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Letters

Orientation-dependent low-cycle fatigue and grain boundary evolution in DMLS-fabricated Haynes 282 superalloy

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ABSTRACT

This study investigates the effect of build orientation on the fatigue performance of Haynes 282 alloy manufactured via Direct Metal Laser Sintering at 0°, 45°, and 90°. Fatigue tests revealed superior service life for 0° and 45° orientations, attributed to equiaxed grains and high-angle grain boundaries identified by EBSD. Vertical builds exhibited columnar grains and reduced fatigue resistance. This work provides the first systematic correlation between grain boundary character and low-cycle fatigue behavior in DMLS-manufactured Haynes 282, expanding current understanding beyond Inconel-based systems and offering insights for orientation-based design optimization in critical high-temperature applications.

1. Introduction

Haynes 282 is a nickel-based superalloy known for its remarkable high-temperature strength, creep resistance, and excellent fabricability. It demonstrates a unique combination of oxidation resistance and stability across a broad temperature range, typically from 600 °C to 900 °C. This makes it ideal for applications in gas turbines, aerospace engines, and other high-stress environments where traditional materials may fail due to thermal fatigue and creep [1]. The alloy's microstructure, characterized by a gamma-prime (γ') precipitate phase, contributes significantly to its mechanical properties. The γ' phase provides precipitation hardening, improving resistance to deformation at elevated temperatures [2]. This microstructural feature, along with a balanced blend of solid-solution strengthening elements, enables Haynes 282 to perform exceptionally well in demanding conditions, making it a preferred choice for critical components that require reliability and durability over prolonged service lives [3].

In recent years, the application of additive manufacturing (AM) technologies, such as Direct Metal Laser Sintering (DMLS), has expanded rapidly, allowing for the fabrication of complex geometries and customized components using superalloys like Haynes 282 [4]. DMLS, a form of powder bed fusion technology, uses a high-power laser to selectively melt and fuse metallic powders layer by layer, building components with intricate designs directly from digital models. However, the anisotropic nature of the additive manufacturing process introduces significant microstructural variations depending on the build orientation [5]. The effect of printing orientation on microstructural evolution is a critical aspect of research, particularly for components subjected to fatigue loading [6]. Horizontal, vertical, and diagonal build orientations result in distinct thermal gradients and solidification patterns, which significantly influence the grain morphology, crystallographic texture, and phase distribution in the material [7,8]. Horizontally built specimens typically exhibit equiaxed grains due to uniform cooling rates, which enhance isotropic mechanical properties [9]. In contrast, vertical orientations often lead to columnar grains aligned with the build direction, creating anisotropy and potentially compromising fatigue resistance [10]. Diagonal orientations present a hybrid microstructure, with mixed equiaxed and columnar grains, providing a balance between isotropy and anisotropy. The grain boundary character distribution, influenced by build orientation, plays a crucial role in fatigue behavior, as high-angle grain boundaries (HAGBs) act as barriers to crack propagation, enhancing fatigue life, whereas low-angle grain boundaries (LAGBs) may facilitate crack initiation [11]. The resulting microstructure after fatigue testing reflects these orientation-specific features, highlighting the importance of tailoring additive manufacturing parameters to optimize the mechanical performance of Haynes 282 components. Different build orientations result in distinct microstructural characteristics, such as grain size,

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shape, and crystallographic texture, which can significantly affect crack initiation and propagation under cyclic loading. Understanding these microstructural changes is essential for advancing the design and application of additively manufactured superalloy parts in industries where high-temperature fatigue resistance is paramount. However, the effect of printing orientation on fatigue response of nickel-based superalloys manufactured by using AM methods is still limited and mainly concentrated on Inconel 718 [12–15]. Therefore, this paper explores the complex relationship between printing orientation and microstructural evolution in DMLS-manufactured Haynes 282, providing insights into optimizing additive manufacturing processes to achieve desired mechanical properties in critical applications.

Despite increasing interest in the fatigue behavior of nickel-based superalloys produced via additive manufacturing, most existing studies have focused on Inconel 718, leaving a knowledge gap regarding other high-performance alloys such as Haynes 282. This study addresses this gap by examining the microstructural evolution and low-cycle fatigue response of DMLS-fabricated Haynes 282 specimens in different build orientations. By coupling EBSD characterization with mechanical testing, this work provides new insights into the role of grain boundary character distribution in fatigue performance—offering critical knowledge for optimizing additive manufacturing strategies for components subjected to cyclic loading.

While prior studies—such as Kopec et al. [6]—have explored orientation-dependent fatigue behavior in additively manufactured materials like 316L stainless steel, they largely focused on macroscopic fatigue performance and fracture behavior without a detailed examination of orientation-induced grain boundary character and its evolution under cyclic loading. In contrast, this work offers a novel, quantitative EBSD-based analysis of misorientation angle distributions (i.e., LAGBs vs. HAGBs) before and after fatigue deformation across multiple orientations in DMLS-manufactured Haynes 282. Such a detailed microstructural perspective is currently lacking for nickel-based superalloys in the literature, particularly for Haynes 282, which has been far less studied than Inconel 718 or 625. The findings provide critical insight into how build orientation influences microstructural evolution and fatigue life through the mediation of grain boundary character.

2. Materials and methods

The Haynes 282 bars of 8 mm in diameter and 52 mm in length were additively manufactured using the Direct Metal Laser Sintering (DMLS). The optimized additive manufacturing (AM) process utilized an EOS M100 printer, with specimens built in three orientations—0°, 45°, and 90° (Fig. 1a) under an argon atmosphere using spherical powder of an average particle size of approximately 45 µm. The chemical composition of Haynes 282 powder (wt. %) included Cr (20 %), Co (10 %) Mo (8.5 %) Ti (2 %), Al (1.5 %), Fe (1.5 %), Mn (0.3 %), Si (0.15 %), C (0.06 %). The printing was conducted with a laser energy density of 104 J/mm^3, laser power set to 100 W, and a scanning speed of 800 mm/s. The specimens were fabricated on a rectangular Inconel 625 substrate plate. The build plate measured 150 mm × 100 mm × 20 mm and featured a machined surface finish (Ra ≈ 1.6 µm) to ensure optimal powder adhesion and thermal contact. Prior to printing, the substrate was cleaned with ethanol and preheated to 80 °C to minimize thermal gradients and reduce the risk of residual stress-induced warping during fabrication. All specimens were built directly onto the plate without support structures, using a zig-zag scanning strategy with rotation between layers to promote uniform grain growth. The printed bars were then machined to the dimensions shown in Fig. 1b and clamped in the testing rigs (Fig. 1c). The fatigue testing in this study was designed to evaluate the material's performance under low-cycle fatigue (LCF) conditions, where plastic deformation occurs during each loading cycle due to stress amplitudes exceeding the yield strength of the material. The LCF regime is characterized by relatively low numbers of cycles to failure (typically less than 105), making it relevant for components exposed to high thermal or mechanical stress fluctuations. Tests were conducted on an MTS 858 testing machine operating in force-controlled mode, with a stress ratio (R) of −1, corresponding to fully reversed loading, and a frequency of 20 Hz. The applied stress amplitudes ranged from ±550 MPa to ±750 MPa, which are within or above the measured 0.2 % offset yield strength of the DMLS-fabricated Haynes 282 specimens. This confirms that the material underwent significant cyclic plastic deformation, meeting the criteria for LCF evaluation. The fatigue testing procedure followed the guidelines outlined in ASTM E606/E606M – Standard Test Method for Strain-Controlled Fatigue Testing, adapted for force-controlled conditions due to the unavailability of direct strain measurements. Each test condition was repeated at least three times to ensure repeatability. The total number of cycles to failure was recorded, and specimens were removed from the test after complete fracture.

Initial microstructural analysis of printed bars was carried out using a Hitachi TM-1000 scanning electron microscope and a Zeiss Axio Scope optical microscope. EBSD measurements were performed with a high-resolution Quanta 3D FEG scanning electron microscope system equipped with integrated EDS/EBSD capabilities, operating at 20 kV. Metallographic preparation included hot-mounting, followed by polishing with a Struers MD-Largo disc and 2 µm diamond suspension, and finishing with a Metrep® MD-Chem cloth and 0.04 µm colloidal silica solution.

3. Experimental results and discussion

The present study investigates low-cycle fatigue (LCF) behavior in the plastic regime, where the material undergoes plastic deformation during each loading cycle due to high applied stress amplitudes. Unlike high-cycle fatigue, which is dominated by elastic deformation and long lifetimes, LCF is characterized by short fatigue lives and significant cyclic plasticity, often occurring in components subjected to high thermal or mechanical loads. In the case of Haynes 282, a superalloy designed for high-temperature applications, understanding plastic deformation mechanisms under cyclic loading is critical for predicting service life and failure modes in real-world conditions such as turbine engines and combustors.

The additively manufactured (AM) specimens were initially tested under uniaxial tensile conditions to assess their mechanical properties (Fig. 2a). The results indicate that specimens built at 0° and 45° orientations showed significantly higher strength as compared to those built at 90°. Such findings are typical for AM nickel-based alloys since Inconel specimens fabricated in a vertical orientation typically display lower strength and greater elongation [16]. This is attributed to the ⟨0 0 1⟩ crystallographic orientation that promotes increased shear stress and subsequent cracking. A similar effect of build orientation on mechanical properties was observed for Inconel 625 produced via selective laser melting (SLM) and laser-engineered net shaping (LENS) [17]. In the following testing, the impact of build orientation on the fatigue behavior of DMLS-fabricated Haynes 282 nickel superalloy was investigated for a stress amplitude range of ±550 MPa to ±800 MPa (Fig. 2b). Similarly with the tensile test results, the 0° and 45° build orientations were found to be advantageous, resulting in extended service life for stress amplitudes below ±700 MPa. A similar enhancement in fatigue life was also observed for Inconel 718 produced using DMLS [18] and SLM [19] when printed in a horizontal orientation.

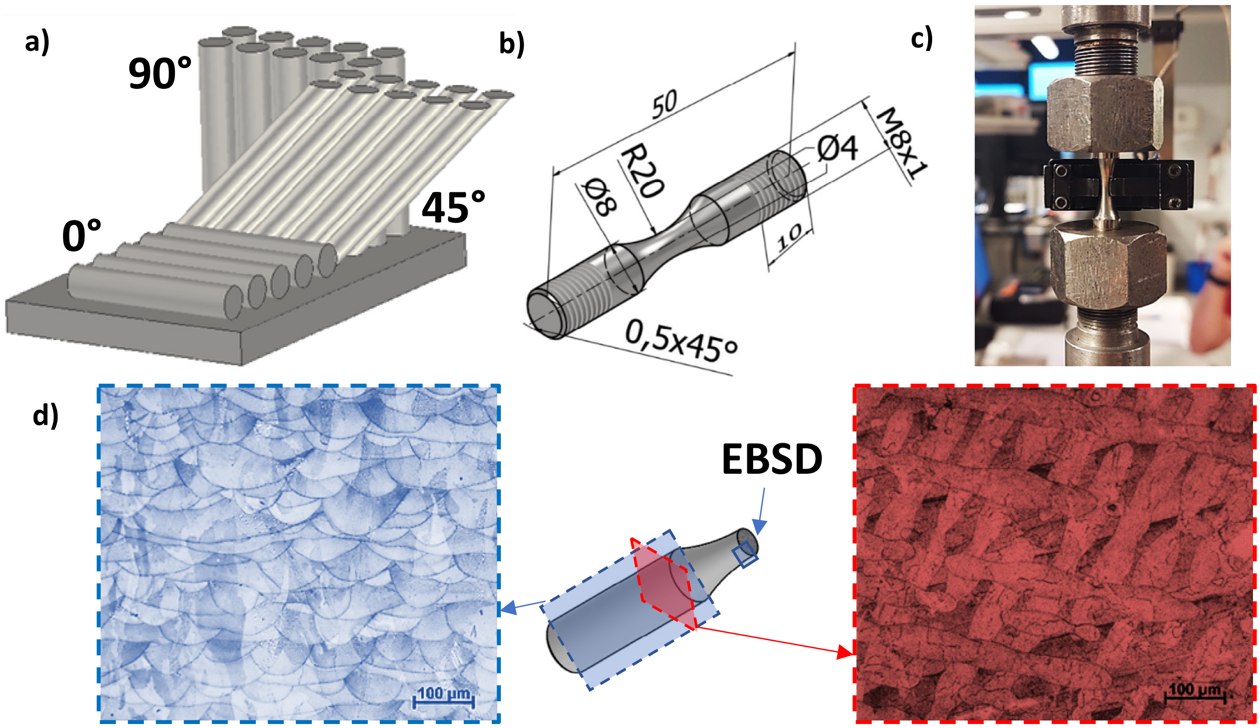

Fig. 1. Printing orientations of the Haynes 282 bars (a); engineering drawing of the hourglass specimen (b); general view of the assembled specimen during fatigue testing (c); schematic drawing of fractured specimen after fatigue testing with exposed view of EBSD region of interest and two cross-sections in which microstructure of the as-built alloy was shown in parallel and perpendicular to the building direction section.

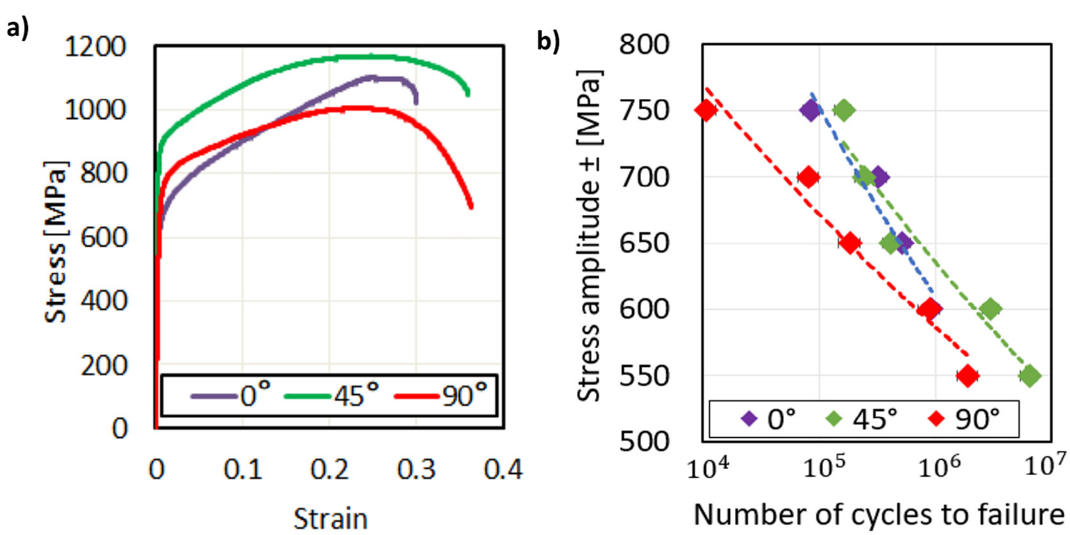

Fig. 2. Stress–strain (a) and S-N (b) characteristics of the DMLS manufactured Haynes 282 printed in different orientations.

The EBSD studies of the microstructural evolution of Haynes 282 superalloy, manufactured by DMLS in different orientations—horizontal, vertical, and diagonal—reveals profound insights into how build orientation impacts grain structure, grain boundaries, and overall fatigue performance (Figs. 3-4). In DMLS, the interaction between rapid solidification rates and directional cooling gradients leads to unique microstructural features in each orientation. For horizontally printed specimens, EBSD analysis reveals a predominantly equiaxed grain morphology, characterized by a relatively uniform distribution of grain sizes. The thermal cycles inherent to this orientation create a balanced microstructure that enhances isotropic mechanical properties. The presence of high-angle grain boundaries (HAGBs) in horizontal builds contributes to improved fatigue resistance, as these boundaries act as formidable barriers to crack propagation [20]. This structural advantage is reflected in the longer fatigue life observed for horizontally printed samples, where equiaxed grains provide multidirectional strength, distributing stress evenly and delaying crack initiation [21]. In contrast, the vertical orientation shows a pronounced columnar grain structure aligned with the build direction, a result of the thermal gradient perpendicular to the base plate. The EBSD results highlight a strong ⟨0 0 1⟩ crystallographic texture, which can introduce anisotropy in mechanical properties [22]. The columnar grains, while beneficial for specific directional loads, present a challenge for fatigue

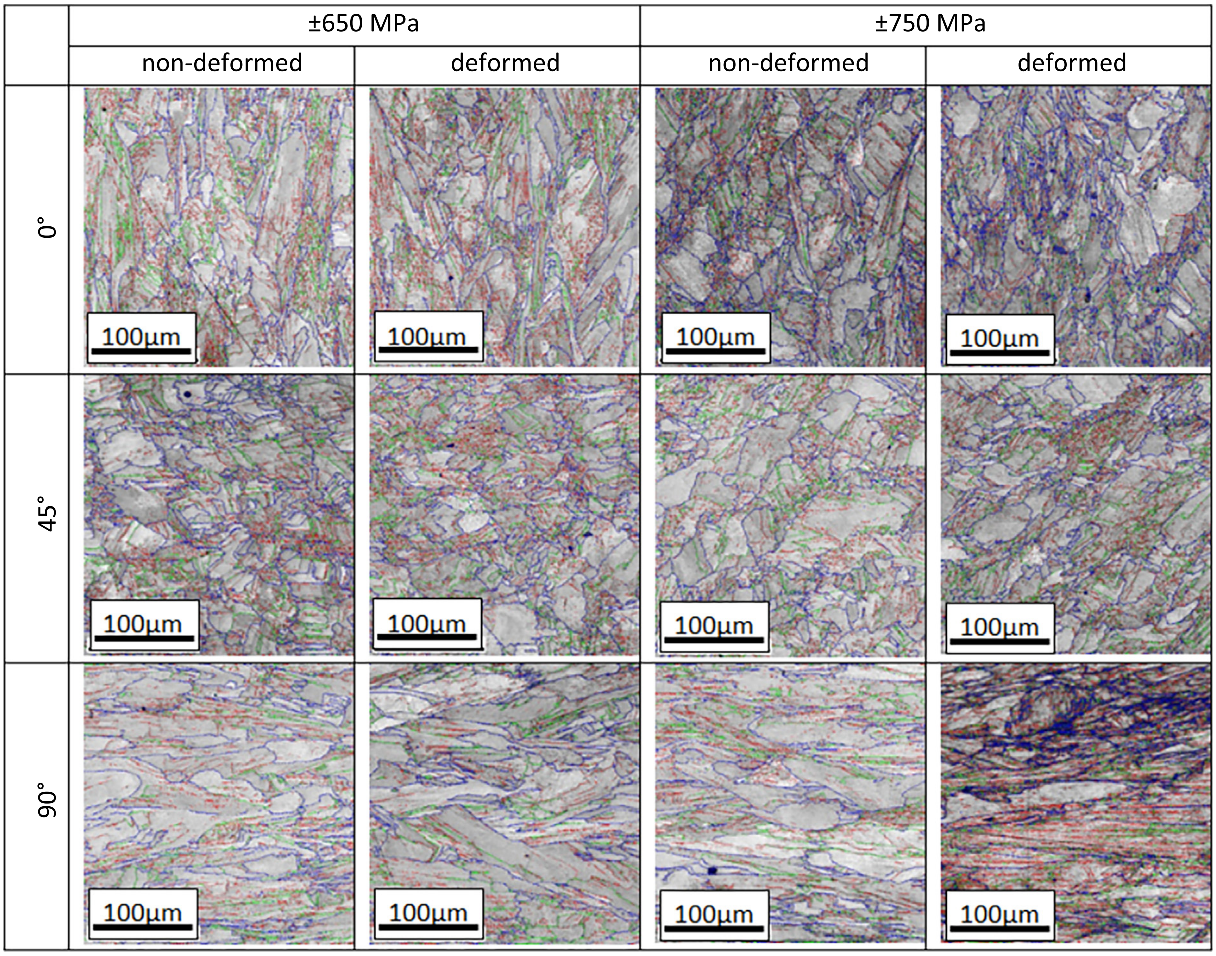

Fig. 3. Grain boundaries maps of Haynes 282 Haynes 282 specimens manufactured at 0°, 45°, and 90° direction and tested at the stress amplitude equal to ±650 MPa and ±750 MPa.

performance due to the increased likelihood of crack initiation along low-angle grain boundaries (LAGBs). These LAGBs, with their relatively weaker bonding compared to HAGBs, facilitate crack growth under cyclic loading, contributing to the reduced fatigue life seen in vertically printed specimens. In vertically printed specimens, the columnar grains are predominantly aligned parallel to the loading direction, which facilitates crack propagation along grain boundaries with minimal resistance. This microstructural alignment reduces the number of transverse grain boundaries that could otherwise deflect or arrest cracks, thereby providing limited resistance to lateral crack growth. As a result, the material exhibits increased susceptibility to fatigue failure due to the ease of crack propagation along the build direction. Diagonally printed samples display a hybrid microstructure, with a mix of equiaxed and columnar grains. This orientation captures the essence of both horizontal and vertical characteristics, resulting in a moderate ⟨1 1 1⟩ texture. The EBSD data for diagonal builds show an intriguing interplay between grain orientations and boundaries, where the combined effect of HAGBs and some LAGBs creates a microstructure that offers intermediate fatigue performance. The diagonal build direction introduces a complex thermal history, leading to varied grain interactions and a distribution of grain boundary angles that can influence crack deflection paths. The mixed grain morphology can aid in impeding crack growth, offering a degree of resistance through varied pathways that disrupt continuous crack propagation. In the similar study on Hastelloy X [23], a nickel-based superalloy produced via additive manufacturing using laser powder bed fusion (LPBF), it was observed that the mechanical properties, particularly yield strength, ductility, and deformation mechanisms, are strongly dependent on crystallographic orientation. Tensile testing performed along ⟨1 0 0⟩, ⟨1 1 0⟩, and ⟨1 1 1⟩ directions revealed that the ⟨1 1 1⟩ orientation exhibited the highest yield strength (807 MPa), while ⟨1 0 0⟩ showed lower strength (693 MPa), and ⟨1 1 0⟩ the lowest (648 MPa), which align with results presented in this paper. Ductility, on the other hand, was highest in the ⟨1 1 0⟩ direction with 49 % elongation compared to 33 % for ⟨1 0 0⟩ and ⟨1 1 1⟩. These differences in mechanical properties are attributed to the underlying deformation mechanisms, particularly deformation twinning, which was observed in the ⟨1 1 0⟩ and ⟨1 1 1⟩ directions but was absent in ⟨1 0 0⟩. This twinning behavior, along with lattice rotation during deformation, plays a crucial role in enhancing ductility and mechanical response, especially in the ⟨1 1 0⟩ and ⟨1 1 1⟩ orientations.

The crystallographic orientation also affects the effective stacking fault energy, which in turn influences the critical stress for deformation twinning. For ⟨1 1 0⟩ and ⟨1 1 1⟩ orientations, this stress was found to be close to or even below the yield strength, facilitating twinning at room temperature. In contrast, the critical stress for twinning in the ⟨1 0 0⟩ orientation was significantly higher than its ultimate tensile strength, effectively preventing twinning. This study highlights the critical role of crystallographic orientation in determining the anisotropic mechanical behavior of nickel-based superalloys produced through LPBF, suggesting that by tailoring texture and orientation, one can optimize the mechanical performance for specific engineering applications. Moreover, the anisotropy in yield strength can be explained through the

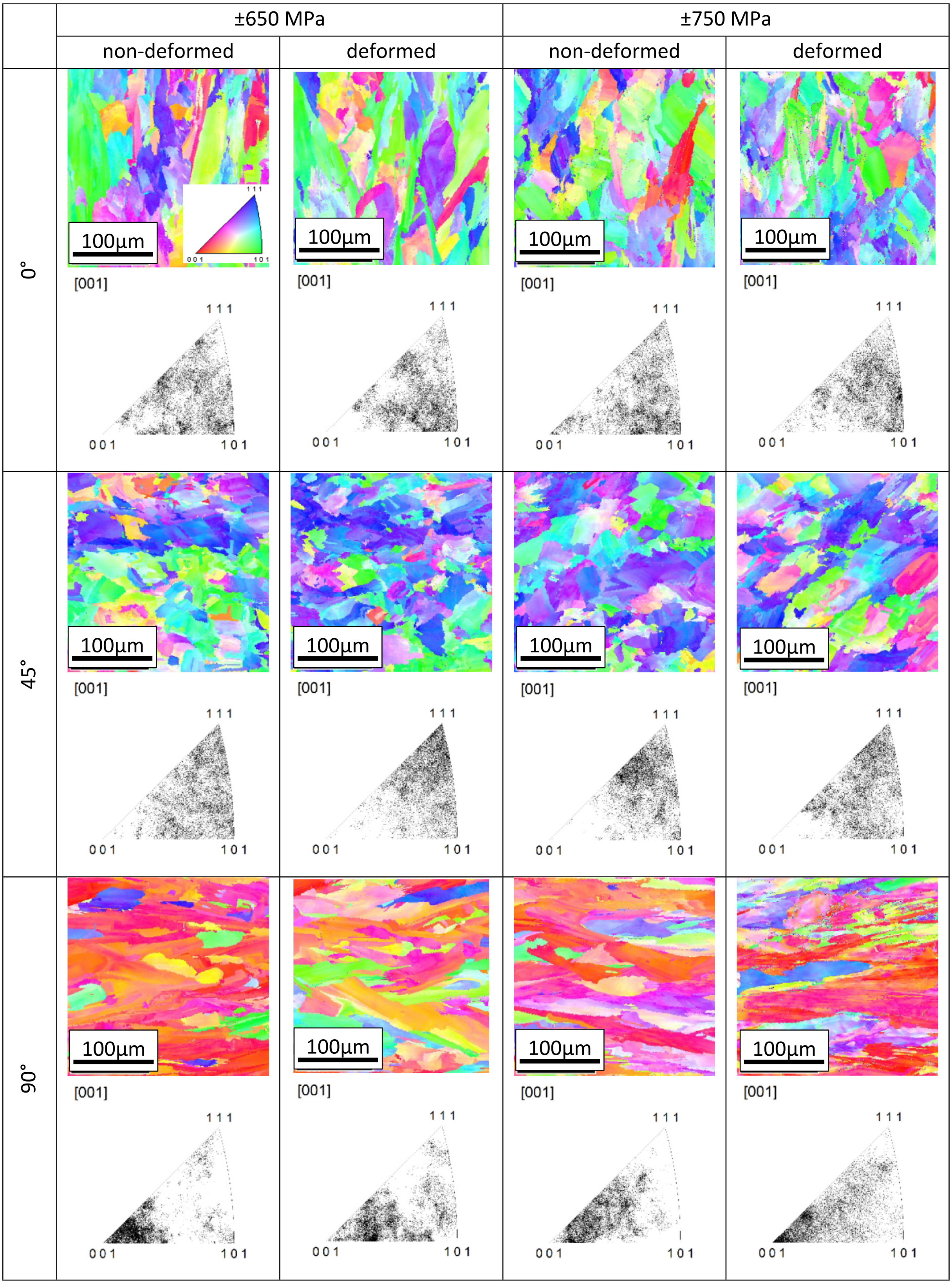

Fig. 4. IPF maps of Haynes 282 Haynes 282 specimens manufactured at 0°, 45°, and 90° direction and tested at the stress amplitude equal to ±650 MPa and ±750 MPa.

Schmid factors associated with different crystallographic orientations, further emphasizing the importance of crystallographic alignment in maximizing the performance of additively manufactured components.

The quantitative analysis of grain size evolution in material in question reveals a distinct orientation- and load-dependent behavior that correlates well with fatigue performance. Under a stress amplitude of 650 MPa, the as-received grain sizes for 0°, 45°, and

90° build orientations were measured at approximately 7.54 μm, 7.17 μm, and 8.00 μm, respectively, indicating a relatively equiaxed and slightly heterogeneous grain morphology. Upon deformation, these grain sizes increased modestly to 8.58 μm, 7.38 μm, and 9.17 μm, reflecting plastic strain-induced grain coarsening, particularly in the 90° orientation, which is known to favor columnar grain growth aligned with the build and loading direction. Conversely, at a higher stress amplitude of 750 MPa, grain refinement dominated the deformation response. For the 0° orientation, the grain size decreased from 7.10 μm in the as-received state to 6.34 μm post-deformation, while the 45° orientation showed a reduction from 8.32 μm to 7.42 μm. The most significant refinement occurred in the 90° orientation, where the grain size dropped sharply from 8.05 μm to 5.82 μm. These findings are consistent with EBSD-based grain statistics provided in the manuscript, where the grain size for the as-built 0° samples was reported to be ~9.6 μm with a standard deviation of 3.1 μm, compared to ~7.8 μm (SD: 2.7 μm) and ~5.4 μm (SD: 2.1 μm) for 45° and 90°, respectively. After deformation at ±750 MPa, the average grain sizes reduced to ~8.2 μm, ~6.9 μm, and ~4.3 μm for the 0°, 45°, and 90° orientations, respectively. This grain refinement is attributed to sub-grain formation and dislocation-induced boundary multiplication during cyclic plastic deformation. Notably, the largest grain reduction occurred in the 90° orientation, aligning with its poorest fatigue performance, as columnar grains with a high density of LAGBs facilitated dislocation glide and early crack initiation. In contrast, the 0° and 45° orientations, characterized by a higher fraction of HAGBs, demonstrated more stable microstructures and enhanced resistance to fatigue-induced grain boundary evolution.

One can identify a clear relationship between grain boundary character and build orientation. Low-angle grain boundaries, defined as misorientation angles between 2° and 15°, dominate across all conditions; however, their proportions vary depending on the orientation and applied stress. In the 0° build orientation, which exhibited the best fatigue performance, high-angle grain boundaries (HAGBs, >15°) accounted for a significant portion of the boundary population—0.319 in the non-deformed state at ±650 MPa, increasing to 0.409 at ±750 MPa. After deformation, HAGBs slightly decreased to 0.314 and 0.392, respectively, indicating some dynamic grain interaction while still maintaining a relatively high resistance to crack propagation. The corresponding LAGB fractions remained relatively stable across deformation (0.681–0.686 at ±650 MPa; 0.591–0.608 at ±750 MPa), suggesting a balanced microstructure. In contrast, the 45° orientation, which showed intermediate fatigue life, exhibited slightly lower HAGB fractions—0.387 and 0.330 in the non-deformed states at ±650 MPa and ±750 MPa, respectively—dropping further upon deformation to 0.361 and 0.320. LAGBs in this orientation ranged from 0.614 to 0.680, reflecting a microstructure that mixed both equiaxed and columnar grain features. The 90° orientation, associated with the lowest fatigue resistance, demonstrated the lowest HAGB fractions under all conditions. For instance, in the deformed state at ±750 MPa, the HAGB fraction was just 0.369, compared to 0.392 in 0° and 0.320 in 45°. Simultaneously, LAGB fractions were highest in this orientation, peaking at 0.685 and 0.671 in the non-deformed and deformed conditions at ±650 MPa, respectively. This high LAGB density is unfavorable, as these boundaries provide easier paths for crack initiation and propagation under cyclic loading.

In the vertical samples, the microstructure is dominated by elongated columnar grains aligned with the build direction, exhibiting a strong ⟨0 0 1⟩ crystallographic texture. This alignment causes a high density of LAGBs, which serve as preferential paths for dislocation motion [22]. During cyclic loading, dislocations can travel with minimal resistance along these LAGBs, promoting localized plastic deformation. This ease of dislocation glide leads to early crack initiation, particularly along grain boundaries that are parallel or nearly parallel to the loading axis.

Furthermore, the columnar grain structure provides few obstacles to deflect or arrest propagating cracks, allowing cracks to grow rapidly and linearly along the build direction. This results in reduced fatigue resistance and a shorter service life for vertically printed specimens. In contrast, the diagonal samples exhibit a hybrid microstructure comprising both equiaxed and columnar grains, with a more complex thermal history resulting in a mixed crystallographic texture, primarily around the ⟨1 1 1⟩ direction. This combination creates a more heterogeneous distribution of grain boundary angles, including a significant fraction of HAGBs. These HAGBs act as barriers to dislocation motion, requiring higher energy for dislocations to pass through or bypass them via mechanisms such as cross-slip or climb. As a result, dislocation motion becomes less straightforward, and stress concentrations tend to build up around these barriers. This impedes the straight-line propagation of fatigue cracks, promoting crack deflection and branching. Consequently, crack growth in diagonal samples is more tortuous and discontinuous, enhancing fatigue resistance compared to vertical samples.

The strengthening mechanisms in DMLS-fabricated Haynes 282 superalloy are closely linked to microstructural features induced by build orientation, including grain morphology, grain boundary character distribution, crystallographic texture, and their evolution under cyclic loading. In the 0° orientation (horizontal build), the dominant strengthening mechanism is grain boundary strengthening, facilitated by a high fraction of HAGBs, up to ~0.409 and equiaxed grain morphology, which according to the Hall-Petch relationship increase resistance to dislocation motion and act as effective barriers to crack propagation. The isotropic grain structure with relatively coarse grains (7.54 μm as-built, 6.34 μm post-fatigue at ±750 MPa) allows for uniform stress distribution, enhancing both tensile strength and fatigue life. This orientation also benefits from strain hardening and dislocation accumulation during cyclic loading, which further promotes sub-grain formation and localized grain refinement. The 45° orientation exhibits a hybrid microstructure with both equiaxed and columnar grains (grain size ~7.17 μm as-built, 7.42 μm post-fatigue at ±750 MPa) and a moderate HAGB content (~0.387 pre-fatigue, decreasing to ~0.320), resulting in intermediate strengthening. Here, both grain boundary strengthening and texture-induced hardening contribute, as the misorientation spread and mixed grain structure induce crack deflection and constrain dislocation glide paths. However, the presence of aligned columnar grains still permits some anisotropic stress accumulation. In the 90° orientation (vertical build), anisotropy is most pronounced due to a strong ⟨0 0 1⟩ crystallographic texture aligned with the loading direction and columnar grains that facilitate directional dislocation glide. This orientation exhibits the highest fraction of LAGBs, up to ~0.685, promoting early crack initiation and fast propagation, while fine grain sizes (8.00 μm as-built, reduced to 5.82 μm post-fatigue at ±750 MPa) indicate grain refinement driven by cyclic plasticity. Despite the Hall-Petch relationship suggesting grain refinement enhances strength, the dominance of LAGBs and aligned texture in this orientation overrides that benefit by providing unimpeded crack paths. Quantitatively, anisotropy in fatigue resistance manifests as a ~60 % reduction in fatigue life in the 90° orientation compared to the 0° orientation, with the 45° orientation falling in between, confirming the strong directional dependence of mechanical performance.

While this study focuses on the influence of grain boundary character and crystallographic orientation on fatigue performance, it is important to acknowledge other microstructural factors intrinsic to additive manufacturing, such as residual stresses and porosity

[24,25]. These factors often interact with grain morphology and boundary characteristics, influencing crack initiation and propagation. For example, tensile residual stresses, typically present along the build direction, can accelerate fatigue crack growth, particularly in orientations with aligned columnar grains [26]. Similarly, lack-of-fusion or gas-induced porosity may serve as early crack initiation sites, especially when located near LAGBs [27]. Although these phenomena were not the primary focus of this work, future studies combining EBSD with residual stress mapping and porosity quantification would further elucidate the complex interplay governing fatigue behavior in DMLS-fabricated superalloys.

4. Conclusions

This study demonstrates that the fatigue resistance of DMLS-fabricated Haynes 282 superalloy is strongly dependent on build orientation due to associated microstructural differences. Specimens built in the 0° (horizontal) orientation exhibited the highest fatigue resistance, which is attributed to their predominantly equiaxed grain structure and a high fraction of HAGBs. These microstructural features act as effective barriers to dislocation motion and crack propagation, promoting crack deflection and distributing plastic deformation more uniformly under cyclic loading. The 45° specimens showed intermediate fatigue resistance, reflecting their mixed grain morphology (both equiaxed and columnar grains) and a moderate HAGB content. This hybrid structure introduces varied grain orientations and boundary types that partially disrupt crack paths, offering some resistance to fatigue damage but not to the extent of the fully equiaxed microstructure. In contrast, the 90° (vertical) specimens exhibited the lowest fatigue resistance, which correlates with their columnar grain structure, strong ⟨0 0 1⟩ crystallographic texture aligned with the loading direction, and a high density of LAGBs. These features facilitate dislocation glide and provide continuous paths for crack initiation and propagation along the build direction, resulting in premature failure. The fatigue resistance mechanisms across orientations are therefore governed by the ability of the grain boundary network and texture to obstruct or promote dislocation motion and crack growth. High HAGB content and equiaxed grains enhance fatigue resistance by deflecting cracks and increasing energy dissipation during cyclic loading, while LAGB-dominated, directionally aligned microstructures reduce this resistance. These findings highlight the critical importance of controlling build orientation and resulting microstructure in the additive manufacturing of fatigue-critical components.

CRediT authorship contribution statement

Mateusz Kopec: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dominika Przygucka:** Investigation, Data curation. **Ryszard Sitek:** Methodology, Investigation. **Stanisław Jóźwiak:** Validation, Methodology, Formal analysis, Data curation.

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.

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