully optimized laser scan parameters as a means of decreasing remnant porosity. Optimal build parameters were able to decrease porosity to below %0.077 of the total part volume, subsequent HIP only further decreased this value (Kasperovich and Haussman, 2015).

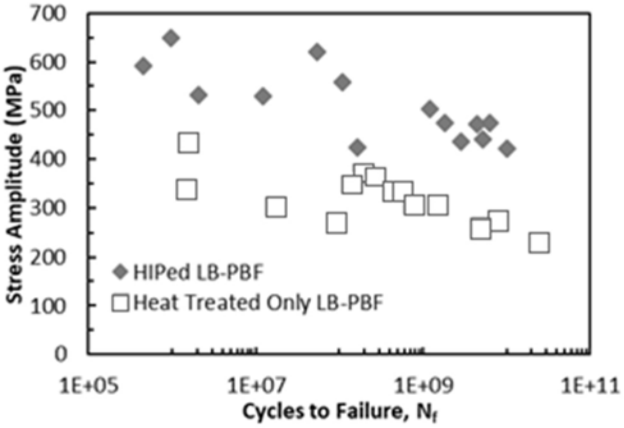


Figure 4. Comparative stress-life (S-N) data of LP-PBF Ti-6Al-4V specimens with and without HIP treatment (Gunther et al., 2017)

Based on the results of the presented studies, it is evident that AM Ti-6Al-4V can be adequately used in structural applications, after a series of post-build treatments. HIP treatment of as-built AM metallic parts is a necessary first step for diminishing the presence of process inherent defects, which are the most common sites for cracks to initiate. In order to advance AM of metals like titanium, continuous improvement of AM technologies, post processing methods, characterization, and mechanical testing are required.

4. Effects of Residual Stresses

AM allows for manipulation of several process control parameters such as laser scan speed, build platform temperature, cooling rates, and vacuum pressure of the chamber (Ahmad et al., 2018). It is known that all these parameters affect the microstructural development of the part, and coincidentally affect mechanical properties and fatigue performance (Seifi et al., 2015, Gunther et al., 2017). Microstructural development of AM metallic parts is primarily a function of build temperature. Wook Na et al. (2018) determined that by increasing the power of the laser in LB-PBF Ti-6Al-4V leads to a higher Vickers hardness of the part. Wook Na et al. (2018) concluded that by increasing the laser power, the overall temperature of the melt pool increased. This increase of melt temperature raises the partial pressure of the gasses trapped within the melt, which increases the chance of outgas (Wook Na et al., 2018)

Gunther et al. (Gunther et al., 2017) analyzed the effects of different heat treatment methods on fatigue behavior of AM Ti-6Al-4V. Three batches of test specimens were built using LB-PBF, two of which were heat treated for two hours at 800°C in Argon, and the third batch was HIPed for two hours at 920°C and 1000 bar. Wrought Ti-6Al-4V test specimens that are stress relieved after machining are known to exhibit superior fatigue performance in the VHCF regime, but this is mostly due to microstructural changes imposed by heat treatment (Adams et al., 2016). The rapid heating and cooling of metal that takes place during the AM process induces the detrimental residual stresses effects on fatigue resistance in parts (Ahmad et al., 2018, Li et al., 2018). In general, compressive residual stresses can be beneficial for fatigue performance, especially in retarding crack initiation and propagation (Stephens & Fuchs et al., 2001).

Distribution of residual stresses in AM metallic parts can be correlated to the build layer orientation. It was found that tensile residual stresses are of the highest magnitude along the build direction and on outer surfaces of LB-PBF parts, while compressive residual stresses are more concentrated in the part center (Ali, 2017). Heat treatment is not the only way to reduce residual stresses. In situ observation of residual stress development in AM Ti-6Al-4V shows that pre-heating the build plate of an LB-PBF machine, and subsequently decreasing the cooling rate to a value much lower than if no pre-heating was applied, significantly increases ductility, which is characteristic of stress relieved parts (Ali et al., 2017).

Residual stress development in parts also varies depending on the AM process utilized. Tensile residual stresses are highest in as-built LB-PBF Ti-6Al-4V test specimens, as compared to specimens built with DLD (Gunther et al., 2017). This is mostly due to the significant difference in cooling rates between the two build processes. DLD build chambers can be held at higher temperatures than LB-PBF machines are capable of. The residual stresses in as-build DLD specimens were found to be very similar in value and distribution to those in LB-PBF specimens. DLD provides an immediate advantage over LB-PBF because superior mechanical properties can be achieved by DLD without the need for post process heat treatment (Gunther et al., 2017).

The effect of residual stresses on fatigue performance of AM Ti-6Al-4V has not yet been studied directly. Siddique et al. (2016) observed both quasi-static and VHCF properties of AM AlSi12 manufacturing using LB-PBF with build platform heating in lieu of post processing techniques such as HIP and heat treatment. The method of build platform heating significantly reduces the temperature difference between the build platform and the metal as it is melted by the laser. This lowers the cooling rate experienced by the metal, which consequently lowers the ultimate tensile strength and yield strength due to coarsening of the microstructure (Siddique et al., 2016). Figure 5 is the resulting S-N curve of this study (Siddique et al., 2016). Build platform heating is an effective means for enhancing VHCF performance of LB-PBF parts without additional post processing.

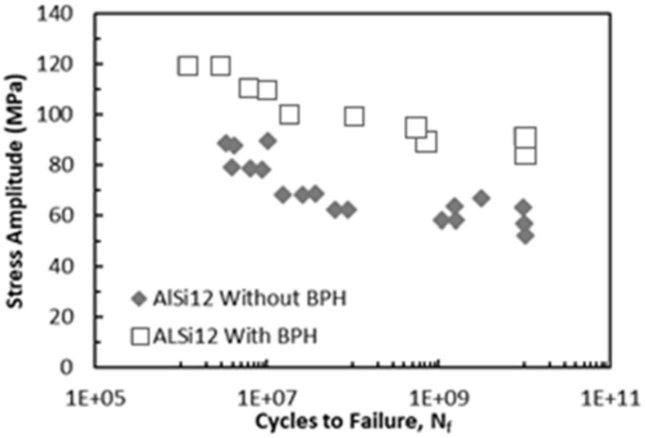


Figure 5. Fatigue life curve of AM AlSi12 up to VHCF with and without build platform heating (BPH) (Siddique, 2016)

5. Conclusions

Fatigue performance of additively manufactured metallic parts shows a strong dependence on microstructural characteristics (i.e., grain size and orientation), as well as phase composition in multiphase materials. In most cases, the presence of surface flaws and internal defects are the two distinct characteristics that lead to fatigue failure in AM metallic parts. In general, it can be concluded that VHCF failure is exclusively due to cracks initiation from process induced surface defects, and that fewer surface cracks can lead to much longer fatigue lives in Ti-6Al-4V specimens. After 106 cycles and up to 109 cycles, the main cause of fatigue failure is the lack of fusion of metal powder or high amounts of porosity. Nonetheless, VHCF performance can be significantly improved by implementing post process HIP to minimized remnant porosity.

Fatigue lives of AM specimens seem to follow the trend observed in the wrought counterparts: as the applied stress decreases, the dominating site for fatigue failure shifts from surface failure to the sub-surface failure. Moreover, the relationship between residual stresses and VHCF of AM metallic parts is not fully understood due to very limited studies. Stress relief of AM metallic parts was found to increase the fatigue strength due to the coarsening of the microstructure. Build plate heating in the LB-PBF process could be utilized as an alternative to post process stress relief as it does not affect the build time, but it has been shown to increase the VHCF resistance over the specimens fabricated on the non-heated build plate.

While the studies presented in this overview paper show a promising future for AM of titanium for structural parts, there is still a significant lack of reliable fatigue data, which means that immediate adaptation of AM as a production method may not yet be applicable. Until Ti-6Al-4V is adequately characterized for its mechanical behaviors and performance, and AM build and test parameters are streamlined by global standards, it may remain in low stress, low risk applications.

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