Effects of Post-processing on the Surface Finish, Porosity, Residual Stresses, and Fatigue Performance of Additive Manufactured Metals: A Review

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Additive manufacturing (AM) has attracted much attention due to its capability in building parts with complex geometries. Unfortunately, AM metals suffer from three major drawbacks, including high porosity, poor surface finish, and tensile residual stresses, all of which will significantly compromise the fatigue performance. These drawbacks present a major obstacle to the application of AM metals in industries that produce fatigue-sensitive components. Many post-processing methods, including heat treatment, hot isotropic pressing, laser shock peening, ultrasonic nanocrystal surface modification, advanced finishing and machining, and laser polishing, have been used to treat AM metals to decrease their porosity, improve the surface finish, and eliminate tensile residual stresses. As a result, significant improvement in fatigue performance has been observed. In this paper, the state of the art in utilizing post-processing techniques to treat AM metals and the effects of these treatments on the porosity, surface finish, and residual stresses of metal components and their resultant fatigue performance are reviewed.

Keywords additive manufacturing, fatigue performance, laser shock peening, post-processing, ultrasonic nanocrystal surface modification

1. Introduction

Additive manufacturing (AM) has the capability, through a layer-by-layer approach, to build parts with complex geometries that are difficult or even impossible to build through traditional subtractive manufacturing processes. AM processes also have other advantages, including a high level of flexibility, a high material utilization, a lower time-to-market, a near-net-shape production without the need for molds, tools, and related equipment (Ref 1–5). Considering its process capability, AM is a game-changing technology with unlimited potential that cannot be matched by conventional manufacturing processes (Ref 5). However, additively manufactured metals suffer from three major drawbacks, namely high porosity (Ref 6), poor surface finish (Ref 7), and tensile residual stresses (Ref 8, 9), the synergistic effects of which significantly compromise the fatigue performance of AM metallic components and structures (Ref 10).

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In addition to poor fatigue performance, in-sample variability and sample-to-sample variability (large scatter in fatigue life data (Ref 11) all present a major obstacle for the application of AM metals in many industries (such as the aerospace industry) that have stringent part requirements (Ref 10, 12). As reported, AM has already been used in the production of nonflight-critical hardware—one example is the bleed air leak detect (BALD) bracket on Lockheed Martin's Joint Strike Fighter platform (Ref 13). For AM metals that are qualified materials for the aerospace industry, significant improvement in the mechanical properties of the metals under both static and dynamic loading is needed (Ref 14, 15). It should be noted that AM metals also suffer from issues of anisotropy and heterogeneity of the microstructure, and these issues also affect the mechanical properties, as reviewed by Kok and co-workers (Ref 9) and reported by Xiang and co-workers for a Co-Cr-Mo alloy (Ref 16).

Numerous research efforts have been conducted to address the issues with AM metals through process optimization and in situ process monitoring/control. For example, Gong and co-workers (Ref 17) studied the effects of energy density, scanning speed, and hatch spacing on the porosity of Ti64 alloy fabricated by selective laser melting (SLM), in which a high-power-density laser is used to melt metallic powders and fuse them together. This study revealed that there exists an optimal process window that can produce a very low porosity in the alloy and, thus, impart a potentially high fatigue performance. However, it has also been recognized that even though optimal process parameters can be selected, defects can still occur for many other reasons, such as a system that is out of calibration (a power drop in the laser, for example), changes in gas flow in the building chamber, and pre-existing pores in the metallic powder (Ref 18). It has been reported that up to 100 different process parameters (including the laser power, build rate, scan rate, beam size, layer thickness, powder characteristics, and other factors) can affect the thermal history and thus the microstructure and fatigue performance of the metals (Ref 19).

As a result, process optimization cannot completely solve the three major issues (high porosity, poor surface finish, and tensile residual stresses).

Post-processing methods are very effective for improving the fatigue performance of AM metals by improving their surface finish, decreasing porosity, and eliminating tensile residual stresses. Popular post-processing methods include heat treatment, deformation-based surface finishing, chemical polishing, and laser polishing. While the most effective way to improve the fatigue performance of AM metals is to combine process optimization with post-processing, this review focuses on how the post-processing methods affect the porosity, surface finish, and residual stress of the AM metals and thus their fatigue performance.

In this paper, we will first review how the surface finish, porosity, residual stress status, and microstructure affect the fatigue performance of AM metals. Next, we will review how popular post-processing methods affect these surface characteristics and thus the fatigue performance of the AM metals.

2. Factors that Influence the Fatigue Performance of AM Metals

AM metals have equivalent or even higher tensile strength when compared to conventional metals, but they have deteriorated fatigue performance [20]. Therefore, it is important to understand why AM metals have poor fatigue performance. When subjected to cyclic loading, fatigue cracks develop in three stages: crack initiation (the stage at which a crack forms), crack propagation (the stage at which the crack grows and spreads through the material), and final fracture (the stage where the component fails). The fatigue life of a component is composed of the crack initiation life and crack propagation life. In the presence of many surface defects, multiple micro-cracks can grow simultaneously under cyclic loading. Eventually, these micro-cracks will link up and lead to final fracture.

Crack initiation and propagation behavior are strongly influenced by the surface finish, porosity, residual stress status, and microstructure of the material. The unique nature of the AM fabrication process results in a surface finish, porosity, residual stress status, and microstructure in the processed metals that are dramatically different from those in metals fabricated using traditional methods, where metals are wrought (the metal is beaten into shape) or produced by casting (molten metal is poured into a mold). While it is known that numerous factors (i.e., surface roughness, porosity, microstructure and residual stress) are mutually correlated with one another (Ref 21), surface roughness and porosity play a dominant role and should be the focus of efforts to improve the fatigue performance of AM metals through post-processing. Typically, AM metals have poor surface finish and high porosity in addition to detrimental tensile residual stresses, all of which will accelerate crack initiation and propagation. As a result, AM metals have much lower fatigue performance and larger scatter in fatigue life data, especially in the high cycle fatigue (HCF) regime as compared to traditionally manufactured metals (Ref 6, 22). For example, at a cyclic stress amplitude of only 50 MPa, the fatigue life of Ti64 samples fabricated by direct metal laser sintering (DMLS) ranges from a few tens of thousands to one hundred thousand cycles (Ref 23). Note that

for typical wrought Ti64, the fatigue strength (corresponding to 1 million fatigue cycles) is around 400 MPa (Ref 24).

The fatigue performance of AM metals is also affected by their strength and ductility (Ref 25). Typically, AM metals have higher strength and lower ductility as compared to traditionally manufactured metals. The lower ductility of AM metals results in poor performance in the low cycle fatigue (LCF) regime, where the crack propagation stage dominates because the crack initiation occurs rapidly, with a short duration at a high stress amplitude. Moreover, both the detrimental tensile residual stresses and the AM microstructure will also reduce the fatigue performance of AM metals.

2.1 Surface Roughness

Since many cracks are initiated from the surface of a metal component, surface finish plays an important role in fatigue performance of AM metals. In general, these materials do not have good surface finish in the as-built conditions (Ref 26, 27). According to a study by Li et al. (Ref 19), the poor surface finish of AM metals has three major causes: (1) the staircase effect from the layer-by-layer manufacturing process (Ref 28, 29), (2) balling (Ref 30, 31) or adherence of partially melted powders to the surface of the metal, and (3) open pores and zones where melting is incomplete.

On a rough metal surface, stress concentrates at many locations on the surface that can serve as potential crack initiation sites (Ref 32). As shown in the schematic diagram in Fig. 1, notches in the near-surface region will result in higher local stresses and a higher stress intensity factor and, thus, poor fatigue performance (Ref 33). This local stress is affected by the stress intensity factor of the notch.

The elastic stress concentration factor, K_t , is calculated using (Ref 35):

$$K_t = 1 + 2\sqrt{\frac{t}{\rho}} \quad (\text{Eq 1})$$

where t is the depth of the notch and ρ is the radius at the root of the notch. It can be observed from Eq. (1) that a greater depth and a smaller root radius will lead to a higher value for K_t . As the average notch depth is rarely measured in practice, Neuber used a semi-empirical equation to relate the surface stress concentration factor with roughness parameters R_z as follows:

Fig. 1 Near-notch stress trajectories for surfaces with a single notch (top) and multiple notches (bottom). Reprinted from [34], Copyright 2002, with permission from Elsevier

$$K_t = 1 + n \sqrt{\lambda \frac{R_z}{\rho}} \quad (\text{Eq } 2)$$

where R_z is the 10-point surface height; ρ is the notch root radius; n is a constant that is equal to 1 when the material is in a shear stress state and 2 when it is in a tension stress state; and λ is the ratio between the width and the height of the notch (i.e., $\lambda = b/t$ in Fig. 1). A typical value of 1 for λ is appropriate for a mechanically processed surface.

Based on Eq. (2), it can be concluded that high surface roughness parameters R_z will typically lead to a higher K_t value, whereas a smooth surface with very low R_z has a K_t value of 1 (ρ goes to a very large number or to infinity). Compared with a surface having a K_t value of 1, a surface with a high K_t value will have a much higher stress concentration, which will lead to rapid crack initiation and propagation and, as a result, poor fatigue performance. For example, in a study by Chan and co-workers (Ref 22), the K_t values for Ti64 treated using electron beam machining (EBM) and laser beam machining (LBM) are 9.1 and 5.4, respectively, and both of the treated specimens exhibited lower fatigue performance as compared to Ti64 that is cast, rolled, or treated using electrical discharge machining (EDM), all of which have a K_t value of 1. Rigon and co-workers (Ref 36) used the El-Haddad model and estimated that the fatigue strength decreases with an increase in the size of the surface defect.

Figure 2 shows the double logarithmic plot of the mean fatigue life of various Ti64 samples as a function of the maximum surface roughness (R_a) from the work by Chan and co-workers (Ref 22). This figure shows a general trend that a lower R_a value corresponds to a higher fatigue life. This behavior can be explained by Eq. (2). As the R_a value increases, the K_t value will also increase, and this creates higher stress raisers. As a result, higher R_a values will lead to a reduced fatigue life, while lower R_a values correspond to a higher fatigue life. Note that in addition to the uncertainty of the surface roughness measurement, the fact that many other factors (such as the microstructure, the strength, and ductility) will affect the fatigue performance of the metal leads to the

Fig. 2 Mean fatigue life as a function of the maximum surface roughness (R_a) for AM Ti64 processed using various methods. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, *Metallurgical and Materials Transactions A*, K.S. Chan, M. Koike, R. Mason, and T. Okabe T., Fatigue Life of Titanium Alloys Fabricated by Additive Layer Manufacturing Techniques for Dental Implants, Copyright 2013 [22]

large scatter in fatigue life data, as manifested by the high error bars in the data points in Fig. 2 (Ref 22).

A similar effect of poor surface finish on the stress concentration factor and, thus, the fatigue performance has been observed by Kahlin and co-workers (Ref 37). The fatigue notch factor K_f , also called the fatigue stress concentration factor, is defined as the ratio of the fatigue strength of a smooth sample to that of a notched sample. The rough surface, together with the geometrical notch ($K_t = 2.5$), resulted in a K_f of 6.15 for SLM-treated Ti64 and 6.64 for EBM-treated Ti64 (Ref 37). As a result, the fatigue limits were reduced by 45% and 75% for SLM-treated Ti64 and EBM-treated Ti64, respectively (Ref 37). Even though mechanical properties, microstructure, and other factors also affect the fatigue performance of AM components, poor surface finish is believed to be the major cause for the poor fatigue performance of AM components in comparison with milled components (Ref 38). For example, the fatigue strength of as-built AM Ti64 is only 300 MPa (at 30 million cycles) because of the poor surface finish (Ref 26). By improving the surface finish to an R_a of 0.3 μm through milling, the fatigue strength was increased to 750 MPa.

As discussed previously, crack initiation life, especially in the HCF regime, plays a dominant role in the total fatigue life. The rough surface features can act as local stress raisers for cracks to initiate and propagate during cyclic loading. Some scholars maintain that the low valleys on the surfaces of AM metals can be treated as short cracks (Ref 39). In that sense, the initial phase of fatigue damage (i.e., crack initiation), which dominates the HCF regime, is bypassed for metals with defects on the surface (Ref 33, 40, 41). Un-melted particles on the surface can also contribute to poor fatigue performance. Yue and co-workers (Ref 42) observed numerous crack initiation sites close to the particle/substrate interface using scanning electron microscopy and found that the crack initiation sites are major sources of weakness under cyclic loading. As a result, the fatigue performance of AM metals is severely compromised.

Greitemeier et al. (Ref 38) also demonstrated that high surface roughness is the dominant factor for the poor fatigue performance of AM Ti64. Even though the porosity has been decreased, the fatigue performance of AM Ti64 was not improved due to the poor surface finish, and most of the crack initiation sites originated at stress concentration sites on the surface. It has also been demonstrated that, for both AlSi₁₀Mg (Ref 23) and Ti64 (Ref 38, 43), as-fabricated AM parts exhibit much lower fatigue performance as compared to machined AM parts.

The ductility of the metallic materials used for manufacturing a component will also affect the sensitivity of the part to surface roughness. In general, ductile materials are less sensitive to stress concentration caused by surface roughness or defects, as a large plastic deformation zone is formed near the defects during cyclic loading (Ref 44). Typically, AM metals are more brittle than traditional metals due to their high defect density and high porosity (Ref 41, 45). For example, the fine-grained α' martensitic microstructure that results from rapid cooling during AM (Ref 45), in conjunction with the high porosity, makes Ti64 very brittle (Ref 41). This could cause AM Ti64 to become even more sensitive to the poor surface roughness. The potential for oxygen pickup by AM Ti64 also contributes to its high brittleness, which will increase its sensitivity to premature crack initiation (Ref 44, 46). Due to its full martensitic microstructure and the presence of pores, AM Ti64 typically exhibits a very brittle behavior (Ref 41, 45).

Even though AM Ti64 has higher yield and tensile strengths as compared to traditional Ti64, the fatigue life is much lower than that for traditional Ti64 due to the much lower ductility (Ref 41).

It is noted that surface roughness measurements in most current studies of AM metals were conducted using non-contact methods. This could be problematic, as non-contact methods cannot distinguish powder particles attached to the metal surface and, thus, may not be able to accurately characterize the actual surface features (Ref 27). Consequently, when we use the surface R_a values to predict the fatigue performance of AM metals, we should be aware of the limitations of using this method. It should also be noted that while the current surface characterization methods (both stylus and light-based profilometry) are able to capture the features of the outermost surface of the material, they are not capable of capturing the three-dimensional (3D) subsurface details. The subsurface features should not be ignored, as subsurface porosity could be detrimental to fatigue performance because they provide stress raisers (Ref 32). As demonstrated by Kahlin and co-workers (Ref 47), surface roughness alone is not a sufficient indicator of fatigue performance, as surface defects can be hidden below a smooth surface. Kantzo and co-workers (Ref 32) demonstrated that by capturing the full 3D surface and subsurface features through synchrotron-based x-ray computed tomography, better prediction of the mechanical properties of AM metals can be achieved.

As claimed in a number of studies (Ref 22, 26, 37, 38), reducing the surface roughness is the single most effective way to improve the fatigue performance of AM metals. It is known that surface roughness can be somewhat controlled by manipulating the process parameters. For example, using a lower laser power in the direct energy deposition process will result in lower surface roughness, as was observed by Zhai and co-workers (Ref 48). By decreasing the layer thickness or by using other process optimization schemes, the surface roughness of AM metals can be decreased to a certain extent. Using a large overlap in the scanning paths in laser-based AM processes can also decrease the surface roughness (Ref 49, 50). However, it should be pointed out that the optimization of AM process parameters can only alleviate the surface roughness issue to a certain extent (Ref 38). The most effective way is still to use post-processing methods (Ref 41, 51).

2.2 Porosity

In addition to poor surface finish, porosity also plays an important role in the fatigue performance of AM metals. Compared with cast or wrought metals, AM metals typically have a higher porosity (Ref 52, 53). As they can serve as stress raisers, pores also significantly decrease the critical stress intensity factors for crack initiation and, thus, significantly compromise the fatigue performance of the metals (Ref 54). Pore-based failure initiation has been observed in AM aluminum alloys (Ref 54), Ti alloys, maraging steel, and stainless steel. The presence of these pores significantly decreased the threshold stress intensity factor (k_{th}) for crack initiation and propagation. This detrimental effect is influenced by the size, shape, density, and location of the pores.

Pores in AM metals are formed in two ways: (1) gas trapped in the metal as a result of vapor recoil during the melting process (Ref 3) and (2) voids between un-melted particles that were not fused during the layer-by-layer manufacturing process

(Ref 55, 56). Pores formed by entrapped gas are typically spherical (as those shown in Fig. 3a), and contamination of the green powder and evaporation during the deposition process are known to contribute to the generation of these pores (Ref 57). In contrast, pores resulting from a lack of fusion result from the selection of improper process parameters (e.g., a laser energy density that is too low). These pores are typically elongated, irregular, and larger than the ones formed by entrapped gas, and they lead to a higher concentration factor near the edges, which contribute to lower fatigue performance for the component (Ref 41). When the component is subjected to cyclic loading, pores with sharp edges will cause the high local stress to reach the yield strength, resulting in local plastic deformation and premature failure. The long edges of these pores are typically parallel to the scanning direction and perpendicular to the building direction (Fig. 3b), and this pore orientation is partially responsible for the anisotropy in the fatigue performance of AM metals. It is also noted that the location of pores is also important: pores in the near-surface region are typically more detrimental to the fatigue performance as compared to pores deeper in the interior (Ref 41), as most crack initiation sites are located in the near-surface region.

Numerous efforts have been aimed at reducing the porosity of AM metals by optimizing the deposition strategy. For example, relative densities up to 99.77% and 99.9% have been achieved in SLM Ti64 (Ref 46). Unfortunately, even though the relative density seems very high, the negative impact of the pores remaining in the material on the cyclic behavior of the AM components is still significant (Ref 46). One of the most effective ways to reduce porosity is through hot isostatic pressing, which will be discussed later.

2.3 Residual Stresses

Due to the high thermal gradient (on the order of -5×10^4 K/cm in beam-based additive manufacturing of Ti64 (Ref 8)) and the rapid cooling rate during additive manufacturing, AM metals typically have high tensile residual stresses. The magnitude of the tensile residual stress in the top surface can go as high as the yield strength of the material (Ref 59). The magnitude and distribution of these residual stresses are affected by the AM process parameters, including the scanning strategy, track length, hatch spacing, laser (electron) beam parameters, and other factors. Due to the higher thermal gradient in the scanning direction, it has been observed that the magnitude of the residual stress in the scanning direction is greater than that in the transverse direction (Ref 60). With the increase in scanning speed, the magnitude of the residual stress in the scanning direction will increase (Ref 59).

These residual stresses, if left unmitigated, may cause immediate distortion, cracking, failure, and low geometry accuracy of the as-built AM parts and will result in poor fatigue performance (as a result of higher susceptibility to crack initiation and propagation) (Ref 57). Using an optimized laser scanning strategy can also mitigate the residual stress issue to a certain extent (Ref 59, 60). In addition, heating the powder bed to a higher temperature can significantly reduce the magnitude of the tensile residual stresses in laser-based AM processes. For example, in a study by Shiomi and co-workers (Ref 61), it was observed that when the temperature of the powder bed was increased to 160 °C, the magnitude of the tensile residual stress in SLM steel was reduced by 40%. Compared with SLM parts,

Fig. 3 Optical images of pores formed in the AM process due to (a) gas evaporation and (b) a lack of fusion. Reprinted from [58], Copyright 2016, with permission from Elsevier

EBM parts typically have a lower magnitude of tensile residual stresses. In a typical EBM process, the powder bed is heated to a much higher temperature (around 500 °C) than that used in the SLM process (around 100 °C). As a result, the temperature gradient is lower in EBM, leading to much lower tensile residual stresses (less than 100 MPa) in the as-fabricated metals (Ref 62).

Unfortunately, the mitigation of the residual stresses by optimizing the AM manufacture strategy has a limited effect. Post-processing methods, including traditional heat treatment and hot isostatic pressing, are needed to relieve the residual stresses in AM metals. Recent studies (Ref 63, 64) have also demonstrated that surface severe plastic deformation (SSPD) technologies—including laser shock peening (LSP) and ultrasonic nanocrystal surface modification (UNSM)—can effectively transform the tensile residual stress to compressive residual stress. These processes will be discussed in more detail later section.

3. Post-Processing Methods for AM Metals

As discussed previously, AM metals suffer from high surface roughness, high tensile residual stresses, and high porosity (Ref 65). These issues have been reported to negatively affect the mechanical properties, especially the fatigue performance, of AM metals (Ref 38, 57, 66). Many methods, including process optimization, can be used to alleviate these issues; however, such methods are not the focus of this review. Instead, the focus is on how the post-processing methods can affect the surface roughness, porosity, and tensile residual stress of AM metals and, thus, influence their resistance to fatigue. In this section, we discuss popular post-processing methods, including heat treatment, hot isostatic pressing, laser shock peening, shot peening, ultrasonic nanocrystal surface modification, advanced finishing, laser polishing, and other methods as well as their applications in the post-processing of AM metals.

3.1 Heat Treatment

Because of the highly localized heat input and the large thermal gradient in laser-based AM processes, tensile residual stresses, segregation, and non-equilibrium phases exist in as-built AM metals (Ref 2). Stress relief heat treatment can eliminate or decrease the magnitude of the tensile residual

Fig. 4 Residual stresses in SLM iron before and after vacuum annealing treatment. Reprinted from [67], Copyright 2014, with permission from Elsevier

stresses, which is believed to be beneficial for fatigue performance. Song and co-workers (Ref 67) demonstrated that vacuum annealing at 640 °C for 2.5 h can eliminate the tensile residual stresses in SLM Iron, as shown in Fig. 4.

The unstable microstructures in as-built AM metals can be made stable through controlled heat treatment. Heat treatment can change the microstructure of AM metals and thus the strength/ductility. Vrancken et al. (Ref 2) found that heat treatment can significantly affect the strength and ductility of AM Ti64. Specifically, it was found that higher heat treatment temperature will result in lower yield strength, lower ultimate tensile strength, and high fracture strain due to the transformation of α' needles to a more complex duplex microstructure composed of α and β phases. It has also been demonstrated by other studies that proper post-heat treatment can improve the ductility of AM Ti64 (Ref 18, 55). Rafi and co-workers (Ref 68) observed that heat treatment at 788 °C for 2 h can increase the tensile strength of SLM 17-4 precipitation-hardenable steel. Wang and co-workers (Ref 69) found that T6-like heat treatment can significantly improve the ductility of SLM AlSi10Mg aluminum alloys without significantly decreasing its strength. Mooney and co-workers (Ref 70) collected comprehensive experimental data of different heat treatment parameters (temperature, duration) on the hardness, strength, ductility, and anisotropy of maraging 300 alloy steel. It has

Fig. 5 HIP process: (a) Gas molecules impinge on the surface-connected porosity as though it were an extension of the surface. (b) After coating, the surface-connected porosity can be enclosed and becomes an internal feature. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, *Metallurgical and Materials Transactions A*, H.V. Atkinson and S. Davies, Fundamental Aspects of Hot Isostatic Pressing: An Overview, Copyright 2000 [74]

been demonstrated that by tailoring the heat treatment parameters, the desirable strength/ductility/anisotropy requirements for AM metals can be achieved.

Heat treatment can bring beneficial microstructure changes that leads to increase in the fatigue crack propagation resistance (Ref 71). As reported by Zhai et al. (Ref 48), the α' martensitic phase resulted in lower ductility and thus a lower fatigue crack growth threshold in AM Ti64. By decomposing the martensitic phase through heat treatment, however, the fatigue crack growth threshold can be significantly increased. A study by Leuders and co-workers (Ref 57) also demonstrated that heat treatment can increase the threshold stress intensity values of AM Ti64 from $1.4 \text{ MPa m}^{1/2}$ to around $4 \text{ MPa m}^{1/2}$ when the crack growth direction is perpendicular to the building direction, from 1.7 to $3.7 \text{ MPa m}^{1/2}$ (850°C heat treatment) and $6.1 \text{ MPa m}^{1/2}$ (1050°C heat treatment) when the crack growth direction is parallel to the building direction. This also resulted in high fatigue performance. Specifically, through heat treatment at 800°C , the mean fatigue life, at a stress level of 600 MPa , of AM Ti64 can be improved from 27,000 cycles to 93,000 cycles. By increasing the heat treatment temperature to 1050°C , the fatigue life can be further increased to 290,000 cycles.

The types of AM process also affect the heat treatment effect. SLM Ti64 is characterized by a very fine martensitic acicular α' microstructure (a hexagonally close packed structure) due to the very fast cooling rate. Heat treatment of SLM Ti64 will transform the fine martensitic acicular α' to balanced $\alpha + \beta$ microstructure. Due to the high process temperature in EBM, any martensite formed during the initial rapid cooling will be tempered to form a balanced $\alpha + \beta$ microstructure, which eliminates the need of annealing heat treatment. Heat treatment of EBM Ti64 at temperatures higher than transition temperature will result in a microstructure composed of elongated α in a β matrix, similar to the microstructure after hot isostatic pressing (Ref 45, 57).

Heat treatment recipes for cast or wrought metals are sometimes applicable for AM metals. For $\text{AlSi}_{10}\text{Mg}$ alloys, heat treatment to achieve T6 temper is very popular for cast samples to obtain high fatigue resistance. The same effect is evident for AM $\text{AlSi}_{10}\text{Mg}$ (Ref 6). Brandl et al. (Ref 54) reported that T6 hardening increases the fatigue limit by 30–50% after eliminating dendrites, the heat-affected zone, and laser traces. Aging heat treatment resulted in higher hardness in SLM maraging steel than that in its traditional counterpart, as

reported by Mutua and co-workers (Ref 72). Note that the highest tensile strength of the SLM maraging steel was obtained by combining solution treatment and aging treatment.

Sometimes, however, heat treatment recipes that are effective for wrought metals are not practical for AM metals. In a study carried out by Yodollahi and co-workers (Ref 44), heat treating AM 17-4 precipitation-hardened stainless steel samples using recipes (solution annealing followed by peak-aging) optimal for wrought samples did not result in an improvement in fatigue resistance in the HCF regime due to the presence of large voids. This calls for re-evaluation of heat treatment recipes for AM metals. It should also be noted that while one recipe might be good for certain AM metals, it might not be good for the same AM metals fabricated in another laboratory, as the AM process parameters can significantly affect the thermal history and thus the resulting microstructure.

In some cases, heat treatment has little effect on the fatigue performance of AM metals. In a recent study by Riemer and co-workers (Ref 73), it was observed that stress relief heat treatment of AM 316L stainless steel at 650°C for 2 h does not affect the microstructure other than the residual stresses. As AM 316L SS has good fatigue performance in comparison with wrought samples, they can be used without post-processing.

In summary, heat treatment may change the microstructure and thus the strength/ductility of AM metals, in addition to eliminating the tensile residual stresses; thus, heat treatment affects the fatigue performance of these materials. Due to the complexity in the thermal history of the AM processes, the microstructure formed in different AM processes will be different. This creates challenges when selecting optimal heat treatment recipes for different AM metals. While some optimal heat treatment recipes for traditional cast/wrought metals may also work for AM metals, some do not work due to the different microstructure resulting from AM. Therefore, care should be taken when selecting optimal heat treatment recipes for AM metals.

3.2 Hot Isostatic Pressing

Traditionally, hot isostatic pressing (HIP) has been widely used as a heat treatment process in the physical metallurgy community. Due to its popularity for treating AM metals and the vast number of studies in the literature, we will consider the HIP processing of AM metals separately in this section. In the HIP process (shown in the schematic diagram in Fig. 5),

metallic parts are subjected to thermal annealing (typically greater than $0.7 T_m$) and pressure (typically around 100 MPa, which is equivalent to 1000 atm) at the same time, which leads to the collapse and weld-up of the pores (Ref 74). Since the pressure is applied with inert gas, it is thus considered to be isostatic. The isostatic pressure results from the collision of gas molecules with the surface of the target sample. The high-temperature treatment during HIP increases metal flowability, while the isostatic pressure closes the pores. The driving force during HIP treatment is the reduction in the surface free energy of the pores. Because gas molecules can reach all surfaces of the component, HIP works reliably for all shapes. In the HIP process, the three main parameters are temperature, pressure, and process duration. Due to the action of simultaneous application of high pressure and temperature, HIP can also homogenize the microstructure and relieve the residual stresses.

HIP has been widely used as an effective post-processing method for AM metals. For example, Tillmann and co-workers (Ref 75) showed that while most pores in AM metals can be eliminated, some pores with entrapped argon gas from the SLM process remain. HIP has been considered as the most effective way to remove pores in AM metals, thereby improving their fatigue performance. Gunther and co-workers (Ref 76) reported that HIP can significantly improve the fatigue performance of SLM Ti64 by removing porosity. In the very high cycle fatigue (VHCF) regime, HIP-processed SLM Ti64 has a similar performance to that of wrought Ti64.

Typically, AM Ti64 has high yield strength, high tensile strength, and low ductility due to the fine acicular martensitic phase (α' phase) that results from rapid cooling during AM fabrication. HIP can decrease the porosity and change the microstructures of the AM metal, and the extent of the microstructure change depends on the HIP temperature. When HIP is carried out at 700 °C for 1 h, the fine martensitic microstructure will transform to a mixture of α and β phases. When HIP is carried out at 900 °C, the martensitic microstructure will change into elongated α grains embedded in α/β phase.

Hrabe and co-workers (Ref 62) reported that HIP alone can effectively close internal pores and voids, leading to significant improvement (more than 100%) in the fatigue strength limit over EBM as-built samples and stress-relieved samples. While all three groups of samples have similar residual stress and surface finish attributes, the improvement in fatigue strength is mainly a result of the lower porosity. Due to the high process temperature (over 600 °C) in EBM, minimal tensile residual stresses (< 100 MPa) were observed in the as-built Ti64, while stress relief heating and HIP did not significantly affect the residual stresses. Note that the HIP treatment increases the α lath thickness (from 0.7 to 1.6 μm), which is detrimental to the fatigue performance (Ref 77, 78). This finding suggests that the beneficial effect of reducing the internal porosity is even more significant. Note that HIP resulted in reduced yield strength and ultimate tensile strength as a result of microstructure coarsening.

HIP treatment is more effective in improving the fatigue performance of AM metals than traditional heat treatment. As reported by Leuder and co-workers (Ref 57), while traditional heat treatment can significantly improve the fatigue performance of AM Ti64, HIP treatment is more effective. Specifically, heat treatment at 800 °C and 1050 °C increased the fatigue life of as-built Ti64 from 27,000 cycles to 93,000 cycles and 290,000 cycles, respectively; however, the HIP-treated AM Ti64 samples did not fail after 2,000,000 cycles. In another

study by Leuder and co-workers (Ref 46), HIP was found to increase the threshold value ΔK_{th} of SLM-processed Ti64 from 1.42 to 4.2 MPa $\sqrt{\text{m}}$ when the stress ratio was 0.1 and from 3.06 to 9.04 MPa $\sqrt{\text{m}}$ when the stress ratio was -1 . While traditional heat treatment was also able to increase the threshold value ΔK_{th} , the improvement was not as significant as that for HIP.

Kasperovich and co-workers (Ref 45) maintain that to best take advantage of HIP, the SLM process needs to be optimized first, followed by the optimization of the HIP process. Through this two-step optimization process, the SLM-HIP-processed Ti64 can have similar strength, ductility, and fatigue performance as that of wrought Ti64. Due to the high cooling rate in the SLM process, the as-built Ti64 assumes an α' martensitic microstructure. While the strength of martensitic Ti64 is very high, its ductility is very low, and this leads to poor fatigue performance. After HIP treatment, the as-built α' microstructure is transformed into a mixture of α and β phases. At the same time, the porosity is reduced. By combining SLM process optimization and proper HIP treatment, the resulting strength, ductility, and fatigue performance of SLM Ti64 can be comparable to those of wrought Ti64 (Ref 45).

Even after HIP treatment, surface roughness is still the dominant factor affecting the fatigue performance (Ref 79). Sometimes, however, HIP leads to an even rougher surface finish due to the formation of depressions or dimples on the surface after the plastic deformation induced by HIP. For example, HIP imparted no improvement in fatigue strength if the surface finish was not improved (Ref 37), since HIP only affects internal porosity and does not affect surface roughness. Uzan and co-workers (Ref 80) studied the effect of stress relief (SR) and HIP on the fatigue performance of AM AlSi₁₀Mg samples. It was observed that SR + HIP leads to inferior fatigue performance as compared with treatment by SR only. The presence of high surface roughness after HIP treatment is responsible for the decrease in fatigue resistance. These surface defects lead to multiple locations for crack initiation during cyclic loading, thus deteriorating the fatigue performance.

In addition, as surface-connected porosity cannot be removed through HIP, some subsurface pores may still remain (Ref 81). During HIP, the pressurized gas presses against the surface-connected pores as though they were an extension of the material surface. One way to solve this issue is to apply a coating on the AM metals prior to HIP treatment. Once coated, these surface-connected pores become internal pores that can be removed through HIP treatment. Following HIP, the coating material can be machined off or dissolved. It should be noted that coating application and removal will increase cost and of implementing this process, which will make the AM+HIP process less appealing.

Chern and co-workers (Ref 20) found that HIP does not eliminate the rough surface or the early crack initiation sites. In addition, HIP has been reported to increase the α lath size from 1.7 to 3.2 μm in AM Ti64, which is detrimental to fatigue strength (Ref 77, 78). By reducing the internal pores and homogenizing the microstructure, however, HIP can reduce the scatter in the fatigue life data, making the fatigue performance more predictable. Large scatter occurs in the fatigue data if the internal pore size is larger than the surface roughness. By removing internal pores, HIP successfully confines the failure mode to surface-initiated cracks.

By combining HIP treatment with surface finishing treatment, many studies have reported significant improvement in the fatigue performance. On the one hand, HIP is able to decrease porosity; on the other hand, the surface finishing treatment can improve surface finish. A good surface finish combined with low porosity typically translates to good fatigue performance. As reported by Masuo and co-workers (Ref 21), HIP treatment alone cannot improve the fatigue performance of Ti64 fabricated by EBM or DMLS; however, surface polishing using #600 emery paper was found to be more effective than HIP treatment. By combining surface polishing and HIP treatment, Masuo and co-workers (Ref 21) improved the fatigue limit of AM metals so that it is close to the ideal upper bound of conventional metals, as shown in Fig. 6.

Many other studies have also confirmed the synergistic effect of HIP treatment with surface finishing treatment. For example, by combining HIP treatment and surface polishing of Ti64, Kahlin et al. found that samples produced using EBM have a fatigue strength comparable to that of wrought samples (Ref 37). Greitemeier and co-workers (Ref 82) observed no difference between traditional heat treatment and HIP heat treatment on the fatigue performance of DMLS Ti64, even though HIP significantly reduced the porosity. When milling was carried out on HIP-treated AM samples, however, a significant improvement in fatigue strength was observed, as milling significantly decreased the surface roughness. Kasperovich and Hausmann (Ref 45) also found that the fatigue strength of AM Ti64 that underwent HIP and machining is two times that of AM Ti64 that underwent HIP treatment only, indicating that post-HIP machining is able to significantly reduce the surface roughness of AM Ti64. It should be noted that HIP treatment should be conducted prior to machining to obtain the most effective treatment (Ref 41).

Another point to note is that HIP can only eliminate irregular pores in AM metals that are caused by incomplete fusion, while spherical pores caused by the precipitation of insoluble gases will remain (Ref 83). HIP will cause the transformation from martensites to a mixture of α and β phases and grain growth in Ti64, thereby reducing its strength. As a result, a high-temperature β -solution heat treatment followed by a quench is typically needed to restore the strength (Ref 53). Unfortunately, the high temperature will cause the growth of the spherical pores retained after HIP processing, and this will

Fig. 6 S–N curves of EBM samples with different post-processing treatments. Reprinted from [21], Copyright 2018, with permission from Elsevier

lead to greater stress concentration when the metal is subjected to cyclic loading.

While HIP has been widely reported to improve the fatigue performance of AM Ti64, it is not as effective in doing so for other alloys, such as 316L stainless steel. As shown in Fig. 7, Leuders and co-workers (Ref 25) reported that HIP deteriorated the fatigue performance of 316L SS fabricated using laser powder bed fusion (LPBF). For AM Ti64, the fatigue performance is dominated by pores; on the other hand, the fatigue performance of LPBF-fabricated 316L SS is dominated by its yield strength, which will be significantly reduced after HIP. The authors reported that HIP decreased the yield strength of SLM 316L SS from 500 to 360 MPa due to recrystallization and dislocation annihilation. As a result, the fatigue performance of SLM 316 SS was significantly compromised, especially in the LCF regime, as compared with the same material in the as-built condition and even lower than that of the heat-treated samples. For 316L SS in the LCF regime, the fatigue behavior is primarily determined by the yield strength and not by pores or defects. Porosity becomes important only in the VHCF regime when pores serve as crack initiation sites.

In summary, HIP can effectively reduce porosity in AM metals and thus could be used as an effective post-processing method for AM metals. While the beneficial effect of HIP on the fatigue performance of AM metals (mostly Ti64) has been well documented, it should be noted that it may not work for some metals (stainless steel, for example). It should also be noted that HIP typically is not effective in closing surface-connected pores and, thus, cannot improve surface finish. As a result, the effect of HIP treatment alone on fatigue performance of AM metals is limited in some cases; the most effective way is to combine HIP treatment with surface finishing.

3.3 Laser Shock Peening and Shot Peening

Peening has been used as an important post-processing method in many industries to treat fan blades, turbine blades, gears, and other metal components. In the peening process, the material is plastically compressed in the normal direction, resulting in the expansion of the material in the lateral direction (Ref 84). This expansion of the material, in turn, will result in compressive residual stresses in the lateral direction. Peening can be used to induce beneficial compressive residual stresses

Fig. 7 S–N curves of SLM 316L SS in the as-built condition, after heat treatment, and after HIP treatment. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, *Journal of Materials Research*, S. Leuders, T. Lieneske, S. Lammers, T. Tröster, and T. Niendorf, On the Fatigue Properties of Metals Manufactured by Selective Laser Melting—The Role of Ductility, Copyright 2014 [25]

and thus reduce the effective stress of a local area of a component subjected to cyclic loading. This will lead to high resistance to crack initiation and propagation, thereby improving the fatigue performance of the component. Peening can also effectively increase the fatigue strength of a part or a component, enabling a more efficient design and the production of a part with a lighter weight.

Several studies have reported the use of shot peening for the post-processing of AM metals. Uzan and co-workers (Ref 85) used shot peening for post-treatment of AlSi₁₀Mg samples produced by SLM. Tensile fatigue tests showed that shot peening significantly improved the fatigue performance of the SLM-produced AlSi₁₀Mg samples. A fractography study revealed that, in the HCF region of the samples under low stress, the depth of crack initiation of the shot-peened samples was much deeper as compared to the un-peened samples as a result of the presence of compressive residual stresses in the near-surface regions. Kahlin and co-workers (Ref 47) used various surface processing methods, including shot peening, laser shock peening, centrifugal finishing, laser polishing, and abrasive finishing to treat AM Ti64. It was observed that by using shot peening and centrifugal finishing, a fatigue strength that is comparable to that of machined materials can be achieved in AM Ti64.

That said, the effect of shot peening is not always beneficial. In a study by Wycisk and co-workers (Ref 86), the effects of mechanical polishing and shot peening on the fatigue performance of 3D-printed Ti64 samples were investigated. It was observed that mechanical polishing alone increased the fatigue strength of 3D-printed Ti64 from 250 to 500 MPa, even though the fatigue life data showed a high degree of scatter. However, when shot peening was carried out following mechanical polishing, the fatigue performance deteriorated, possibly due to the poor surface finish caused by shot peening.

Denti and co-workers (Ref 15) combined tumbling and shot peening with the aim to improve the fatigue performance of AM Ti64. In the tumbling process, the AM parts were placed in a barrel along with water, abrasive media, and other compounding agents. The rotation of the barrel caused abrading of the parts by the abrasive media, thus improving the surface finish. By using an optimized tumbling process followed by shot peening, the authors were able to improve the fatigue performance of the AM Ti64 samples.

Similar to the process of shot peening, in surface mechanical attrition treatment (SMAT), a metal surface is bombarded with numerous metallic balls to induce surface nanocrystallization, which improves the mechanical performance of the sample surface. In a recent study by Portella and co-workers (Ref 87), SMAT was used to process AM 316L stainless steel. They demonstrated that SMAT can decrease the surface roughness from 11 to below 1 μm and to increase the surface hardness from 220 to 334 Hv. In addition, SMAT was able to transform the tensile residual stresses into compressive residual stresses, leading to a high tensile strength. Unfortunately, the fatigue performance of the AM 316L stainless steel was not evaluated.

Laser shock peening (LSP) has been widely used to impart beneficial compressive residual stresses on metal surfaces to improve their fatigue performance. Compared with shot peening, laser shock peening typically induces a very small amount of cold work (perhaps 3% to 5%), which results in much higher stability of the compressive residual stresses. In addition, the depth of the compressive residual stress is greater in LSP (around 1 mm) as compared to that for SP (0.1 to

0.2 mm). This makes LSP an ideal process for the post-treatment of AM metals. Morgano and co-workers (Ref 64) measured the residual stresses in 316L stainless steel built by LPBF. It has been demonstrated that the residual stress can extend to nearly 1 mm below the surface; within a layer that is approximately 100 to 300 μm from the surface, the compression effect is the most significant. There are two ways to use LSP with AM metals: the most common way is to post-process the 3D-printed metals using LSP, and the second way is to integrate LSP with the AM process in situ, in a hybrid fashion.

Chen and co-workers (Ref 88) demonstrated that LSP can be used to improve the oxidation resistance of AM TiC/Inconel 625 nanocomposites. Chi and co-workers (Ref 89) demonstrated that LSP can transform the residual stresses from tensile to compressive stresses in AM Ti17 alloys, in addition to significantly increasing the hardness through grain refinement and work-hardening. Hackel and co-workers demonstrated that LSP outperformed shot peening for improving the fatigue performance of AM 316L with and without notches (Ref 84); LSP was found to improve the fatigue strength of AM 316L with notches by 60%. Although LSP can enhance the fatigue performance, the effectiveness of LSP on fatigue performance is dependent on the peening strategy, as reported by Zhao and co-workers (Ref 90). Therefore, care must be taken to use LSP process parameters that result in beneficial compressive residual stress in the most critical region.

Kalentic and co-workers (Ref 91, 92) reported a hybrid method that introduces LSP treatment during the SLM processes, and they call this process 3D laser shock peening (3D LSP). In 3D LSP, one or a few layers of metals are printed in the SLM chamber before the part is moved to the LSP station for LSP processing. Cuboidal Ti64 and 316L stainless steel samples were printed using this hybrid manufacturing process, and a significant improvement in geometrical accuracy was observed. Higher and deeper compressive residual stresses on the surface and in the subsurface of the printed samples were observed. The magnitude of the compressive residual stresses will increase with the overlap ratio, but this comes at a cost to the efficiency. A deeper and higher magnitude of compressive residual stress is expected to improve the fatigue performance, even though fatigue testing has yet to be carried out. It should be noted that LSP treatment during SLM printing does not significantly decrease the grain size even though it increases the stored energy (Ref 93). Subsequent annealing does, however, produce a refined equiaxed structure. This offers an ideal strategy for manipulating the process conditions to control the microstructure and, thus, the properties of the 3D-printed metals.

Recently, in a study by Lu and co-workers (Ref 94), an integrated process for additive manufacturing of AM Ti6Al4V was realized by integrating SLM with LSP. LSP was carried out after every few layers of material were printed using SLM. The integration of LSP with SLM resulted in high hardness, high tensile strength, and the transformation of tensile residual stress into compressive residual stress. The authors attributed the beneficial effects imparted by LSP to atomic diffusion processes at the layer interfaces that were induced by two kinds of laser shock waves.

Note that in addition to laser peening and shot peening, water jet peening and cavitation peening have been developed. As of the time this review was written, neither water jet peening nor cavitation peening has been used as a post-processing method for AM metals.

3.4 Ultrasonic Nanocrystal Surface Modification

Ultrasonic nanocrystal surface modification (UNSM) is a recently developed surface severe plastic deformation technique that can improve the fatigue performance of metallic components (Ref 95-97). In the UNSM process, a tungsten carbide (WC) tip strikes the samples at an ultra-high frequency (20 kHz) as it burnishes the surface. Because of the plastic strain induced by UNSM, this process generates grain refinement, induces work hardening, and generates compressive residual stresses in the near-surface region of the metal. As a result, UNSM contributes to improving the resistance of these materials to wear and fatigue. In recent years, UNSM has been widely used to improve the surface hardness (Ref 98, 99), wear resistance (Ref 100-102), and fatigue performance (Ref 97, 98, 103, 104) of metallic materials.

It has been demonstrated the UNSM can effectively improve the surface finish of AM metals. For example, Ma and co-workers (Ref 101) demonstrated that UNSM can decrease the surface roughness of AM NiTi from 12.1 to 9.0 μm . As can be noticed from Fig. 8, the rough surface finish (Fig. 8(a), (b) and (c)) of the as-printed metal became very smooth (Fig. 8(d), (e) and (f)). During UNSM, the burnishing effect removes the particles at the surface and the ultrasonic striking eliminates the roughness peaks by pushing them toward the valleys. This process results in a much better surface finish. In addition, higher wear resistance, higher corrosion resistance, lower porosity, and much higher hardness (an increase from 300 to 400 Hv at the surface) have been observed. However, the effect on fatigue performance was not studied.

In a follow-up study, Zhang and co-workers (Ref 63) reported that UNSM treatment can significantly improve the fatigue performance of AM Ti64, as can be seen from the

results shown in Fig. 9. In addition to lower surface roughness and porosity, it was reported that the tensile residual stresses originally present in the as-fabricated Ti64 were transformed to compressive residual stresses (Fig. 10). The synergistic effect of better surface finish, lower porosity, higher hardness, and the presence of beneficial compressive residual stresses contributed to significantly improved fatigue performance. Kim and co-workers (Ref 105) also studied the effects of UNSM on AM M4 high-speed tool steel that contains molybdenum and tungsten. It has been demonstrated that UNSM was capable of significantly reducing the surface roughness, transforming the residual stresses from tensile to compressive stress and significantly increasing the surface hardness and wear resistance of the AM M4 steel.

Due to the high hardness of the AM Ti64, the UNSM effect is sometimes not as effective at processing this material as it is for treating softer metals. To address this issue, Zhang and co-workers combined *in situ* electric heating with UNSM treatment, referred to as electrically assisted UNSM (EA-UNSM) to process AM Ti64. In EA-UNSM, the AM Ti64 is subjected to simultaneous electric heating and UNSM treatment. As a result of the resistive heating, the AM Ti64 is softened and has a higher plasticity, which results in more effective material flow when the sample is subjected to ultrasonic striking. Because of this, EA-UNSM is able to close pores in the surface of the material more effectively. As can be noticed from Fig. 11, while UNSM treatment decreases the porosity of AM Ti64, EA-UNSM is even more effective. Following EA-UNSM treatment, only very small pores (having an area smaller than 5 μm^2) remain, and all of the larger pores have been eliminated.

While EA-UNSM is very effective for post-processing AM metals, the application of an electric current to a sample is not always practical, and it might be more efficient to heat the

Fig. 8 SEM images at different magnifications: (a, b and c) as-printed and (d, e and f) UNSM-treated nickel-titanium alloy specimens. Reprinted from [101], Copyright 2017, with permission from Elsevier

sample by using a laser beam, as this technology is more accessible. To take advantage of this, an innovative process called laser-assisted UNSM (LA-UNSM) was proposed (Ref 107). In the LA-UNSM process (Fig. 12), a focused laser beam heats the sample locally, while at the same time, a tungsten carbide tip strikes and burnishes the locally softened metal. As the metal softens, the ultrasonic strikes are able to effectively close subsurface pores. In addition, the surface finishing improves as the locally softened material flows from high peaks to low valleys due to the burnishing. At the same time, tensile residual stresses are relieved and beneficial compressive residual stresses are imparted. Finally, the surface work-hardens due to plastic deformation. The synergistic effects lead to improved fatigue performance in AM metals.

Laser irradiation plays a key role in the LA-UNSM process. By increasing the local temperature, laser irradiation improves the plasticity of AM metals. Compared with traditional induction heating, in which the bulk assumes a uniform temperature, laser heating can be precisely localized to specific regions to be processed. The drawbacks associated with bulk heating, including metal softening, sample distortion, and high energy consumption, can be avoided. In addition, a laser can be easily integrated through a fiber delivery system, and LA-UNSM can be deployed to process samples with complex geometries via a robotic arm. It is expected that LA-UNSM will be more effective for post-processing AM metals than other methods and will receive greater attention from the research

community in the years to come. Although UNSM would seem to be very effective for this purpose, it should be noted that (1) UNSM is a surface treatment process and cannot affect the porosity in the interior and (2) it is challenging to use UNSM to treat AM components with complicated geometries.

3.5 Advanced Finishing and Machining

Kaynak and co-workers used a number of advanced surface finishing processes, including finish machining (FM), vibratory surface finishing (VSF), and drag finishing (DF), to process SLM 316L stainless steel. It was observed that all three processes were able to improve the surface finish of SLM 316L stainless steel. FM was also found to improve the surface and in-depth hardness, while VSF and DF only increased the hardness slightly. Even though better surface finish can potentially improve the fatigue performance, this effect has yet to be confirmed by fatigue tests.

Tan and co-workers (Ref 108) used ultrasonic cavitation abrasive finishing (UCAF) to treat AM Inconel 625 samples. In the UCAF process, bubble explosion on the target sample surface causes surface erosion that leads to the removal of surface irregularities. The addition of abrasive particles could also lead to abrasive erosion, improving the process efficiency of UCAF. It was observed that UCAF could improve surface finish of AM Inconel 625, and the effectiveness depends on the initial surface conditions. High hardness was observed in UCAF-treated AM Inconel 625 samples. Unfortunately, the effect of UCAF on the fatigue performance was not evaluated.

Figure 13 shows an as-deposited and post-machined BALD bracket (Ref 13). It can be observed that the dull surface of the as-deposited bracket acquired a very good surface finish. Typically, machining would be used to decrease the surface roughness and thus improve the fatigue performance. However, in a study by Edwards and co-workers (Ref 109), it was found that machining did not improve the fatigue performance of SLM Ti64 as compared to the as-built condition. The authors observed that after machining, subsurface pores were brought to the surface and served as new stress raisers that compromised the fatigue performance. In the machined samples, internal defects might also have played a role in the poor fatigue performance.

In a study by Fatemi et al., machining was reported to produce a fourfold increase in the fatigue life of Ti-6Al-4V through a reduction in the surface roughness (Ref 41). While improving surface finish can improve the fatigue strength of AM metals, the effect is not as significant as that for traditional

Fig. 9 S-N curves from rotation bending fatigue tests of AM Ti64 before and after UNSM treatment. Reprinted from [63], Copyright 2017, with permission from Elsevier

Fig. 10 In-depth residual stress profile of AM Ti64 samples (a) along the UNSM transverse direction and (b) along the UNSM scanning direction before and after UNSM treatment. Reprinted from [63], Copyright 2017, with permission from Elsevier

Fig. 11 Change in porosity of the 3D-printed Ti64 for control, UNSM-treated and EA-UNSM-treated samples: (a) optical micrograph, (b) processed grayscale image, and (c) histogram of pores of different sizes. Reprinted from [106], Copyright 2018, with permission from Elsevier

metals due to the presence of defects or pores in the subsurface (Ref 41). Unfortunately, machining is not always an option for highly complex samples (Ref 37). In addition, the improvement in fatigue performance in AM metals brought about by machining or surface finishing is not as significant as that for traditional metals, as subsurface pores move to surface after the removal of the rough surface (Ref 41).

3.6 Laser Polishing

While many mechanically based surface finishing methods are very effective in improving the surface finish of AM metals, most of these methods cannot be used to treat components with complex geometries. Many of the mechanically based surface finishing methods are time-consuming, labor-intensive, and have low productivity, and the extent of the automation is limited (Ref 110, 111). Laser polishing has been widely used for polishing metals due to its high efficiency, low environmental impact, high controllability of surface roughness, high flexibility, and capability for treating a localized area. In the laser polishing process, surface melting and re-melting occur when metals are subjected to laser irradiation. During the re-melting process, surface asperities are removed due to surface tension in the molten pool, as shown in Fig. 14. This leads to lower peak-to-valley heights compared with the original surface asperities. Parameters involved in laser polishing include laser

power density, defocus, overlap ratio, number of layers applied on the metal surface, and material feed rate. It is observed that, in addition to laser power, scanning velocity, object distance, hatch spacing, and shield gas flow rate all influence the effectiveness of the laser polishing process (Ref 112, 113).

In contrast with mechanically based surface finishing methods, in the laser polishing process, there is no physical contact between the laser system and the target samples and thus no tool wear. Material is not removed in a laser polishing process; rather, it is relocated as a melting pool (Ref 112). In addition, laser polishing can be fully automated (Ref 114). It has been successfully employed to improve the surface finish of various non-metallic materials (including diamonds, glass, and silica) as well as metallic materials (steels, nickel alloys, titanium alloys, and aluminum alloys, for example) (Ref 111).

In recent years, laser polishing has been widely used for processing AM metals. For example, Lamikiz and co-workers (Ref 115) demonstrated that, when using optimized parameters, laser polishing can decrease the surface roughness of SLS 420 stainless steel from 7.5 to 1.2 μm . Ma and co-workers (Ref 116) demonstrated that laser polishing can decrease the surface roughness of AM Ti64 and TC11 alloys from 5 μm to less than 1 μm . It was also observed, in the same study, that laser polishing changes the $\alpha + \beta$ dual phase microstructure to an α' martensitic phase, leading to a 30% increase in the micro-hardness and, thus, to higher wear resistance. Tian and co-

Fig. 12 LA-UNSM: (a) Schematic of the process, and (b) setup for LA-UNSM in the lab

Fig. 13 As-deposited (top) and post-machined BALD bracket (bottom). Reprinted from [13] with permission of ASM International. All rights reserved. www.asminternational.org

workers (Ref 117) demonstrated that laser polishing can significantly reduce the surface roughness of EBM Ti64. It was also noted, however, that laser polishing resulted in tensile residual stresses (up to 580 MPa) in the near-surface region. These tensile residual stresses were eliminated after a simple stress relief heat treatment (750 °C for 4 h in vacuum, followed by furnace cooling). Wang and co-workers (Ref 118) reported that, in addition to reducing surface roughness, laser polishing

Fig. 14 Schematic of laser polishing. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, *The International Journal of Advanced Manufacturing Technology*, E.V. Bordatchev, A.M.K. Hafiz, and O.R. Tutunea-Fatan, Performance of laser polishing in finishing of metallic surfaces, Copyright 2014 [111]

can also significantly improve the corrosion resistance of an additively manufactured CoCr alloy through the generation of complex oxide films on the surface. Fang and co-workers (Ref 119) reported that laser polishing can decrease the surface roughness and increase the in-depth hardness of an SLM Inconel 718 alloy. Bhaduri and co-workers (Ref 114) demonstrated that a maximum of 94% reduction in surface roughness can be achieved with optimized laser polishing conditions on AM 316L stainless steel; lower porosity and high hardness were also observed in the top 100 µm after laser polishing using optimized process conditions. When the laser power density is too high, laser ablation will occur, leading to even higher porosity. Rosa and co-workers (Ref 120) demonstrated a multi-pass strategy, in which the use of an argon shielding gas can improve the laser polishing effectiveness (by improving the surface integrity).

In addition to better surface finish, laser polishing can sometimes decrease porosity in the near-surface region. The re-melting process in laser polishing can also refine the grains and lower the porosity, leading to higher surface hardness. Yasa and co-workers (Ref 121) reported that laser polishing of SLM 316L stainless steel can decrease the porosity in the near-surface region from 0.77% to 0.036%. This study demonstrated that laser polishing can improve surface finish and decrease the surface porosity of AM metals to achieve a higher surface integrity.

In most laser polishing work, a continuous wave laser or a pulsed laser with nanosecond or microsecond pulse width is used. Worts and co-workers (Ref 122) used a femtosecond laser (10 kHz repetition rate, 185 fs, 100 µJ pulse energy) to process AM metals. In contrast with traditional laser polishing, which uses surface re-melting without material removal, femtosecond laser polishing uses plasma-mediated ablation to remove material from the surface of the metal. In addition to removing loose particles, a femtosecond laser can also be used to machine microscale features into the surface in order to control the wettability performance. While this study still used a femtosecond laser as a post-processing tool, it is also envisioned that a femtosecond laser could be integrated into the SLM/SLS system for in situ laser polishing of AM metals.

Table 1 Summary of effects of post-processing methods for AM metals

Post-processing method	Effect on surface finish	Effect on porosity	Microstructure changes	Effect on residual stress	Effect on material properties
Heat treatment	n/a	n/a	Decreases defect density and increases microstructure stability	Eliminates/ decreases tensile residual stresses	Reduces yield strength and ultimate tensile strength, improves ductility and fatigue performance
Hot isostatic pressing	Increases surface roughness	Decreases porosity	Homogenizes the microstructure	Relieves residual stresses	Reduces yield strength and ultimate tensile strength, improves ductility and fatigue performance
Laser shock peening and shot peening	Increases surface roughness	n/a	Produces refined grains and high-density dislocations	Converts tensile stresses to compressive stresses	Increases hardness, improves fatigue performance
Ultrasonic nanocrystal surface modification	Improves surface finish	Decreases near-surface porosity	Produces refined grains and high-density dislocations	Converts tensile stresses to compressive stresses	Improves surface hardness, wear resistance, corrosion resistance and fatigue performance
Advanced finishing and machining	Improves surface finish	n/a	n/a	n/a	Improves hardness and fatigue performance
Laser Polishing	Improves surface finish	Decrease porosity in the near-surface region	Refines the grains	Results in tensile residual stresses	Improves surface hardness, corrosion resistance, and fatigue performance
Chemical and electrochemical polishing n/a = not applicable	Reduces surface roughness	n/a	n/a	n/a	Improves the fatigue performance

3.7 Chemical and Electrochemical Polishing

Compared with other surface finishing methods, chemical polishing has its own advantages, including the capability to polish a complex surface without the need for special tools as well as easy access to parts (e.g., internal channels) that are not accessible by other methods. Scherillo and co-workers (Ref 123) demonstrated that chemical polishing can easily remove the sharp peaks and deep valleys on the surface of AM metals. Persenot and co-workers (Ref 33) demonstrated that chemical polishing can significantly reduce the surface roughness of EBM Ti64 and, as a result, increase the fatigue strength by 60% (to 200 MPa).

Tyagi and co-workers (Ref 124) also demonstrated that both chemical polishing and electropolishing can significantly reduce the surface roughness of AM 316L. While electropolishing could be more effective, it is also limited by the accessibility of the counter electrode in AM parts with complex geometries. Chemical polishing, in comparison, is more versatile. As the surface morphology from chemical polishing and electropolishing is dramatically different, the effect of these methods on the fatigue performance of AM metals will require future investigation.

Zhang and co-workers (Ref 125) used electrochemical polishing to polish AM Inconel 718. It was reported that 5 min of electrochemical polishing can significantly improve the surface finish of this alloy. It was also observed that electrochemical polishing resulted in lower hardness and modulus, both of which were partially caused by the release of tensile residual stresses. While a better surface finish is expected to result in better fatigue performance, most studies of chemical or electrochemical polishing did not study the impact of the process on fatigue performance, except for a study by Persenot and co-workers (Ref 33). More rigorous fatigue testing is needed.

4. Summary

In Sect. 3, the effects of many post-processing methods on the surface finish, porosity, residual stresses, and fatigue performance have been reviewed. Table 1 serves as a summary of the discussion in this section. It should be noted that the information in this table only serves as a general reference.

5. Conclusion

Additive manufacturing is a promising technology that could be a game-changing technology for many industries. However, the poor fatigue performance of AM metals is a major roadblock for the wider application of AM technology in key industries where components are subjected to cyclic loading. While many efforts are made to combat the issues of porosity, poor surface finish, and the presence of defects and tensile residual stresses in AM metals, post-processing will play an increasingly important role in additive manufacturing in future. Different post-processing methods have different effects on the surface integrity, porosity, and tensile residual stresses of AM metal. For example, heat treatment can effectively reduce or even eliminate the tensile residual stresses in AM metals, but

it cannot eliminate porosity. HIP can reduce porosity and release tensile residual stresses, but it will increase the surface roughness results from the depressions or dimples induced by plastic deformation during HIP processing. Both LSP and SP can transform residual stresses in AM metals from tensile to compressive, however, with little effect on surface roughness. UNSM is also a surface strengthening technology based on plastic deformation similar to LSP and SP, so it can also convert residual stresses from tensile to compressive. In addition, the ultrasonic striking in UNSM can eliminate the roughness peaks by pushing them toward the valleys and decrease/eliminate porosity in the near-surface region. Laser polishing can reduce porosity and improve surface integrity, but the re-solidification of the metals will lead to harmful tensile stresses. Advanced finishing, machining, and chemical/electrochemical polishing can reduce surface roughness and improve surface integrity, but have no effect on residual stresses or porosity. Even though some post-processing techniques have shown great potential for treating AM metals, one should be aware that they may limit the appeal of using AM technology, for which the capability to produce complex geometries is the most attractive attribute. One way to solve this issue is to post-process only critical locations that are vulnerable to crack initiation under cyclic loading. In addition, one should note that while the laboratory studies conducted to date show huge potential in terms of innovative ways for post-processing AM metals, the issues with scalability and applicability need to be addressed before they can be applied in industrial manufacturing.

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