



The combined effect of microstructure anisotropy and surface integrity on the fatigue resistance of AM and wrought Ti6Al4V titanium alloy

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ABSTRACT

The paper investigates the combined effects of microstructural anisotropy and surface integrity on the fatigue performance of Ti6Al4V in wrought-equiaxed (W-E), wrought-lamellar (W-L), and laser powder bed fusion lamellar (LPBF-L) conditions under flood and cryogenic machining. Although the W-E condition shows the highest fatigue limit, it lacks the crack-deflection capability typical of lamellar microstructures. Among the lamellar states, LPBF-L exhibits greater resistance to crack propagation due to its lower anisotropy compared with W-L. Cryogenic machining improves fatigue behavior in all conditions, with lamellar microstructures benefiting the most, as their anisotropy promotes the formation of a thicker plastically deformed layer (PDL).

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1. Introduction

Ti6Al4V is a highly attractive alloy due to its high specific strength, excellent resistance to corrosion, fatigue, and creep, and proven biocompatibility, making it suitable for demanding aerospace and biomedical applications where fatigue strength is critical for long-term safety and reliability.

The fatigue strength of Ti6Al4V is known to depend strongly on its microstructural state, particularly on the morphology, size, and distribution of the α and β phases that characterize the alloy. The comparison between fine bimodal and coarse lamellar Ti6Al4V microstructures showed that the latter exhibits improved mode I fatigue-crack propagation resistance, attributed to its higher strength and more tortuous crack paths [1]. Nevertheless, the increase of either the α grain size or α lamellar width was found to be responsible for reduced high-cycle fatigue strength [2]. Besides the microstructure, significant efforts have been spent on relating surface integrity and fatigue performance [3]. Equiaxed Ti6Al4V samples were fatigue-tested under pull–pull cyclic loading after machining under dry, minimum quantity lubrication, cryogenic, and high-pressure air jet conditions. The results showed that cryogenic machining enhances fatigue strength due to significant grain refinement [4]. In contrast, equiaxed Ti6Al4V exhibited comparable fatigue life under flood and cryogenic machining conditions [5].

The recent adoption of additive manufacturing (AM) to produce Ti6Al4V parts makes the relationship between fatigue strength, microstructure, and surface integrity even more critical, due to the presence of AM-induced defects and distinctive AM-generated microstructures. Extensive literature reviews report fatigue data of AM metals as a

function of the AM and post-processing parameters (see, for instance, [6]), reflecting the strong interest of the scientific community in this topic. Much effort has been put into evaluating the effect of the building direction on the fatigue performance of AM-ed Ti6Al4V, pointing out the correlation with the AM-induced microstructural features [7,8]. Different approaches have been used to assess fatigue strength, including conventional stress–life (S–N) diagrams and linear elastic fracture mechanics (LEFM)-based methods, the latter appearing to be more suitable for AM metals because they can explicitly account for the influence of inherent AM defects [9]. Post-processing operations applied to AM parts can modify their surface integrity (beyond surface topography alone) and thus significantly affect fatigue strength. The effect of post-processing operations, namely electro-plasma polishing and machining, on LPBF Ti6Al4V was assessed. Machining resulted in the highest fatigue strength by removing the surface waviness typical of additively manufactured parts, whereas electro-plasma polishing introduced additional defects that limited fatigue performance [10]. Cryogenic machining was shown to increase the fatigue strength of LPBF Ti6Al4V compared with conventional flood machining, an effect attributed to the formation of a hard, harmonic microstructure [11]. The comparison of fatigue data between wrought and AM specimens usually shows a clear drop in the fatigue performance of the latter, especially in the high-cycle fatigue regime. Nevertheless, several studies have shown that post-processing (particularly hot isostatic pressing) can be beneficial in reducing internal defects, enabling fatigue strengths comparable to those of wrought counterparts [12].

What emerges from the literature is: (i) a lack of systematic investigations into how fatigue strength varies under the combined effects of Ti6Al4V microstructural features and surface characteristics, and (ii) the absence of studies comparing fatigue datasets from wrought and AM samples using a unified approach that accounts for the role of defects, namely an LEFM framework.

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Within this context, the present study provides new insights into the role of microstructure and surface integrity in governing the fatigue strength of Ti6Al4V across different microstructural states. Three representative microstructures with varying degrees of anisotropy were subjected to flood and cryogenic machining, resulting in different surface integrity conditions. Fatigue datasets partly derived from the authors' previous works [5,11] were analysed together with new experimental results in order to establish a consistent comparison of fatigue performance on the same basis. Fatigue strength was modelled using an LEFM framework based on the Murakami approach. This approach successfully accounts for manufacturing-induced features and demonstrates the model's capability to predict the fatigue response across the different Ti6Al4V microstructural states.

2. Microstructural states of Ti6Al4V

In this study, three different Ti6Al4V microstructural states were selected due to their high relevance in demanding load-bearing industrial applications. For the microstructural investigation, the samples were first mechanically ground using progressively finer SiC abrasive papers and subsequently polished. Afterwards, the microstructures of the three conditions were examined using a Tescan SOLARIS dual-beam field-emission scanning electron microscopy (FE-SEM). Electron backscatter diffraction (EBSD) analyses were performed using an Oxford Instruments CMOS Symmetry detector installed in the FE-SEM to obtain pole figures. The latter are used to show the orientation distribution of crystallographic planes in the material, providing information about its anisotropy. Indentation measurements were performed using the instrumented indentation platform Nanomechanics iMicro equipped with a Berkovich tip, in accordance with ISO 14577–1:2015. For each condition, 40 indentations were performed using a load of 10 mN. Results were then converted into an equivalent Vickers-hardness map. Uniaxial tensile tests were also conducted using an MTS 858 MiniBionix II servo-hydraulic testing machine, equipped with an MTS 632.13F-20 extensometer featuring a 10 mm gauge length. The tests were performed at a crosshead separation rate of 0.3 mm/min, with the procedure repeated three times for each Ti6Al4V microstructural state.

W-E (wrought-equiaxed) Ti6Al4V was purchased as a 12 mm diameter and 3200 mm long bar from LLS Titanium. W-E exhibits a very fine, fully recrystallized microstructure characterized by equiaxed α phase grains with intergranular β phase regions, as evidenced in Fig. 1a. The variety of colors observed in the EBSD map shown in Fig. 1d suggests a random crystallographic texture, indicating a broad distribution of grain orientations. In addition, W-E exhibits homogeneous hardness with negligible local variations in mechanical properties (Fig. 2). The very fine equiaxed microstructure in W-E induces the highest UTS and toughness among the three investigated microstructural states (Table 1).

W-L (wrought-lamellar) Ti6Al4V was obtained by heat treating the as-received W-E material under a protective argon atmosphere. The heat-treatment cycle consisted of heating to 1035 °C for 15 min, air cooling, and subsequent aging at 750 °C for 80 min. This heat treatment results in a fully lamellar ($\alpha+\beta$) Widmanstätten microstructure, which is particularly suitable for high-temperature and creep-resistant applications. The slow

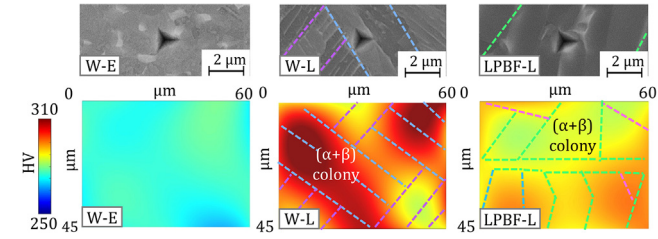


Fig. 2. SEM image of a single indentation (top) and hardness maps (bottom) of the specimen cross sections.

cooling from above the β -transus transforms most of the β phase into α , arranged in colonies of parallel lamellae within each prior β grain (Fig. 1b). Overall, this results in ($\alpha+\beta$) colonies with a highly preferred orientation, resulting in a pronounced anisotropy as seen in the EBSD map of Fig. 1e. W-L exhibits higher hardness with respect to W-E, as a consequence of this arrangement of colonies and a much higher α phase fraction, as estimated from EBSD-based phase analysis (Table 1). The hardness map of Fig. 2 also shows significant heterogeneity, being characterized by localized zones of elevated hardness. Additionally, the local hardness appears to be correlated with grain orientation as in [13]. For instance, light blue-colored ($\alpha+\beta$) colonies, in which indentation occurs almost perpendicular to the prismatic plane $\{10\bar{1}0\}$ exhibited the highest hardness, whereas violet-coloured ($\alpha+\beta$) colonies were markedly softer. To facilitate comprehension, the orientations of the ($\alpha+\beta$) colonies were schematically depicted in Fig. 2 based on SEM images of the indentation array. For clarity, high-magnification SEM images of a single indentation are shown at the top of Fig. 2. Finally, W-L exhibits the lowest UTS and toughness among the three microstructural states, due to its coarser microstructure and greater anisotropy.

LPBF-L (laser powder bed fusion-lamellar) Ti6Al4V was produced on the MYSINT 100 SISMA LPBF machine using gas-atomized spherical powders with particle sizes ranging from 15 to 45 μm , under a high-purity argon atmosphere.

Hourglass specimens were manufactured with their axis parallel to the building direction using the parameters previously optimized [11]. After the LPBF process, the specimens were heat-treated in a Carbolite Gero laboratory furnace by heating to 950 °C for 30 min in a protective argon atmosphere, followed by furnace cooling under argon. This heat treatment is necessary to decompose the as-built α' martensite, obtain the fine ($\alpha+\beta$) morphology, limit prior β grain coarsening, while meeting ductility requirements of high-performance applications [14]. The heat treatment, close but below the β -transus, induces the formation of a fine lamellar mixture of α and β phases inside prior β grain, as shown in Fig. 1c. Although ($\alpha+\beta$) colonies are still present, their orientations differ from one another, resulting in less pronounced anisotropy compared to W-L (Figs. 1e and 1f). LPBF-L exhibits hardness values similar to those of W-L, but with variability intermediate between W-E and W-L. Accordingly, the mechanical properties of LPBF-L lie between those of W-E and W-L.

Table 1
Microstructural and mechanical characteristics (values are reported as mean $\pm$ standard deviation).

	W-E	W-L	LPBF-L
α - titanium	0.974	0.982	0.977
β - titanium	0.026	0.018	0.023
UTS/MPa	1019 $\pm$ 6	902 $\pm$ 4	996 $\pm$ 3
Toughness/MPa	1401 $\pm$ 5	87 $\pm$ 2	110 $\pm$ 18

3. Machining and fatigue testing of Ti6Al4V

Fatigue specimens were machined on a Mori Seiki CNC lathe using VCET 110301-UM 1115 inserts from Sandvik. Specifically, hourglass specimens with a minimum diameter of 4.5 mm and a total length of

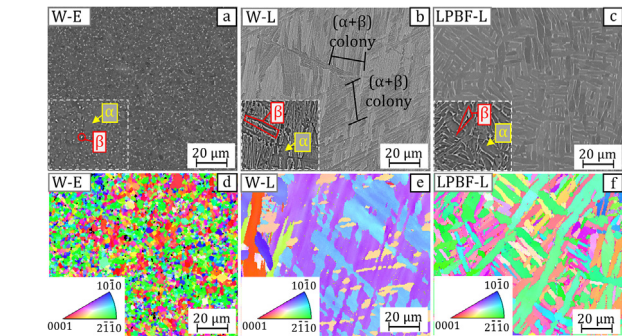


Fig. 1. (a, b, c) SEM images and (d, e, f) electron backscattered diffraction EBSD α orientation imaging and inverse pole figure (IPF) of the specimen cross sections.

80 mm were selected to promote failure within the medium- to high-cycle fatigue regime. Depth of cut of 0.25 mm, cutting speed (V) of 45 m/min, and feed of 0.03 mm/rev were adopted for the finishing pass of the specimen gauge length, which was always performed using a fresh tool. Flood and cryogenic cooling were used as lubrication-cooling strategies; a detailed description of the experimental apparatus can be found in [5]. Cryogenic cooling was considered as an alternative to flood lubrication, as it is well known to enhance surface integrity and fatigue life of metals [15,16]. At least 35 fatigue specimens were machined for each Ti6Al4V microstructural state, with a subset sacrificed for post-machining characterization, which was performed in the gauge region.

The machined surface finish was evaluated using confocal microscopy on a Sensofar S-Neox optical profiler. A 2.5 μm S-filter and 0.25 mm L-filter were applied to evaluate the areal texture parameters on the S-L surface.

The fatigue performance of the machined Ti6Al4V samples was evaluated using a rotating bending fatigue test configuration, chosen for its capability to capture machining-induced alterations at the surface. Tests were conducted under fully reversed loading conditions ($R = -1$) at a frequency of 200 Hz using a METRO COM fatigue testing machine. The fatigue test was considered terminated, either the fracture of the sample's whole section was attained, or the run-out criterion was reached.

At the end of each fatigue test, the fracture surfaces were examined by SEM at various magnifications to identify the location of the critical (“killer”) defect. Fatigue crack initiation was attributed either to surface roughness features (quantified by optical profilometry) or to subsurface defects. The adopted procedure followed Murakami's prescriptions reported in [17]. This method accounts for the defect size parameter $\sqrt{\text{area}}$, which is defined as the square root of the area of the identified killer defect projected onto the plane perpendicular to the maximum principal stress.

4. Results and discussion

Fig. 3 reports the experimental fatigue data of the Ti6Al4V different microstructural states (W-E (5), W-L, and LPBF-L (11)) expressed in terms of gross nominal stress range $\Delta\sigma_g$ (differentiating between failed and run-out samples) as a function of the $\sqrt{\text{area}}$ parameter, and combines them with the Murakami model prediction in the case of flood and cryogenic machining. The graphs highlight three regions based on the defect size: i) the defect-free region, ($\sqrt{\text{area}} < \sqrt{\text{area}_c}$), ii) the small defects region ($\sqrt{\text{area}_c} < \sqrt{\text{area}} < \sqrt{\text{area}_t}$), and iii) the long cracks region ($\sqrt{\text{area}} > \sqrt{\text{area}_t}$). $\sqrt{\text{area}_c}$ denotes the transition defect size between the defect-free and short crack regimes, while $\sqrt{\text{area}_t}$ denotes the transition defect size between short crack and long crack regimes. Whether a sample falls into one region or another depends strictly on the fatigue fracture initiation site—namely, the killer defect—which is itself

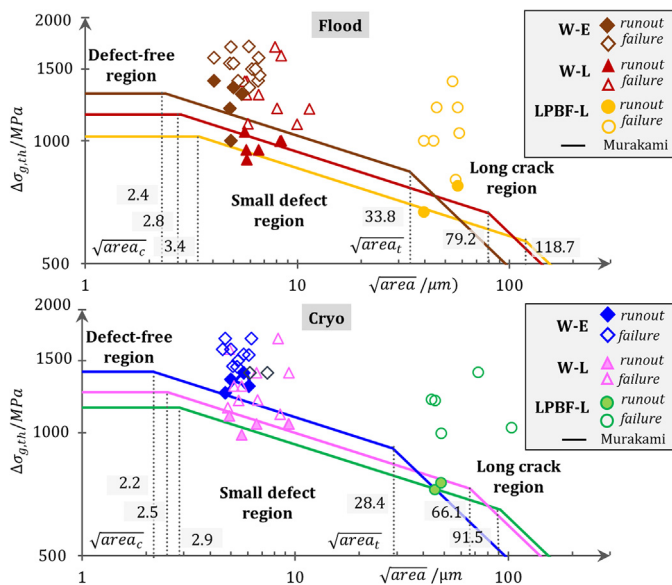


Fig. 3. Experimental fatigue data and fatigue limits predicted according to the Murakami model.

correlated with the manufacturing route. For W-E and W-L, fatigue cracks initiated at surface roughness valleys, placing them in the small defect region. In this case, the $\sqrt{\text{area}}$ parameter was estimated from the maximum profile height R_z , calculated in accordance with ISO 4287, using λ_s filter equal to 2.5 μm and a cut-off λ_c of 0.8 mm, as proposed by Murakami [17]. In contrast, LPBF-L consistently fell within the long-crack region, as fatigue crack initiation was driven by porosities. Fig. 4 illustrates the differences in killer defect type and location at varying Ti6Al4V microstructural states. Table 2 reports the input data of the Murakami model. Specifically, the hardness HV corresponds to the average of the values measured within the plastically deformed layer (PDL) of the machined samples (see Fig. 5), as determined by indentation measurements. The long crack propagation threshold ($\Delta K_{th, LC}$) was derived from fatigue tests carried out on sharp V-notched samples of the three Ti6Al4V microstructural states. $\Delta K_{th, LC}$ was assumed to be identical for both flood and cryogenic machining, as it is primarily governed by the bulk microstructure rather than surface integrity. The defect-free fatigue limit ($\Delta\sigma_{0, est}$) was estimated using the modification proposed by the authors in [5] for both the W-E and W-L, as the killer defect originated from the surface roughness.

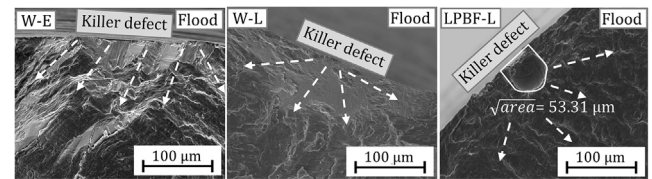


Fig. 4. Detail of the killer defect on the fatigue fracture surfaces.

Table 2

Input (HV, $\Delta K_{th, LC}$) and output ($\Delta\sigma_{0, est}$) data of the Murakami model, and main parameters of the Wöhler curve ($\sigma_{A, 50\%}$, N_A).

Series		HV	$\Delta K_{th, LC}$ /MPa·m ^{0.5}	$\Delta\sigma_{0, est}$ /MPa	$\sigma_{A, 50\%}$ /MPa	N_A /10 ⁶ cycles
Flood	W-E	303	5.64	1307	686	1.2
	W-L	319	6.84	1159	513	0.7
	LPBF-L	320	7.14	1024	278	2.0
Cryo	W-E	308	5.64	1408	696	0.9
	W-L	329	6.84	1256	538	0.8
	LPBF-L	360	7.14	1152	361	2.0

This was necessary to overcome the common assumption that the fatigue ratio, defined as the ratio between the fatigue limit in terms of stress amplitude and the UTS, is always equal to 0.5. This hypothesis does not generally hold for titanium alloys, and even less so in the presence of machining effects.

Fig. 3 shows that a good agreement between the experimental and predicted data was achieved, as the fractured samples (labelled as “failure” in the legend of Fig. 3) lie well above the theoretical estimation of the fatigue limit, while the run-out samples lie below it. It is worth noting that Fig. 3 does not include the $\pm 20\%$ error bands associated with the Murakami model to preserve graph readability. This good level of agreement was attained even without accounting for the residual stresses induced by machining, as they are often partially relaxed during cyclic loading, making their overall contribution difficult to predict [18]. Besides fatigue limit prediction, Fig. 3 provides further useful information. Regardless of the machining conditions, W-E exhibits the highest

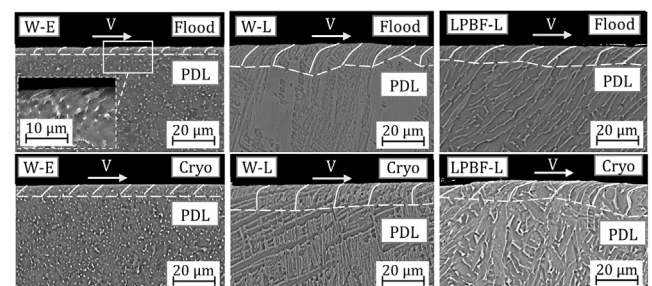


Fig. 5. SEM images of the PDL regions.

fatigue limit, reflected by the highest $\Delta\sigma_{0,est}$. This is attributed to the fact that equiaxed α grains accommodate local stress concentrations more effectively than lamellar structures. As expected, LPBF-L exhibits the lowest fatigue limit, as its internal porosity provides pre-existing crack-like defects that promote early crack initiation. On the other hand, W-E consistently exhibits both the lowest $\sqrt{area_c}$ and the lowest $\sqrt{area_t}$ (see the values corresponding to the dotted lines in Fig. 3), since cracks can easily propagate along relatively straight and smooth paths. Conversely, lamellar microstructures provide a higher resistance to crack propagation by deflecting cracks along more tortuous paths. In particular, LPBF-L exhibits higher crack propagation thresholds than W-L, as the continuously varying orientation of the α lamellae hinders crack advance, as evidenced by Fig. 1f compared with Fig. 1e.

On average, Fig. 3 shows that W-L exhibits larger and higher scattered $\sqrt{area}$ values than W-E. This outcome is consistent with the higher and more scattered surface roughness parameters reported in Table 3, particularly Svk. Compared with Sa, Svk is more informative when assessing surface integrity from a fatigue-performance perspective, as it directly quantifies the depth and severity of surface valleys, which are the primary initiation sites for fatigue cracks [19,20].

Table 3

Surface roughness parameters (values are reported as mean $\pm$ standard deviation).

	W-E	W-L	LPBF-L
Flood			
Sa/ μm	0.4 ± 0.1	0.52 ± 0.14	0.39 ± 0.07
Svk/ μm	0.26 ± 0.06	0.38 ± 0.21	0.29 ± 0.02
Cryogenic			
Sa/ μm	0.36 ± 0.12	0.44 ± 0.16	0.42 ± 0.02
Svk/ μm	0.34 ± 0.03	0.30 ± 0.24	0.26 ± 0.02

The more pronounced anisotropy of the W-L microstructure (see Fig. 1) may lead to a less uniform deformation response during machining. As a consequence, the tool–material interaction becomes more heterogeneous, resulting in greater variability in the resulting surface roughness, as similarly found in [21]. Conversely, for LPBF-L, the influence of surface roughness is secondary, as crack initiation consistently occurs at subsurface defects, making $\sqrt{area}$ values much higher compared to both W-E and W-L.

Coming to the influence of the machining conditions, cryogenic cooling generally reduced the extent of the small defect region, as both $\sqrt{area_c}$ and $\sqrt{area_t}$ decrease. At the same time, under cryogenic cooling, $\Delta\sigma_{0,est}$ was consistently higher than under flood conditions, irrespective of the Ti6Al4V microstructural state. In other words, cryogenically machined Ti6Al4V demonstrates enhanced fatigue performance in defect-free conditions. Conversely, in the presence of defects, even small imperfections become more critical, as they facilitate crack initiation.

Nevertheless, the benefit of cryogenic cooling strongly depends on the Ti6Al4V microstructural state, with lamellar microstructures showing greater sensitivity than the equiaxed counterpart. The percentage increase in the fatigue strength under cryogenic machining is indeed the highest for LPBF-L, followed by W-L and, finally, W-E, as determined from the Wöhler-curve parameters reported in Table 3 (see the nominal stress amplitude at the fatigue limit condition, $\sigma_{A,50\%}$). This behaviour can be associated with changes in surface integrity, specifically microstructural alterations, introduced during machining, as discussed below.

SEM images of the subsurface (Fig. 5) show that machining induces a PDL in all Ti6Al4V microstructural states [22], irrespective of the lubrication-cooling condition. However, the extent of the PDL varies with the initial microstructure: both W-L and LPBF-L always exhibit a deeper PDL than W-E. This behaviour can be explained by the fact that, in the W-E case, significant crystallographic reorientation is required to transform the initially broad and random texture into a more concentrated one. In contrast, crystallographic reorientation during deformation is facilitated in both LPBF-L and W-L, as these microstructures already exhibit pronounced anisotropy before machining, resulting in a thicker PDL.

The latter statement is supported by the pole figures in Fig. 6, which compare the bulk microstructure orientations presented in Fig. 1 with

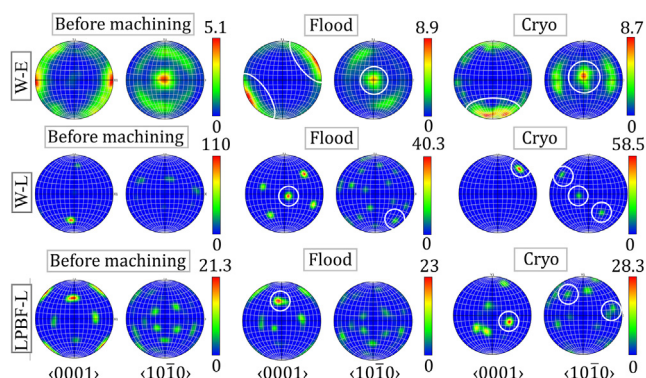


Fig. 6. Poles figures of the PDL regions.

those corresponding to the PDL regions in Fig. 5. After machining, localized color clustering is clearly observed, in agreement with [23], and is attributed to the deformation induced by machining. The resulting textures, particularly those highlighted by the white circles in Fig. 6, correlate well with the typical textures associated with pure shear deformation in hexagonal close-packed crystal structures [24]. Nevertheless, the degree of anisotropy before machining still influences the material properties after machining, with W-E exhibiting a broader texture, followed by LPBF-L and W-L, as evidenced by the maximum pole density projection. When cryogenic cooling is applied, a further increase in PDL depth is observed for a given microstructure, indicating that the substantial reduction in cutting temperature increases the alloy's resistance to deformation and promotes more intense deformation. Overall, the harder and more anisotropic the initial microstructure, the thicker the resulting PDL. Nonetheless, cryogenic cooling is more effective in the case of LPBF-L, owing to the presence of intrinsic manufacturing defects that are more effectively closed by the strain hardening induced by cryogenic machining.

5. Conclusions

The paper showed that the combination of microstructural anisotropy and surface integrity governs the fatigue behaviour of Ti6Al4V in wrought-equiaxed, wrought-lamellar, and laser powder bed fusion-lamellar conditions, following both flood and cryogenic machining. While the W-E microstructure exhibits the highest fatigue strength, it does not provide the crack-deflection mechanisms typical of lamellar architectures. Between the lamellar variants, the LPBF-L condition shows enhanced resistance to crack growth, which is associated with its reduced anisotropy relative to the W-L state. Surface integrity improvements achieved through cryogenic machining led to enhanced fatigue performance across all microstructural conditions; nevertheless, lamellar microstructures show a greater response, as their intrinsic anisotropy facilitates the development of a thicker plastically deformed layer, which also plays a key role in at least partially mitigating the detrimental effects of inherent defects in LPBF-L.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rachele Bertolini: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Andrea Stramare:** Investigation, Formal analysis, Data curation. **Alberto Campagnolo:** Writing – original draft, Investigation, Formal analysis, Data curation. **Andrea Ghiotti (1):** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Enrico Savio (1):** Writing – review & editing, Validation, Methodology, Formal analysis. **Stefania Bruschi (1):** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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