

Article

Experimental Investigation of Material Characteristics That Can Affect Fatigue Behavior of Ti6Al4V Alloys Produced by Additive Manufacturing SLM and EBM Processes

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Abstract

Ti alloys are widely used in aerospace and biomedical fields due to their high mechanical properties under severe loading. Interest in additively manufactured Ti6Al4V has increased, but further research is needed to fully characterize their properties. This work compares the effects of surface properties, internal defects, microstructure, hardness, and Hot Isostatic Pressing (HIP) or Vacuum Heat Treatment (VHT) on the fatigue behavior of Ti6Al4V produced by Selective Laser Melting (SLM) and Electron Beam Melting (EBM). Printing parameters and post-processing were optimized to achieve high density and minimal porosity, providing a solid basis for realistic fatigue comparisons. Samples were characterized in terms of microstructure (optical microscopy and SEM), mechanical properties (hardness mapping), surface texture (confocal microscopy), and internal defects (image-based analysis). Uniaxial fatigue limits were determined by a Dixon-Mood staircase method, and failed specimens were analyzed for fracture surfaces and defect areas. Applied load on flaws was evaluated to identify root causes of fatigue failure. Results showed that fatigue of as-printed samples is governed by surface roughness, while machined specimens are controlled by internal defect size. Machining increased the fatigue limit roughly threefold, and HIP further improved it by 10–20% by reducing internal porosity. In conclusion, with properly optimized melting parameters, both EBM and SLM produce similar mechanical performance at comparable roughness, supporting their use for structural components.

Keywords: Ti6Al4V; SLM; EBM; HIP; microstructure; fatigue; internal defects; surface texture



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1. Introduction

Ti alloys are important materials used in various fields where high mechanical performance combined with environmental stability and lightness are required. Considering these properties, it is well known they are used in aerospace [1–3] and biomedical fields

for the production of human implants [4–7]. In recent years, the increasing interest in the production of components by additive manufacturing processes has put Ti alloys at one of the main studied materials, since their manufacture in Near Net Shape (NNS) makes the use of such an expensive material economically sustainable. In fact, with this manufacturing approach, the costs due to material loss are reduced to a minimum [2].

The mechanical performances of Ti alloys, in particular the Ti-6Al-4V (Ti gr.5), produced by additive manufacturing processes have been extensively studied by many researchers, in particular focusing on the microstructure [8–11], the internal defects [12–15], the anisotropy [13], the tensile strength, and the fatigue resistance [7–9,12–25]. In terms of production techniques, many studies have focused attention on Electron Beam Melting (EBM) [17,26–28] and Selective Laser Melting (SLM) [13,16,20,28–30], where powders of appropriate geometry and size are deposited layer by layer, and between each deposition are melted by a heat source, which can be a laser or electron beam [22,31].

Recent studies have begun to directly compare Ti-6Al-4V components produced by SLM and EBM. For example, Takase et al. [27] systematically investigated how L-PBF and EB-PBF process parameters influence phase evolution and residual stresses in Ti-6Al-4V, providing insight into process-specific thermal histories and microstructural outcomes. Chastand et al. [28] compared fatigue properties of SLM and EBM Ti-6Al-4V specimens, examining the effects of surface roughness, manufacturing direction, and HIP treatment, and reported that under certain conditions both processes can exhibit similar fatigue performance. These comparative works highlight important process-dependent differences and motivate the present study, which aims to evaluate fatigue behavior of SLM and EBM materials in technologically relevant conditions.

In terms of mechanical properties, due to the high mechanical performance required of components manufactured from Ti alloys, fatigue resistance is one of the key properties, and it has been extensively studied in the past years. In particular, the effect of both internal defects [12,13,15,22,25] and surface texture [12,23,24,31] on fatigue resistance has been analyzed in depth. Masuo et al. [12] described that the most critical internal defects are (gas) pores and lack of fusion. They stated that the presence of detrimental defects predominates in the microstructure of the material itself. They also concluded that the most detrimental parameter in controlling the fatigue resistance of the material is the surface roughness. Shamir et al. [25] observed that the microstructure of the material and its orientation in the proximity of the internal defect play a crucial role in the fatigue resistance and in some cases can prevail over the defect size by causing scattering of the fatigue data. Some attempts have also been made to predict fatigue life using numerical analysis based on real CT scans taken on the samples [30,32]. In this case, the results are encouraging, although strongly dependent on the CT resolution [33]. They also observed a strong correlation between the fatigue life and the microstructure in the proximity of the defect, where the size of the α lath determines the crack nucleation of the material. Pessard et al. [20] also studied the scale effect on the fatigue resistance of the SLM Ti gr.5 alloy. In particular, they observed a slight increase in fatigue resistance due to the probabilistic effect of the defect distribution, which is reduced in small-sized samples.

Some authors have also investigated the effect of microstructure on the fatigue resistance; for instance, a material showing a fine $\alpha + \beta$ lamellar microstructure can positively impact the fatigue resistance, provided that no internal defects are present [10,29,34]. For SLM samples, the goal is usually achieved by post-printing heat treatments [19] or Hot Isostatic Pressing (HIP) [35], which also plays an important role in reducing internal defects [22,23,36]. In the case of SLM it is also necessary to reduce the high residual stresses due to the production process [19]. In the EBM process, the HIP process can be used to reduce the pores, but usually the microstructure is coarsened due to the acicular shape in

the as-printed state [37]. In general, the control of the α lamella dimension, to obtain a fine size, is necessary to control the fatigue strength of the material [12,36,38].

The effect of surface treatments has been studied to reduce the surface roughness, such as mechanical and chemical surface treatments or machining [12,23,24].

Other researchers have investigated heat treatment processes by including a HIP step prior to the final heat treatment [36]. The main purpose of HIP is to close the pores, and the final heat treatment is to produce the desired microstructure. In the latter case, the strong relationship between mechanical properties and microstructure was observed by producing a fine $\alpha + \beta$ lamellar microstructure after a complete solubilization step.

Surface treatment has also been the subject of research by many authors investigating the fatigue resistance of the additive manufactured Ti alloys [9,38–40]. In this case, any surface treatment that greatly reduces the severity of the printed surface is a benefit to fatigue life. Most of the researchers showed that simple machining of the as-printed surface increased the fatigue resistance of the material; some authors also introduced some treatments to induce compressive stresses [38] on the surface, such as shot peening or tumbling [9]. The negative effect of the surface on fatigue resistance has generally been related to the high roughness of the printed materials and also to the layered structure of the printed sample [31]. In all cases the surface acts as a series of small notches, which can act as stress raisers.

The main goal of this study is to characterize Ti6Al4V material produced by EBM and SLM processes from the point of view of fatigue performance by considering the surface finish and thermal and thermomechanical treatment effects. The aim of this work is to evaluate the fatigue resistance of the Ti6Al4V alloy through a comprehensive experimental methodology, incorporating the analysis of potential crack initiation sites, including surface morphology, microstructural characteristics, and internal defects. The study compares two additive manufacturing processes, assessing their influence on the alloy's mechanical performance as a function of both intrinsic material properties and applied post-processing treatments. SLM and EBM processes exhibit fundamentally different thermal histories, resulting in distinct microstructures and defect distributions. In this study, samples were processed according to the standard industrial practices for each technology, allowing a realistic comparison of fatigue performance under conditions representative of current applications, thereby addressing gaps in the literature regarding process-specific material behavior. Although previous studies have compared the fatigue performance of SLM and EBM Ti6Al4V, a systematic investigation explicitly separating and correlating the effects of surface condition and internal defects under comparable and industrially relevant conditions is still lacking. This work addresses this gap by providing an integrated and defect-based analysis of fatigue behavior. The fatigue results, and in particular the failed samples, are deeply investigated in order to seek correlations of the defects that nucleated the fracture with the fatigue resistance of the material.

2. Materials and Methods

2.1. Sample Design and Preparation

The specimen geometry adopted for the fatigue tests in this study, illustrated in Figure 1, was designed in accordance with the ASTM E466-15 [41]. A total of 100 samples were produced in a single build for the EBM technology, and a total of 100 samples were produced in four different builds for the SLM technology. For EBM technology, two different surface finishes (as-printed and machined) and two microstructural conditions (NO-HIP and HIP) were investigated. For the SLM technology two different surface finishes (as-printed and machined) and two microstructural conditions were investigated (VHT and HIP). The SLM samples underwent stress relief treatment in a vacuum (VHT) in order to

both slightly modify the microstructure and relieve the internal stresses induced by the SLM process [19,27]. In addition, the treatment should modify the microstructure of material in order to fulfill the tensile test results requirements according to ISO 5832-3:2021 [42]. The heat treatment was performed in a vacuum following a recipe developed in LimaCorporate. For the SLM specimens, the NO-HIP conditions indicated in the work correspond to a stress-relieved condition. The HIP treatment is compliant with ASTM F3001-14(2021) [43] and the parameters used are in agreement with those commonly reported in the literature for additively manufactured Ti6Al4V [35].

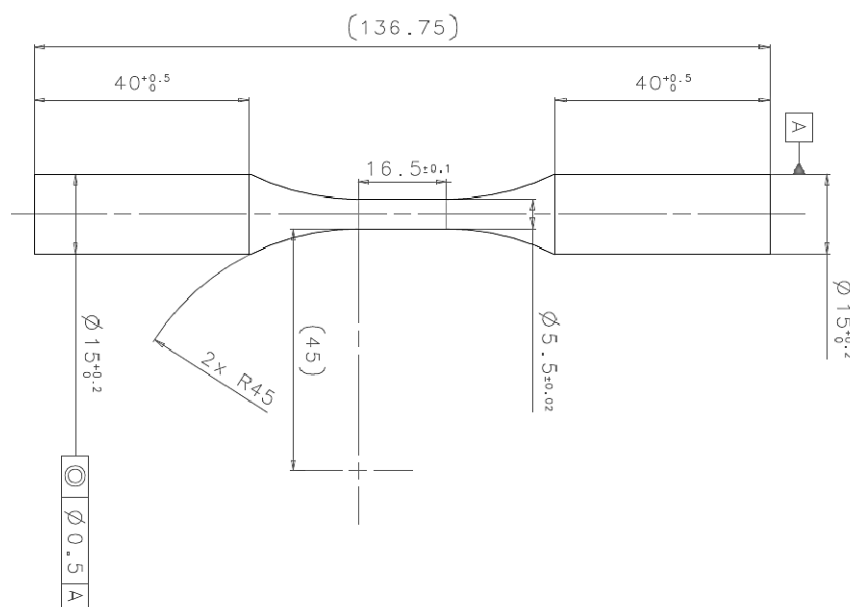


Figure 1. Specimen geometry used for fatigue tests, units in mm.

A representative example of the surface finish obtained on the analyzed samples is presented in Figure 2, while the different processing conditions investigated in this study are summarized in Table 1.

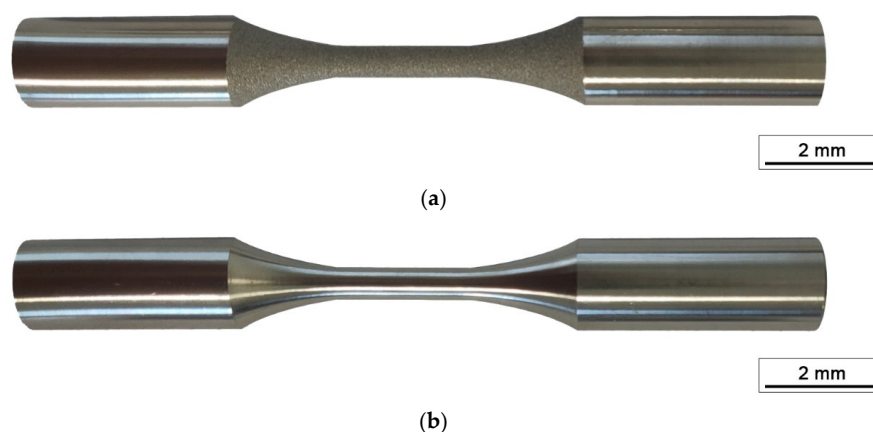


Figure 2. Different surface finishing of the analyzed samples: (a) as-printed surface, (b) machined surface.

For both technologies, EBM and SLM, the samples were produced with a vertical orientation in respect to the building plate, which usually is the printing direction with the lower mechanical resistance of the material [17,28]. All batches were subjected to dimensional tests according to the specific drawings and a degreasing washing step before being made available for mechanical testing. Each build includes dedicated test coupons to characterize the material in different thermal conditions (NO-HIP and HIP). Traceability of

each sample was maintained throughout the production chain by micro-milling marking of the gripping head.

Table 1. Different conditions of the analyzed samples.

Thermal Condition	Surface Finishing	Printing Technique
NO-HIP	as-printed	EBM
HIP	as-printed	EBM
NO-HIP	machined	EBM
HIP	machined	EBM
NO-HIP (stress relieved, VHT)	as-printed	SLM
HIP	as-printed	SLM
NO-HIP (stress relieved, VHT)	machined	SLM
HIP	machined	SLM

Machine models and printing conditions are summarized in Tables 2 and 3 for EBM and SLM technologies, respectively. It is noted that the parameters adopted for each technology, including powder particle size and layer thickness, were defined in accordance with the company's standard procedures and were obtained following optimization processes conducted to achieve the best possible material performance. In particular, for SLM, the reported oxygen content of 0.15% represents the maximum allowable threshold specified by the machine manufacturer and not the nominal operating condition. Under normal processing conditions, the oxygen concentration is typically much lower ($\approx 0.05\%$), with possible transient increases due to minor air infiltrations or powder handling. The process parameters (normally called melting themes) are invariant along the samples' production. The available print volume has been divided into five zones, one central and four at the perimeter, as reported in Figure 3. Five samples for each different condition in each area were manufactured, for a total of 25 samples for each build. An illustrative build layout used for this study is reported in the same figure.

Table 2. Printing conditions for EBM samples.

Instrument	Q10plus Version 2.1 with EBM Control 6.1 GE Additive (Arcam) (LaB6 crystal)
Powders size	45–105 μm
Atmosphere	Vacuum 4.0×10^{-4} mbar
Scan strategy	Snake with optimized layer orientation
Layer thickness	50 μm

Table 3. Printing conditions for SLM samples.

Instrument	M 290-EOS with EOSSystem (HCS) 2.11.552.0 control (Yb fibre laser with a wavelength of 1060–1100 nm)
Powders size	15–45 μm
Atmosphere	inert argon atmosphere with 0.15% of max residual oxygen
Scan strategy	Stripes with 5 mm of width adjacent one to each other without overlap and optimized layer rotation.
Layer thickness	60 μm

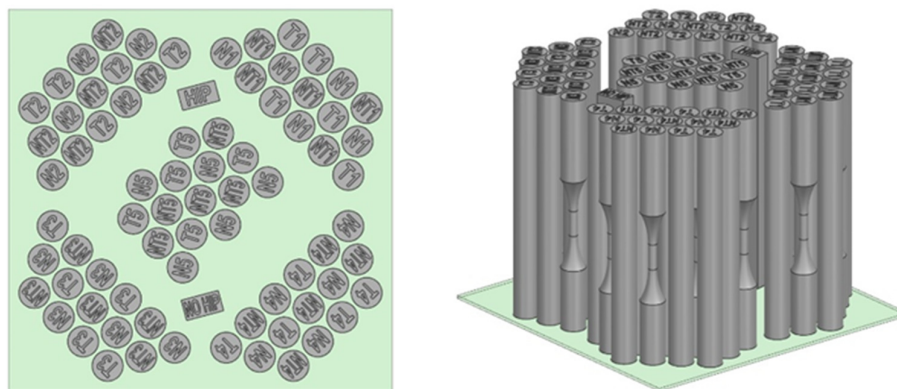


Figure 3. Top and lateral view of the build design used for the production of the EBM batches.

2.2. Microstructural Characterization

A detailed microstructural and mechanical characterization was performed on the samples. Two samples for each heat treatment condition and printing technique were used for the microstructural analysis. A detail of the sample extraction is shown in Figure 4.

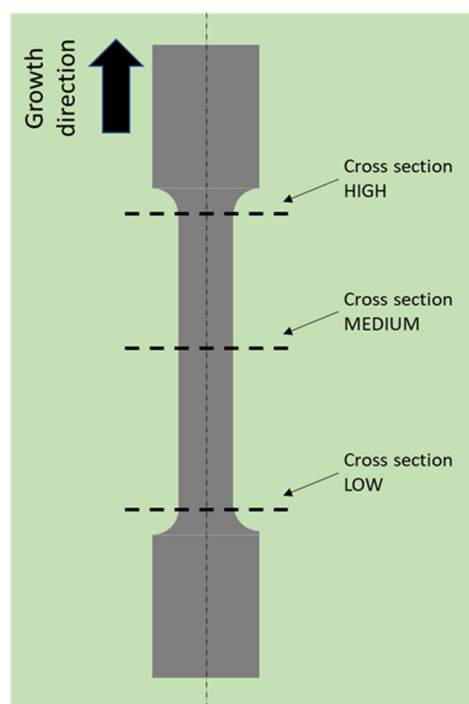


Figure 4. Scheme of the sample extraction map for both microstructural and mechanical characterization.

The extracted samples were embedded in epoxy resin and then subjected to a standard metallography preparation in order to obtain a mirror-like surface. The prepared cross-section samples were subjected to a size and defect distribution analysis, performed by light microscope on five different analysis areas of each sample. The samples were then etched using Kroll's reagent (100 mL deionized water mixed with 3 mL of hydrofluoric acid and 3 mL of nitric acid) for 60 s. Subsequently, the etched microstructures were examined using a Zeiss Axio Vert.A1 optical microscope (Carl Zeiss Microscopy GmbH, Göttingen, Germany). The β -phase content and α -phase grain size were determined via phase analysis and the linear intercept method, respectively. Quantitative image analysis was performed using Zeiss ZEN core 3.5 software.

Subsequently, the previously characterized samples were subjected to further metallographic preparation to obtain a suitable surface finish for microhardness mapping. In the

cross-sectioned samples, a polar HV0.3 pattern was used in order to have a circumferential and radial spacing of 0.25 mm between each indentation. A total amount of 257 points were collected for each sample, and the results are presented in 2D parametric graphs. The average microhardness value ($\overline{HV}$) of the cross-sectioned sample (HIP machined EBM) extracted from the central region for each heat treatment condition was used to make the mechanical properties employed in this study non-dimensional according to the following equation:

$$\chi = \frac{\Delta\sigma \cdot 100}{\overline{HV}} \quad (1)$$

where $\Delta\sigma$ represents the difference between the maximum and the minimum value of the applied stress in the specific condition.

The surface texture of the samples in the as-printed condition was analyzed in the same three different sections shown in Figure 4. The measurements were carried out by following these procedures:

- acquisition of an EDF (motorized focus) image via a Zeiss Axio Zoom V16 optical stereoscope (Carl Zeiss Microscopy GmbH, Göttingen, Germany) at a 50× magnification, with a PlanNeoFluar Z 1x/0.25 FWD 56 mm lens and slice thickness equal to 1 µm;
- post-processing of the raw image with the surface analysis workbench of the software ConfoMap 8.0, using the Minidoc for the profile extraction and selecting the right λ_s (25 µm) and λ_c (8 mm) filters as per ISO 21920-3 2021 [44];
- extrapolation of the surface characteristics via color maps and quantitative data combined with a table where are listed all the surface and linear metrics (R_a , R_t , R_z).

The surface properties of machined specimens were evaluated by means of a Veeco Dektak 150 stylus profilometer with five scans for each sample along the growth direction, in accordance with ISO 21920-3:2021 [44]. The acquired data were the same as as-printed surfaces (R_a , R_t , R_z).

With the surface data characterization, the K_t factor was evaluated as indicated by Arola et al. with the following equation [45,46]:

$$K_t = 1 + 2 \left(\frac{R_a}{\bar{\rho}} \right) \left(\frac{R_y}{R_z} \right) \quad (2)$$

where R_a is the average surface roughness, representing the mean deviation of the surface profile from the nominal line, $\bar{\rho}$ is the average radius of curvature of the surface asperities, indicating how sharp or rounded the peaks are, R_y is the maximum peak-to-valley height in the measured window, representing the tallest asperity relative to the local valley, and R_z is the average maximum peak-to-valley height over five consecutive sampling lengths, used to normalize R_y and provide a dimensionless ratio. This formulation accounts for the combined effect of surface roughness amplitude, asperity sharpness, and relative peak heights on the local stress amplification.

To calculate $\bar{\rho}$, the longitudinal samples were analyzed in the proximity of five deeper surface notches.

2.3. Tensile Tests

Static tensile tests were conducted to characterize the properties of the material under investigation according to ISO 5832-3:2021 [42]. In particular, the specimens are the same used for the fatigue characterization. The tensile tests were performed in mixed control mode: strain control up to a strain of 2% and displacement control up to rupture. The strain rate used was 0.5 (mm/mm)/min, and the displacement rate was 5 mm/min. The Yield Strength (YS), Ultimate Tensile Strength (UTS), and Elongation at break (E%) were

acquired for each analyzed specimen, with all stress values calculated based on the nominal diameter of the samples. Tensile tests were performed on specimens in both the as-printed and machined conditions. Specimens were extracted from different locations across the build plate to verify material homogeneity.

2.4. Fatigue Tests

Fatigue tests were performed on a minimum of 12 samples for each batch presented in the previous paragraph. The experimental condition for the fatigue tests consisted of applying a uniaxial load with $R = 0.1$ and a frequency of 40 Hz with a run-out reached at 10^7 cycles, also identified as the fatigue endurance limit. A staircase approach was used, and the initial load was determined from the scientific literature review [12,47]. After each failure or run-out event, the applied load was varied by ± 20 MPa. This value represents a compromise between experimental resolution and the number of specimens required, in accordance with established testing practice. It should be noted that the frequency was selected considering both the duration of the tests and the instrumental limitations of the testing machine, ensuring practical acquisition of statistically significant results without affecting the relative comparison of SLM versus EBM Ti6Al4V fatigue properties. Moreover, the selected load increment was defined to be sufficiently small with respect to the expected scatter of the fatigue data, typically within 5–10% of the fatigue limit, ensuring a statistically reliable estimation of the mean fatigue strength. Smaller load increments would not significantly improve the accuracy of the fatigue limit estimation, whereas larger increments would result in a loss of data resolution. The data obtained were plotted on an S-N diagram, and the fatigue limit was calculated using the Dixon-Mood approach [48]. Some run-out samples were re-tested at significantly higher stress amplitude to partially populate the High Cycle Fatigue regime of the S-N curve. These additional tests were not included in the statistical evaluation of the fatigue limit obtained through the staircase method in order to preserve the consistency and validity of the procedure and were considered only for qualitative support in the high-stress regime. All the data obtained were presented in dimensionless form for the stress-related data by dividing the fatigue limit result in accordance with Equation (1). The failed samples were analyzed by SEM to obtain information on the crack initiation point and the area of the crack nucleation defect [49].

3. Results and Discussion

3.1. Microstructural Characterization

The evaluation of the internal defects' content and distribution is key information to better understand the fatigue behavior of the material and also to evaluate the accuracy of the printing parameters. In Figure 5 the volumetric content and the relative internal defect distribution are shown for all batches analyzed with different postprocessing treatment conditions (NO-HIP and HIP). The volumetric content, as shown in Figure 5a, reveals that the SLM sample in as-printed condition (VHT) is similar to the EBM ones. Possible variations of the volumetric content as a function of the analyzed area may be correlated to measurement errors rather than process parameters due to the small differences found between each analyzed sample. On the other hand, the HIP treatment strongly reduced the internal defects in both the analyzed samples to levels near zero. The detected defects are mainly labeled as spherical pores and lack of fusion defects [17]; the latter are fewer in number as compared with the pores but larger in characteristic size.

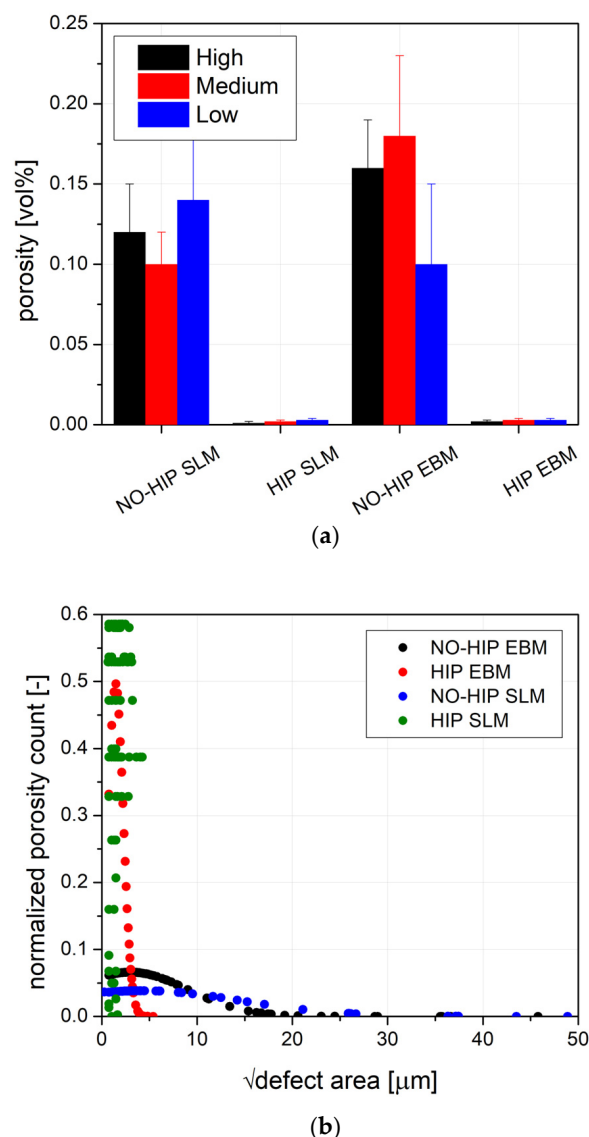


Figure 5. Porosity characterization results: (a) volumetric content, (b) dimensional distribution.

The internal defects size distribution, as shown in Figure 5b, shows a broad range for the as-printed samples, with defect sizes ranging from a few μm to hundreds of μm . The EBM samples, when compared to the SLM ones, show a broader distribution with defects of slightly higher dimensions.

In both samples, the HIP greatly reduced the distribution of defects, becoming narrower in the proximity of small circular pores, which are also likely to be confused with the background noise of the image analysis. It can be stated that, for both technologies, the post-HIP situation is totally comparable when referencing internal defects. This agrees with the analysis of other authors [50].

Figure 6 shows that the red areas are mainly pores, some of them elongated. The porosity is barely visible in samples that underwent HIP. This is in agreement with what is expected from material treated by HIP.

The microstructures of the analyzed samples are shown in Figure 7, for samples in NO-HIP condition, and Figure 8, for samples in HIP condition.

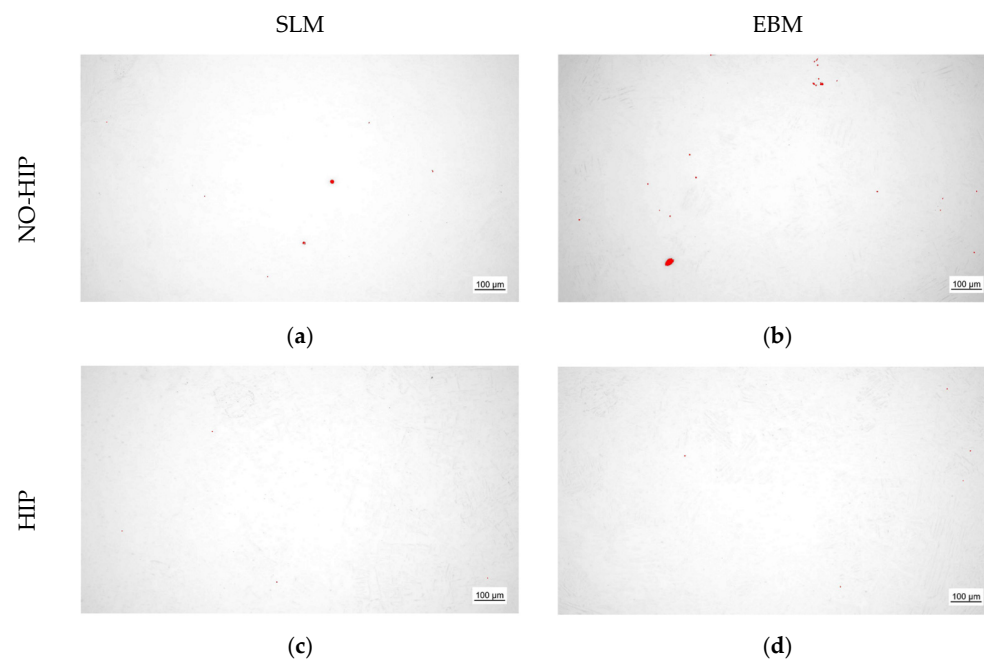


Figure 6. Representative images of the internal voids detected by image analysis. In red are highlighted the voids: (a) NO-HIP SLM, (b) NO-HIP EBM, (c) HIP SLM, (d) HIP EBM.

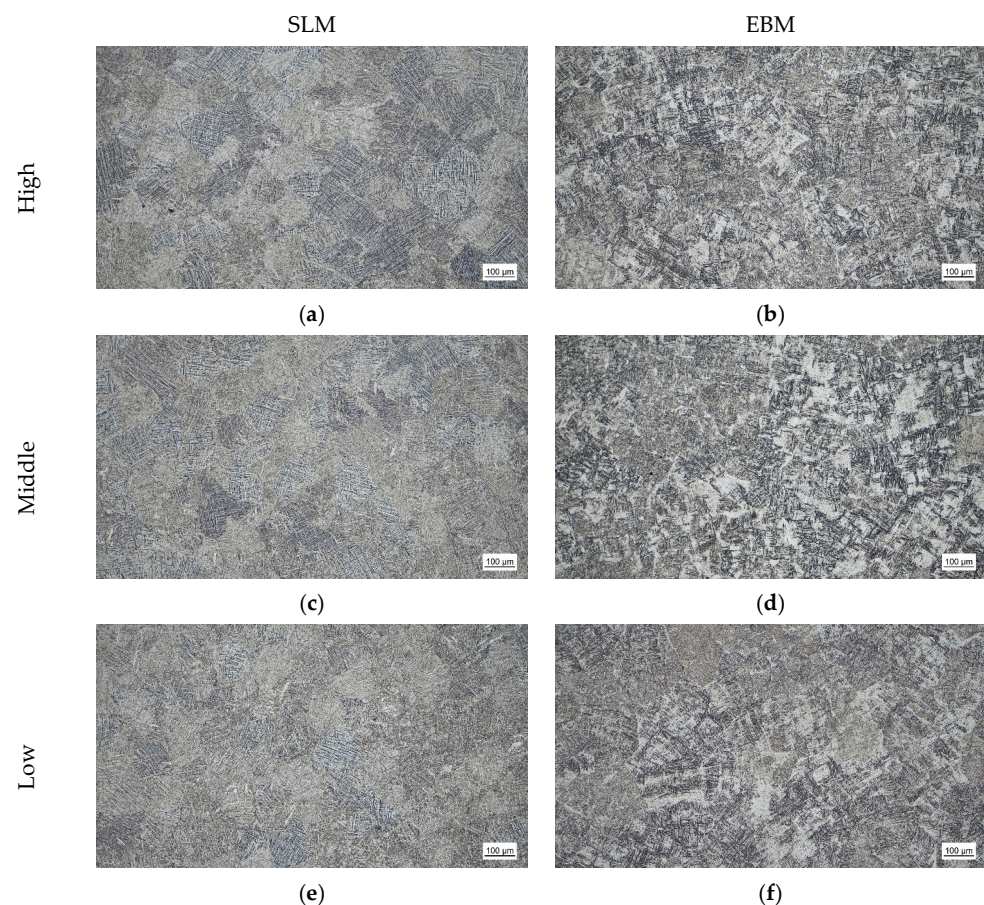


Figure 7. Microstructure of samples in the NO-HIP condition: (a) SLM high, (b) EBM high, (c) SLM middle, (d) EBM middle, (e) SLM low, (f) EBM low.

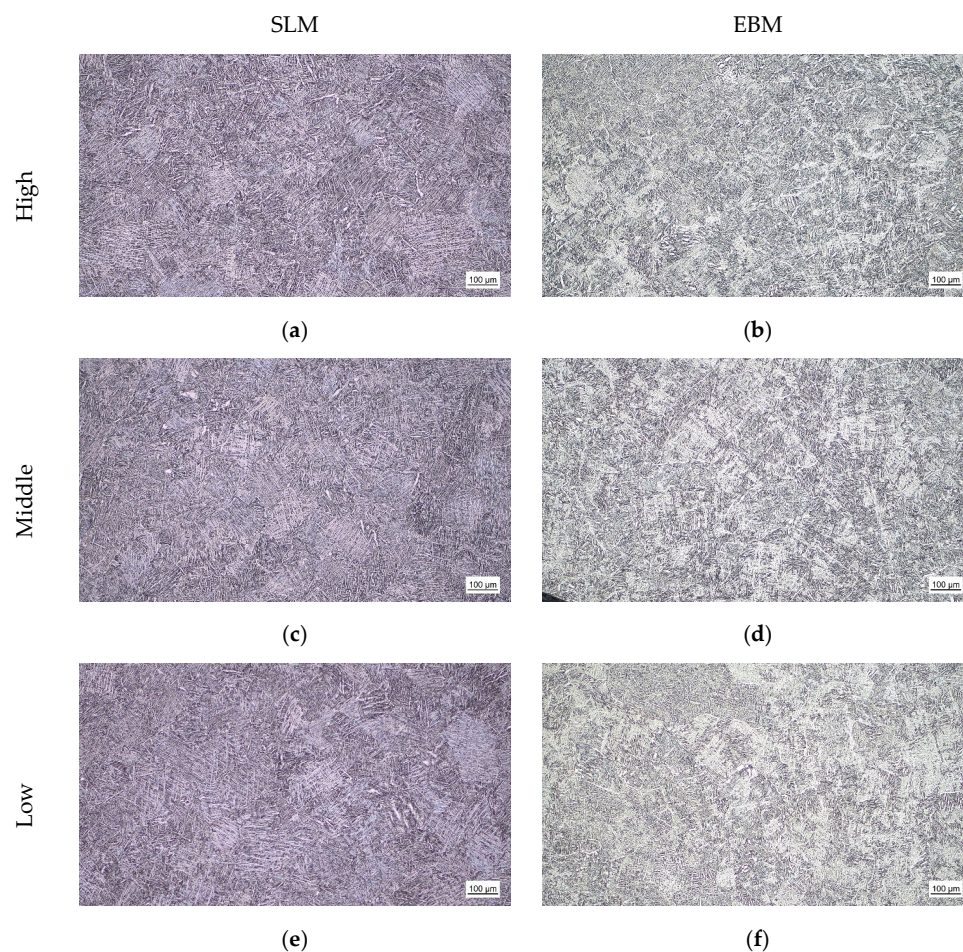


Figure 8. Microstructure of samples in the HIP condition: (a) SLM high, (b) EBM high, (c) SLM middle, (d) EBM middle, (e) SLM low, (f) EBM low.

Both samples show an α acicular microstructure with the presence of a β -phase in the α inter-laths. In the case of the SLM samples, it is also possible to observe the prior β grains with a dimension of about 150 μm . The EBM samples show the same microstructure, but the prior β grain is not detected. The microstructure of the EBM seems to be less homogeneous compared to the SLM samples. The HIP treatment has the effect of producing a coarser microstructure for both analyzed samples. No differences were found between the regions of the analyzed samples.

In order to better characterize the microstructure of the analyzed samples, the α -phase dimension and the β -phase distribution were calculated using image analysis software, with the procedure previously described. The results are summarized in Figure 9. The β -phase content is lower in the SLM samples compared to the EBM ones. This is probably because the SLM samples start from a Ti martensite microstructure, which decomposes into α - and β -phases after the heat treatment. The amounts are also lower since in SLM samples the β -phase also precipitates within the α -phase. In this case the phase is so small that the light microscope cannot resolve the dimension, and it is probably underestimated by image analysis. It is also to consider a certain amount of untransformed martensite that probably is present in the material [19]. In general, the microstructural differences between the two batches in the as-printed condition are related to the different initial microstructure of the materials, which is decomposed martensite in the SLM samples and acicular α -phase with interactive β -phase in the EBM samples [22]. In fact, this is usually related to a difference in the two microstructural parameters analyzed in this work, which are usually lower in SLM.

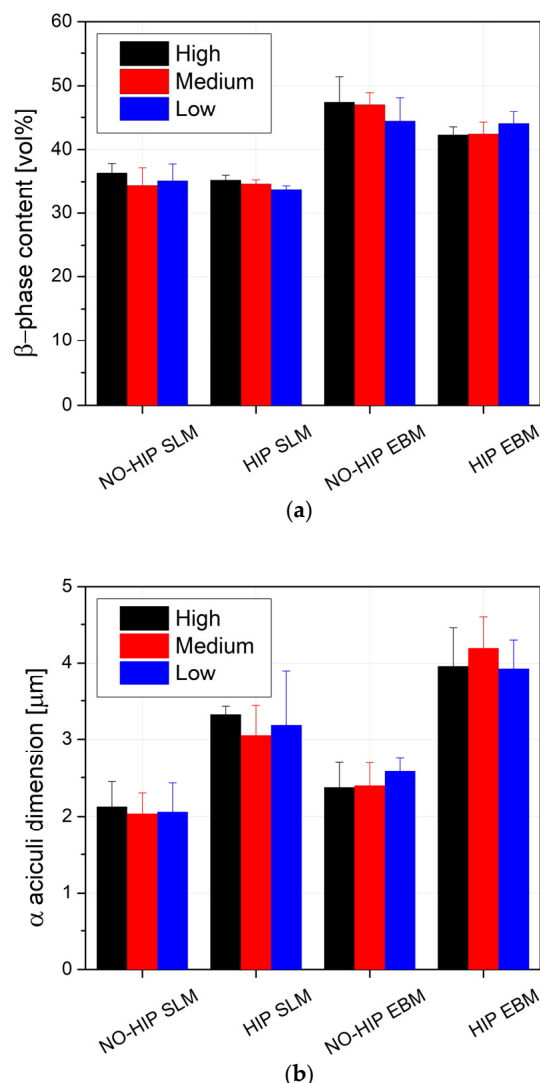


Figure 9. (a) β -phase content and (b) α aciculi dimension of the samples with different thermal conditions.

However, in both cases, no difference was observed along the length of the sample in terms of β -phase content, and the HIP process appears to have a negligible effect on it, at least in this experience. By analyzing the α -phase dimension, it is possible to observe that this is homogenous along the length of the sample. As indicated above, the SLM samples have a finer microstructure compared to the EBM ones, and again, as expected, the HIP process seems to slightly increase the grain size in both cases. This is due to the fact that HIP takes place at high temperatures under relatively high pressures, which can promote the formation of coarser phases [15]. In addition, in the case of HIP, the starting microstructure has a strong effect on the material response in terms of β -phase content and α -phase dimension. In general, the SLM samples present lower β -phase content and finer grain size. This is because the SLM samples should at the beginning decompose the martensitic microstructure, while the EBM samples are only undergoing coarsening of the initial microstructure due to the grain growth mechanism at high temperature.

3.2. Roughness Characterization

Another important parameter to consider in the evaluation of the fatigue properties of the material is the surface roughness. A detailed investigation, reported in Figure 10, was conducted on the samples in the as-printed texture because it is most relevant to characterizing the fatigue-related crack initiation behavior.

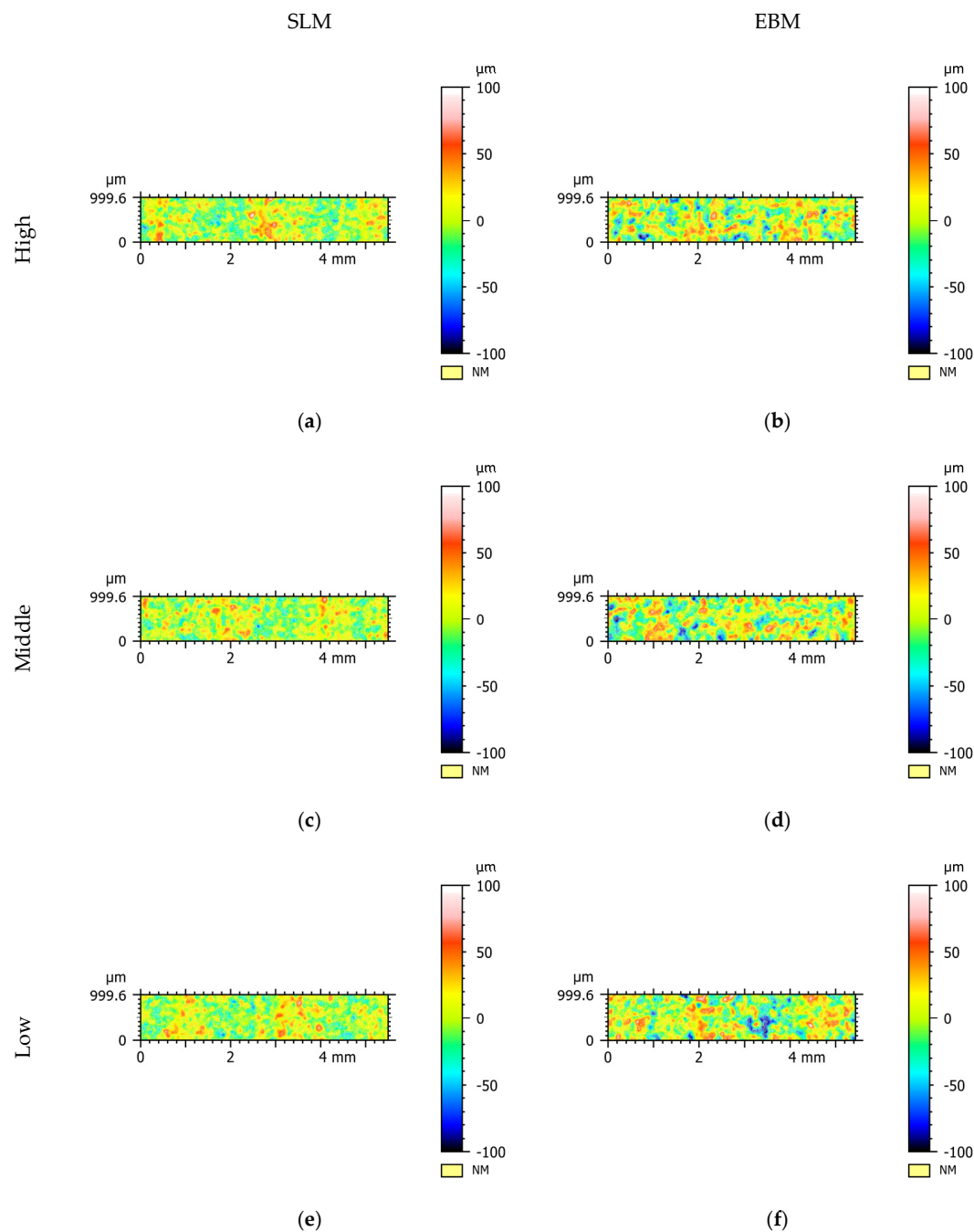
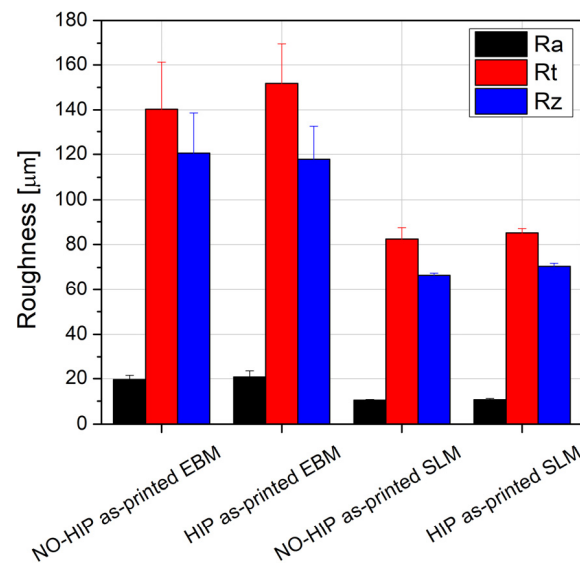


Figure 10. Surface texture of the as-printed samples: (a) SLM high, (b) EBM high, (c) SLM middle, (d) EBM middle, (e) SLM low, and (f) EBM low.

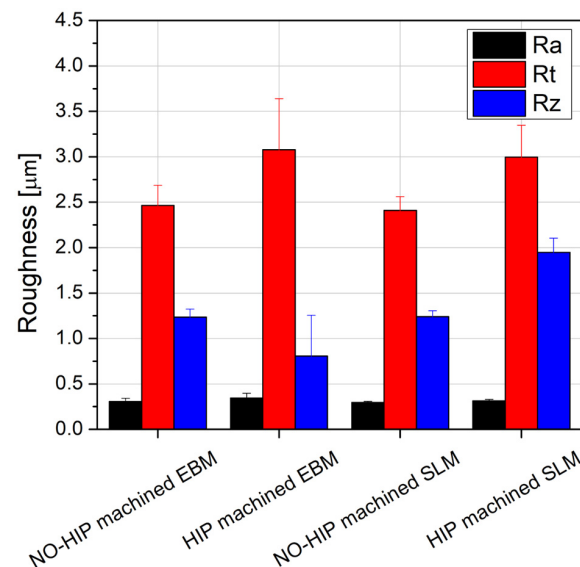
The surface texture of each sample analyzed is homogeneous along the length of the gauge and presents comparable surface characteristics in terms of R_a , R_t , and R_z in all regions analyzed. The colormaps indicate the heights of different points on the surface, which in the present case are roughly distributed between $-100 \mu\text{m}$ and $+100 \mu\text{m}$ relative to the average surface. Specifically, the points that deviate negatively are represented with a range of colors from light green to deep blue. In contrast, points that are positively offset have a color scale from yellow to deep red.

Some differences are observed between the SLM samples and the EBM samples, as shown in Figure 11. In fact, as expected, the EBM samples are rougher, in agreement with several studies carried out on the surface texture of additively manufactured components [49]. This difference is related to the printing conditions in terms of printing

parameters (beam spot dimension) and powder size, which is typically coarser in the EBM process. The machining process removes all the as-printed surface by smoothing the surface of the sample. In addition, the HIP process does not seem to have an effect on surface morphology.



(a)



(b)

Figure 11. Surface roughness of the samples with (a) as-printed surface and (b) machined surface.

The surface intensity factor K_t is then calculated according to Arola Williams indications [45] and shown in Figure 12. It is possible to observe that the K_t of the as-printed surface is too large with respect to the machined samples. This probably will have a great effect on the fatigue properties of the material by decreasing the fatigue life. By analyzing in detail the K_t values, it is possible to observe that the SLM presents, in as-printed condition, a lower K_t with respect to the EBM. The HIP process increases the surface K_t , probably because some unmelted particles will drop from the surface by increasing the R_t (see Figure 11).

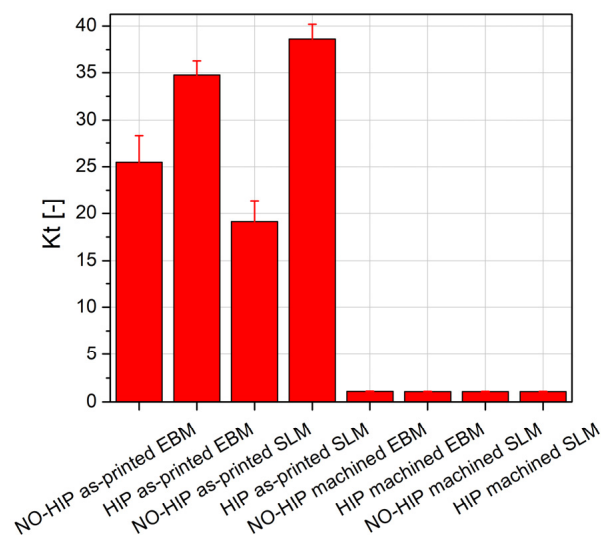


Figure 12. Kt values of the samples with as-printed surface and machined surface.

3.3. Microhardness Characterization

Another important parameter to consider in the evaluation of the fatigue properties of the material is the material microhardness. Figure 13 shows the microhardness maps obtained on the cross-sectional areas listed in Figure 4 for the as-printed samples.

The hardness maps obtained on the cross sections of the as-printed samples show a slightly heterogeneous distribution of the mechanical properties. In fact, for both the SLM and EBM samples, some softer areas are detected, associated with regions where the microstructure is heterogeneous, such as regions enriched in α -phase or regions where the grains are slightly coarser (see the α grains in Figure 14). The EBM sample presents the higher amount of these regions, which are homogeneously distributed in the three analyzed positions. On the other hand, the SLM samples show a higher amount of these soft areas in the upper part with respect to the lower part. This is probably due to its thermal history, which is modified during the printing process due to the gradual increase in temperature of the printed component [27].

HIP has a beneficial effect on hardness homogeneity. The HIP treatment improves hardness homogeneity by reducing internal porosity and slightly coarsening the microstructure, resulting in a more uniform local mechanical response across the samples. In fact, the hardness maps do not show areas of lower hardness. In general, when comparing the results in Figure 15, there is a gradual decrease in hardness associated with the effect of the heat treatment, which has reduced the heterogeneities by slightly coarsening the microstructure. A more homogenous hardness distribution is observed in the SLM samples. This probably is due to the fact that the starting microstructure (Ti martensite), before the HIP treatment, is more homogeneous in the SLM samples with respect to the EBM samples, which present their coarsened as-printed microstructure after HIP.

Although the hardness values reported in this study are presented in a non-dimensional form, they are consistent with hardness behavior observed in the scientific literature for Ti6Al4V, produced by additive manufacturing using both SLM and EBM processes. Previous works have documented similar trends in hardness for SLM-processed Ti6Al4V and comparative studies on EBM and SLM Ti6Al4V also support comparable mechanical properties [11,51,52]. In addition, broad reviews on Ti6Al4V AM describe consistent microstructure–hardness relationships across powder-bed fusion processes, confirming that the qualitative hardness trends observed here align with established results for additively manufactured Ti6Al4V alloys [53,54].

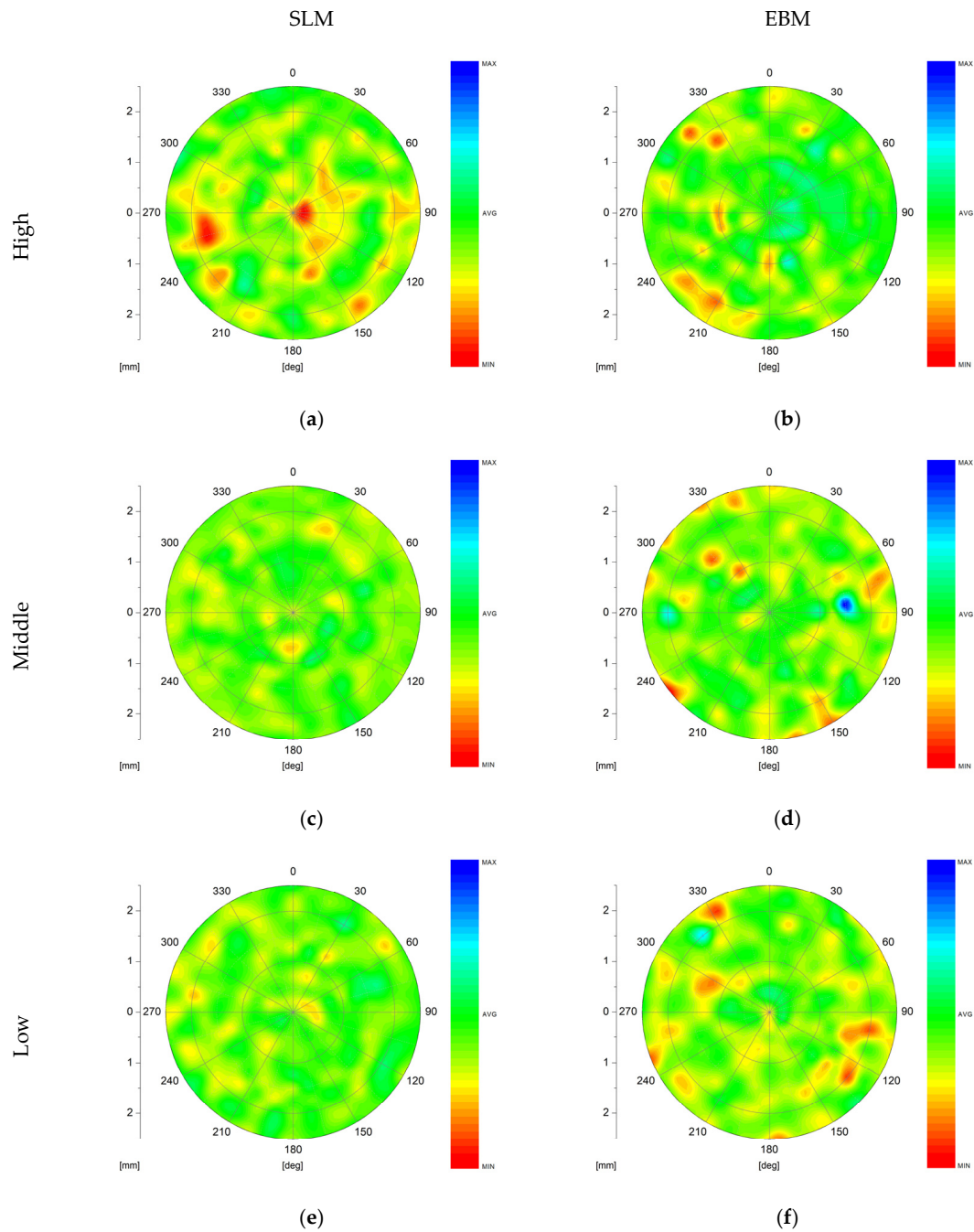


Figure 13. Microhardness maps on different regions of the NO-HIP samples: (a) SLM high, (b) EBM high, (c) SLM middle, (d) EBM middle, (e) SLM low, (f) EBM low.

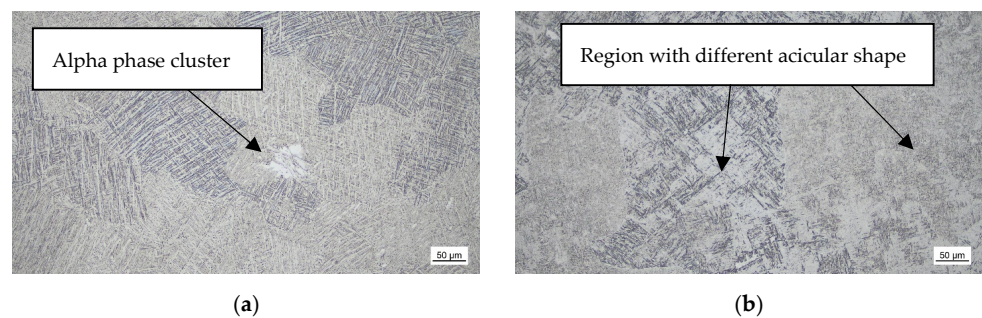


Figure 14. Heterogeneities that can cause local reduction of hardness in as-printed samples: (a) alpha phase cluster, (b) region with different acicular shape.

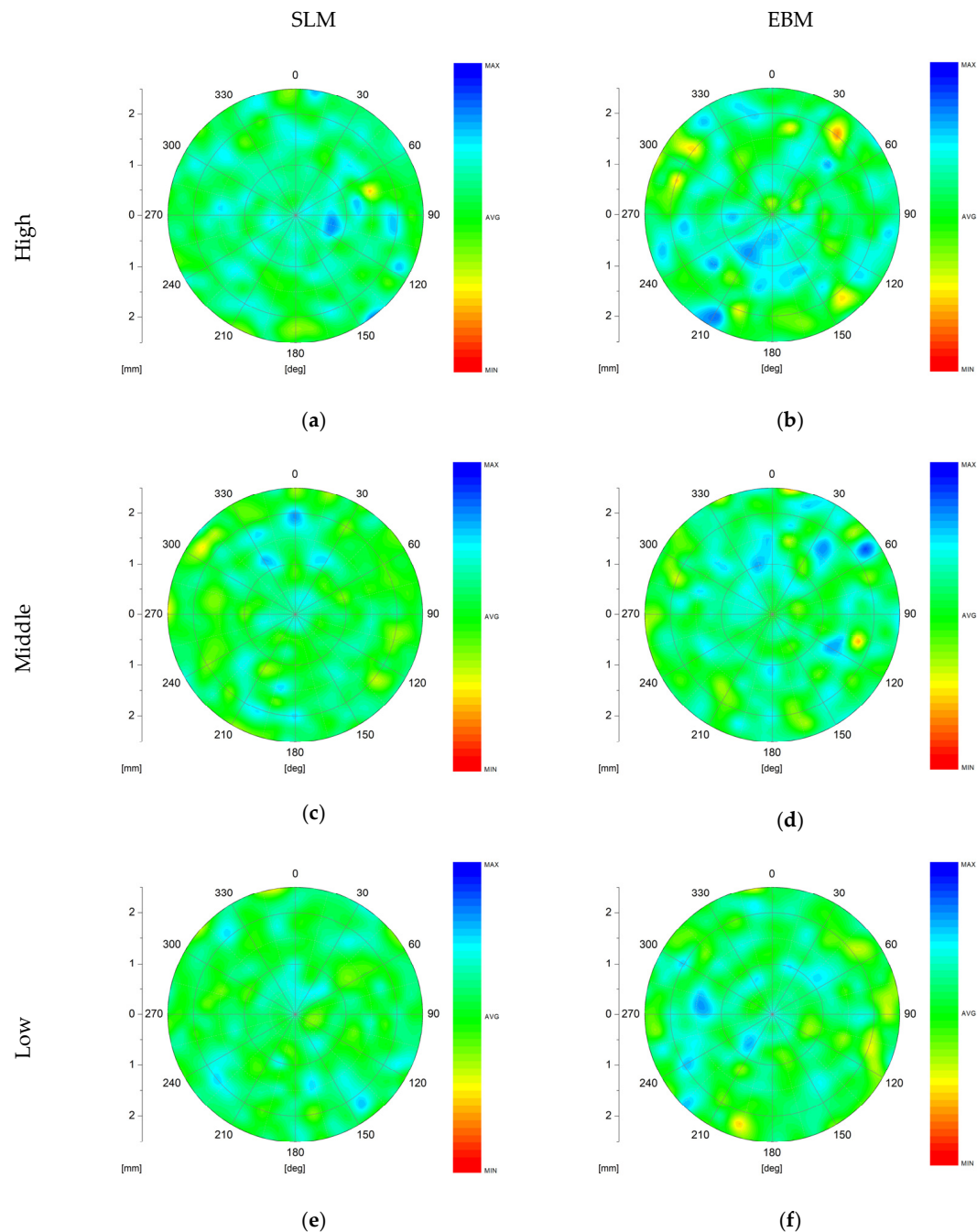


Figure 15. Microhardness maps on different regions for HIP samples: (a) SLM high, (b) EBM high, (c) SLM middle, (d) EBM middle, (e) SLM low, (f) EBM low.

3.4. Tensile Tests

Table 4 shows the tensile test results obtained on analyzed specimens. The results are in agreement with ISO 5832-3:2021 [42]. It is to highlight a slight difference in mechanical properties between the HIP and NO-HIP samples, in particular for the YS and UTS. As observed, the EBM and SLM samples present the same properties in HIP conditions. In as-printed EBM samples and SLM heat-treated samples some differences were detected. In particular, the SLM samples present slightly lower mechanical properties with respect to the EBM samples; this is probably related to the slightly different microstructure of materials.

Table 4. Tensile strength results.

Material Condition	YS (Rp0.2) [MPa]	UTS (Rm) [MPa]	Elongation [%]
NO-HIP EBM	961 (12)	1051 (13)	18 (1)
HIP EBM	877 (19)	1002 (6)	20 (1)
NO-HIP SLM	959 (6)	1039 (6)	17 (0.3)
HIP SLM	839 (3)	938 (3)	19 (0.1)

No significant differences in tensile properties were observed between as-printed and machined specimens or among specimens extracted from different zones of the build plate, confirming that surface condition and build location did not affect the tensile behavior of the material.

3.5. Fatigue Tests

Uniaxial fatigue tests were carried out on all the batches analyzed in the experimental procedure. The main objective was to determine the effect of both heat treatment and surface finishing on the fatigue resistance of the material for samples produced by EBM and SLM techniques.

The results of the staircase procedure using the Dixon-Mood estimates are reported in Table 5. The number of specimens tested per batch, as well as the ratio of failures to run-outs, are listed, along with the non-dimensional fatigue endurance limit—calculated according to the Dixon-Mood method and made non-dimensional as described in Equation (1)—and its standard deviation.

Table 5. Fatigue results using the staircase procedure.

Material Condition	Number of Samples (Fail/Runout Ratio)	Non-Dimensional Endurance Fatigue Limit [-]	Standard Deviation of Non-Dimensional Endurance Fatigue Limit [-]
As-printed SLM	14 (6/8)	61.8	4.3
Machined SLM	21 (6/15)	177.4	11.7
As-printed/HIP SLM	13 (7/6)	60.0	4.3
Machined/HIP SLM	13 (6/7)	195.0	5.0
As-printed EBM	14 (8/6)	41.5	2.8
Machined EBM	13 (5/7)	132.4	2.8
As-printed/HIP EBM	12 (6/6)	38.9	2.4
Machined/HIP EBM	12 (6/6)	182.6	3.1

The graph shown in Figure 16 reports the mean value and standard deviation of the non-dimensional fatigue endurance limit for each batch. It is possible to observe that the as-printed samples present lower fatigue performance, as expected. In fact, it can be observed that the failure occurs at low applied stresses. Comparing the two printing techniques analyzed in this test campaign, it is possible to observe that the EBM as-printed samples present the worst fatigue resistance, and this agrees with the surface characterization of the samples, which showed a higher roughness with respect to the SLM ones. In this case, it appears that the fatigue behavior is controlled more by the surface condition than by the internal defects or microstructure, as suggested by the fracture surface analysis, which showed typical crack nucleation in the proximity of the surface asperities (Figure 17a). When the asperity is removed, the fatigue resistance increases abruptly, still in favor of the SLM samples. This demonstrates how the surface asperities are more critical than the internal defects, which are the predominant cause of failure when the as-printed surface

is removed (Figure 17b). Indeed, this statement is also confirmed by the fatigue behavior of the EBM samples, which is lower than the SLM ones, and this is in agreement with the internal defect characterization, which showed a higher amount of coarse defects in the EBM samples.

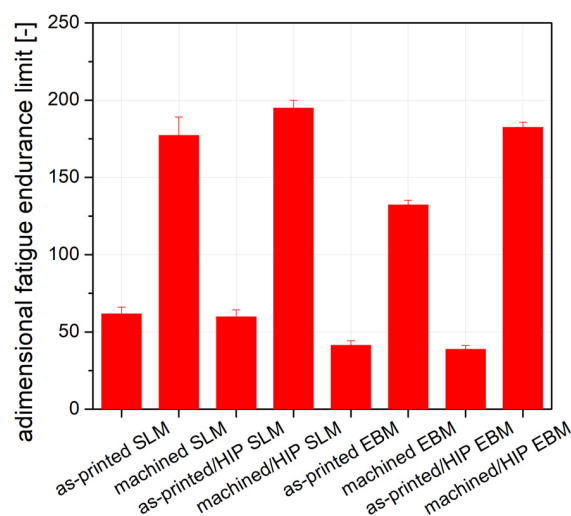


Figure 16. Fatigue endurance limit calculated from the fatigue testing (error bars refer to 1-standard deviation intervals).

On the other hand, the HIP treatment increases the fatigue resistance of the machined samples for both EBM and SLM techniques, and also in this case the SLM presents even better fatigue resistance. The failures usually occur at a number of cycles very close to the run-out, and the crack nucleation is usually observed close to the microstructural heterogeneities rather than to the internal defects or to the surface condition (Figure 17c). The HIP process on an as-printed surface is not effective to improve the fatigue properties of material due to the fact that the surface asperities are controlling the fatigue crack nucleation.

Looking at the fatigue limit calculated by the Dixon-Mood approach, a strong agreement with the S-N curve discussion can be observed. In particular, the SLM samples show a better fatigue performance in each condition analyzed with respect to the EBM samples. This behavior is in agreement with the previous discussion: the SLM sample in as-printed condition presents a smoother surface, and the SLM one in machined condition presents fewer and lower amounts of internal defects. The HIP treatment, in the case of as-printed surfaces, is not effective in increasing the fatigue properties of material that presents the same behavior as the NO-HIP condition. The same consideration concerning the difference between SLM and EBM on fatigue life is still valid for machined and HIP conditions even if the difference in this case seems negligible between the technologies due to the similar microstructure obtained on both EBM and SLM samples after HIP treatment. It is also to highlight that the fracture surface of the HIP samples, in most of the analyzed ones, presents a crack nucleation site that does not correspond to an internal defect but rather to a microstructural discontinuity that can be correlated to possible areas where the pore was present and, after HIP, closed with a dynamic recrystallization. In particular, some authors have observed that the microstructure is equiaxed and biphasic [37].

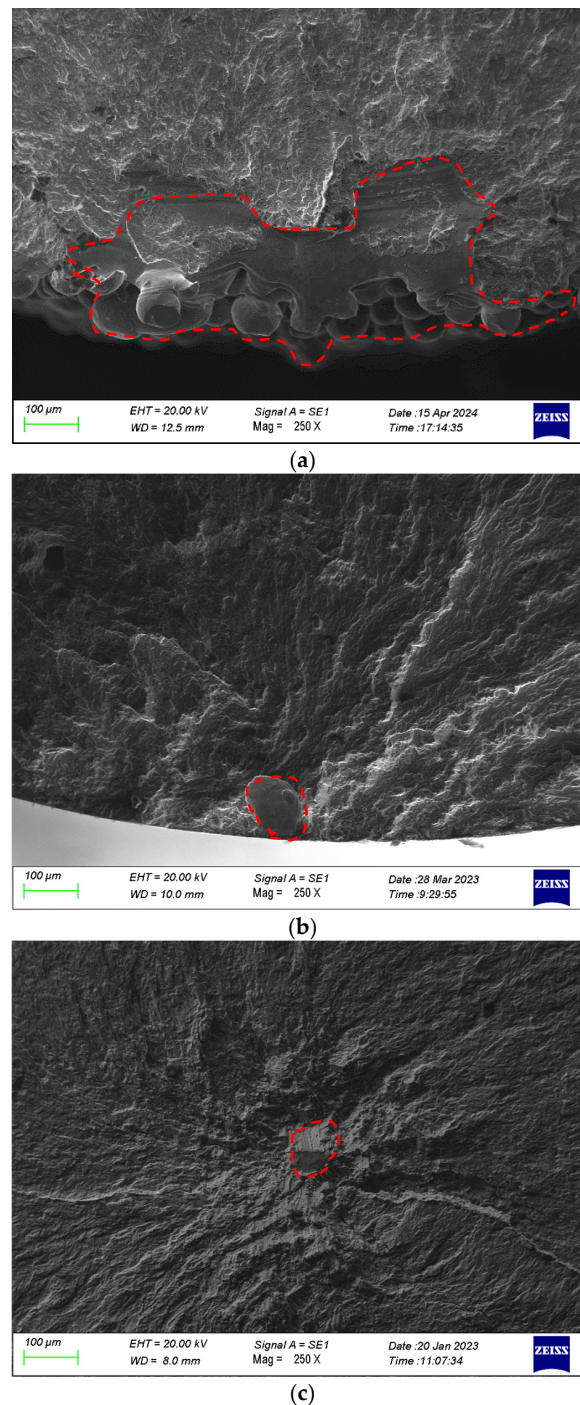


Figure 17. Typical crack nucleation morphologies for (a) as-printed samples, (b) machined samples, and (c) HIP samples. The crack nucleation sites are indicated with dotted lines.

In order to better characterize the failures occurring at the critical defect from which the crack nucleated, Figure 18 shows a graph summarizing, for failed samples, the number of cycles as a function of the dimensionless applied load and the defect extension. As previously mentioned, the as-printed samples exhibit larger internal defects compared to other conditions. Among the two printing techniques, EBM samples show the coarsest defects, a trend also observed in the machined condition. These larger defects in EBM are reflected in the bigger crack nucleation sites found in failed samples. On the other hand, the HIP samples present smaller defects that caused the samples to fail, which usually occurs with low data scatter and failures closer to the fatigue limit. In addition, it is possible

to observe that the effect of the dimensionless applied load is to anticipate the failure of the samples when it is increased. It is also evidenced that the applied load becomes less invasive on cycles to failure when the dimension of the crack nucleation site is becoming finer. This probably is related to the severity of the crack nucleation discontinuity that in HIP samples is usually finer and round-shaped with respect to the other tested conditions. Again, the SLM samples show the smallest extension of the crack nucleation area. By analyzing in detail the graphs, it is possible to observe that each tested condition presents a dimension class of the defects responsible for the crack nucleation. These defects are coarser for the EBM samples due to the fact that the surface texture is of lower quality compared to the SLM ones. In addition, the dispersion of the data is higher for the EBM samples. In this case, the defects are usually gas pores or lack of fusion and correspond to the internal defects detected in Figure 6 [17]. In fact, the EBM again presents the higher data dispersion due to the wider dimensional distribution of the defects observed during the characterization of the internal voids. As expected, the HIP samples show a critical flaw, a discontinuity in the dimensional class below 50 μm . This again corresponds to the dimensional distribution of the internal defects. Moreover, the EBM samples have the coarser defects. It can be seen that a reduction in the size of crack nucleation defects means a failure closer to the fatigue limit of the material.

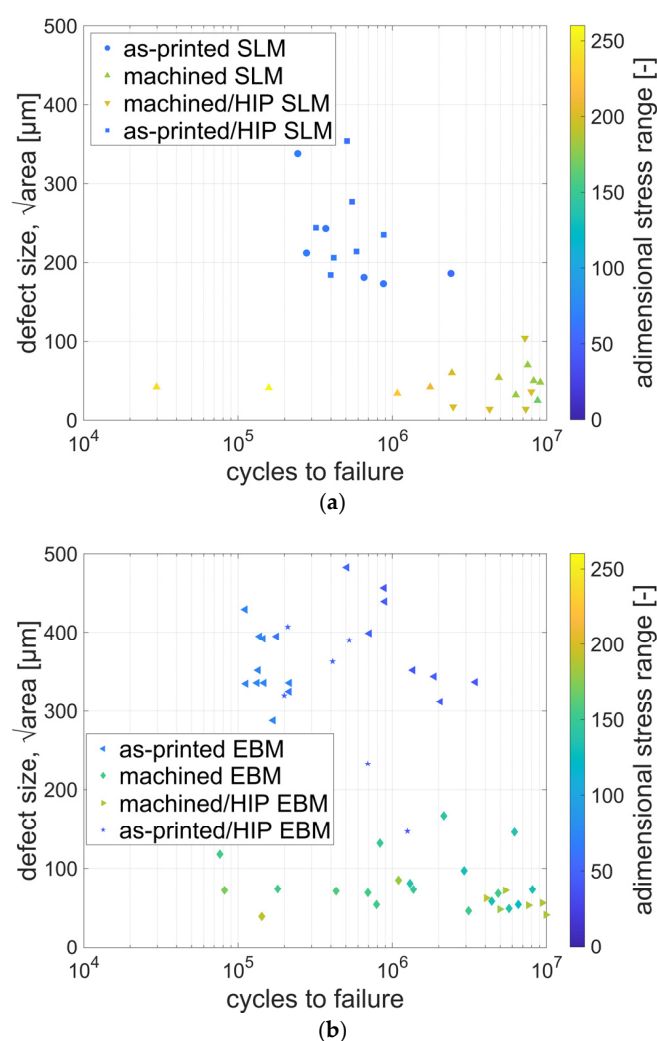


Figure 18. Square root of the defect area as a function of the number of cycles to failure for all batches: (a) SLM, (b) EBM.

By analyzing the effect of defect size as a function of applied load, it can be observed for machined samples that failure occurs at a lower number of cycles when the applied load is higher. This is probably related to the fact that increasing the applied load means anticipating the activation of the flaw and thus the failure of the material. This is also true for the as-printed samples, but in this case the initial defect extension is widely dispersed and is the main cause of crack nucleation. In machined samples subjected to HIP, the internal defects are probably local microstructural changes, as previously demonstrated, whose dimensions are within a very narrow dispersion range. On the other hand, the defects that produced the crack nucleation in HIP as-printed samples present similar dimensions with respect to the NO-HIP samples with as-printed surfaces. This confirms that HIP treatment has little effect on as-printed surfaces, as surface asperities dominate the material's fatigue behavior.

4. Conclusions

The present work aims to highlight the state of the art in terms of fatigue studies concerning the fatigue properties of the Ti6Al4V alloy produced by the last released industrial SLM and EBM processes. Particular attention has been paid to the surface finish and the thermal treatments used as post-processing for the additive manufactured products.

The main results obtained from this work are the following:

- the internal defects, limited by a correct choice of printing parameters, are usually coarser for the EBM samples with respect to the SLM ones. HIP greatly reduced the content and dimension of these defects;
- the microstructure of the samples is similar, while the fraction of beta phase differs quantitatively, with EBM samples generally exhibiting a slightly higher beta phase content and coarser metallurgical features. This is also observed in the HIP samples. The causes are related to the initial microstructure prior to heat treatment (no heat treatment for EBM samples) or the HIP process. This is also reflected in the microhardness distribution, although the HIP process made the microstructure more homogeneous;
- the surface texture in the as-printed condition is strongly influenced by the printing technique and also by the process parameters. The fatigue resistance of the samples is strongly influenced by the surface condition and texture, which is also the origin of the fatigue failures. In this case, the EBM samples exhibited the worst fatigue behavior in the as-printed condition. When the as-printed texture is removed, the fatigue life is strongly influenced by internal defects. The HIP treatment of rough surfaces, such as the as-printed ones, is not effective in increasing the fatigue life of material. The difference in fatigue resistance between EBM and SLM is strongly reduced for machined and HIP samples;
- the applied load plays a role in fatigue crack nucleation. In particular, for the same defect size, the defect induces an anticipated failure at higher applied loads.

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Data Availability Statement: The raw/processed data required to reproduce these findings cannot be shared at this time, as the data also forms part of an ongoing study.

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Abbreviations

The following abbreviations are used in this manuscript:

HIP	Hot Isostatic Pressing
VHT	Vacuum Heat Treatment
SLM	Selective Laser Melting
EBM	Electron Beam Melting

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