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Effects of growth direction on fatigue behaviour of EBMed Ti6Al4V specimens

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Abstract

Electron Beam Melting (EBM) is an additive manufacturing process able to produce near-net-shape Ti6Al4V components, but the resulting anisotropic microstructure can lead to directionally dependent mechanical properties. This study investigates the influence of build orientation on the fatigue crack growth (FCG) behaviour of EBM-fabricated Ti6Al4V. Compact Tension specimens were manufactured in three distinct orientations relative to the build direction: horizontal (HH), vertical-horizontal (VH), and vertical-vertical (VV). FCG tests were conducted according to ASTM E647. The results revealed a strong FCG anisotropy. The VV configuration exhibited superior fatigue resistance, characterised by the lowest crack growth rates. Conversely, the HH orientation demonstrated the poorest performance, with significantly faster crack propagation. Fractographic analysis via SEM confirmed that the worst behaviour of the HH specimen was due to a low-energy, transgranular quasi-cleavage mechanism, exacerbated by process-induced porosity. These findings highlighted that building orientation is a critical design parameter that must be optimised to ensure the structural integrity and service life of fatigue-critical EBM components in demanding applications.

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Keywords: Fatigue crack growth; Additive manufacturing; Titanium alloy; Anysotropy.

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1. Introduction

Additive Manufacturing (AM) has become an important technology in advanced manufacturing, enabling the fabrication of components, even with complex geometry, directly from digital models (Frazier (2014), Borrelli et al. (2024)). Among the various AM processes, Powder Bed Fusion (PBF) techniques, based on a high-energy source to melt selectively and fuse layers of metallic powder, have earned significant attention for producing high-performance, end-use parts. In particular, Electron Beam Melting (EBM) emerged for its ability to produce parts made of high-temperature reactive alloys in a high-vacuum environment, leading to components with low contamination and reduced residual stresses compared to laser-based counterparts (Murr et al. (2012), Körner (2016)).

The Ti6Al4V titanium alloy ranks among the top candidates for the EBM technology. With an exemplary combination of high specific strength, exceptional corrosion resistance, and exceptional biocompatibility, it has emerged as a keystone material in the challenging sectors of aerospace, defence, and biomedical implants (Bellini et al. (2024b), Cantaboni et al. (2024)). Synergy of the design freedom contributed by EBM and the outstanding properties of Ti6Al4V presents a logical path to the production of next-generation structural components, patient-specific orthopaedic implants, and intricate aerospace hardware (Bellini et al. (2023), Epasto et al. (2019)). The potential of Ti6Al4V produced via EBM is, however, fully realisable only if its mechanical properties, especially under cyclic loading conditions, are fully known and guaranteed. The fatigue life of the component is often the most critical design driver in these applications, as catastrophic failure can have catastrophic consequences.

The mechanical behaviour of EBM-manufactured parts is intrinsically linked to the unique thermal history experienced by the material during the layer-by-layer fabrication process. The rapid heating from the electron beam, followed by conductive cooling through previously solidified material, results in complex thermal gradients and solidification dynamics, as found by Kobryn and Semiatin (2001). This, in turn, dictates the evolution of the material microstructure and the formation of process-induced defects. In Ti6Al4V, the EBM process typically produces a characteristic microstructure dominated by coarse, columnar prior-β grains that grow epitaxially across multiple layers, aligned with the primary direction of heat dissipation, that is the build direction (Z-axis), as stated by Al-Bermani et al. (2010) and Tan et al. (2015). Within these prior-β grains, a finer Widmanstätten or basket-weave α+β lamellar structure forms upon cooling, as reported by Bellini et al. (2024a). This hierarchical and highly textured microstructure is fundamentally different from the equiaxed microstructures found in conventionally wrought or cast Ti6Al4V, leading to significant mechanical anisotropy (Rafi et al. (2013)).

A major challenge hindering the widespread adoption of EBM for fatigue-critical applications is the inherent variability and anisotropy of the resulting mechanical properties. The orientation of the part with respect to the build platform, that is the build orientation, is one of the most critical factors governing this anisotropy. The direction of grain growth relative to the applied stress axis profoundly influences material response. Several studies have documented the anisotropic tensile properties of EBM Ti6Al4V, often reporting that tensile specimens built vertically, that is with the tensile axis parallel to the build direction, exhibit lower ductility compared to those built horizontally, with the tensile axis perpendicular to the build direction, as found by Gong et al. (2015). This difference is attributed to the orientation of the long columnar prior-β grain boundaries, which can act as preferential paths for damage accumulation when loaded transversely. A study of Seifi et al. (2017) examined the influence of location-specific defects and microstructure, and the effects of post-process Hot Isostatic Pressing (HIP). Using EBSD, μCT scans, and fractography, the authors correlated microstructural features with mechanical performance. Although as-deposited samples showed defects like lack of fusion and porosity, their fracture properties were comparable to wrought Ti-6Al-4V. The HIP treatment eliminated these defects but caused microstructural coarsening, which distinctly altered the material toughness and fatigue crack growth resistance.

This anisotropy is even more pronounced and critical under fatigue loading conditions. The fatigue life of a material is highly sensitive to both its microstructure and the presence of defects, which act as stress concentrators and crack initiation sites. The build orientation influences both of these aspects. Firstly, the orientation of the lamellar α+β colonies within the columnar grains relative to the loading direction affects the tortuosity of the crack path, thereby influencing the fatigue crack growth rate, as reported by Edwards and Ramulu (2014). A crack propagating perpendicular to the long axis of the columnar grains may encounter more microstructural barriers, constituted by the grain and colony boundaries themselves, than a crack propagating parallel to them. Secondly, the nature and orientation of process-induced defects, such as lack-of-fusion (LoF) pores, can be dependent on the build orientation. These defects, often elongated and planar, are particularly detrimental when oriented perpendicular to the principal stress axis, as they behave like sharp pre-cracks (Fleishel et al. (2023)).

While the anisotropic fatigue behaviour of AM Ti6Al4V is generally acknowledged, a systematic investigation that decouples the effect of build orientation from other process variables is essential for developing robust design guidelines. Specifically, understanding how different orientations of the component and, consequently, different orientations of the crack propagation plane relative to the material microstructural texture, affect fatigue resistance remains an area of active research. This knowledge is vital for designers to strategically orient parts on the build plate to maximise performance in the most critically stressed directions.

Therefore, the primary objective of this study is to systematically investigate the influence of build orientation on the fatigue behaviour of Ti6Al4V specimens manufactured via EBM. To isolate this effect, plates were fabricated in two principal orientations: one with the largest dimension parallel to the build platform (horizontal) and another with the largest dimension aligned with the build direction (vertical). From these plates, Compact Tension (CT) specimens were machined to evaluate fatigue properties. Moreover, for the vertically built plates, two distinct specimen families were created to investigate the behaviour of the fatigue crack propagating either parallel or perpendicular to the build direction. This experimental design enables a direct assessment of microstructural anisotropy on both fatigue life and crack propagation behaviour. The study involves detailed scanning electron microscopy (SEM) of the fracture surfaces to identify crack initiation mechanisms and correlate them with the observed fatigue performance. The findings are intended to provide a deeper understanding of the microstructural origins of fatigue anisotropy in Ti6Al4V, offering valuable data for the design, validation, and certification of additively manufactured components in safety-critical applications.

2. Materials and Methods

The experimental investigation was conducted on Compact Tension (CT) specimens, fabricated in accordance with the ASTM E647 standard for fatigue crack growth rate testing. As visible in Fig. 1, each specimen had a nominal thickness of 8 mm and an in-plane profile of 52 mm by 48 mm. A 2 mm wide starter notch was machined, with its tip positioned 8 mm from the pin-loading axis. To enable precise measurement of the Crack Opening Displacement (COD), the specimens were equipped with integral knife-edges for mounting a clip-on extensometer. The material used for this research was a Ti6Al4V titanium alloy powder, a grade widely employed in the aerospace and biomedical industries for its exceptional mechanical properties. The powder was sourced directly from the additive manufacturing system provider, ensuring optimal compatibility and high quality, which was further confirmed by micrographic analysis revealing a consistent and spherical particle morphology.

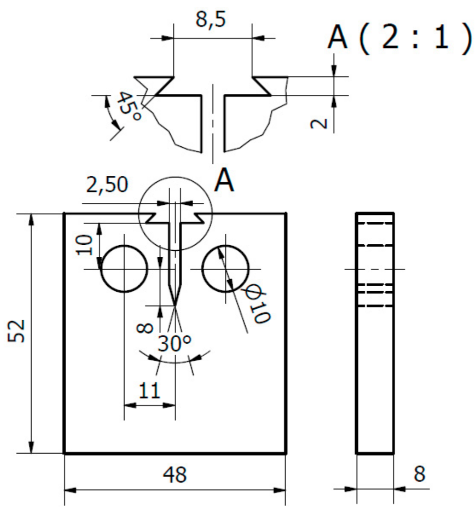

Fig. 1. Dimensions of the CT specimen.

The specimens for this study were fabricated using an ARCAM A2X system via the Electron Beam Melting (EBM) process. The manufacturing workflow followed standard EBM procedures. Initially, the specimen geometries were digitally designed, nested within the build volume, and sliced into layers using the system proprietary software. The subsequent machine preparation involved filling the powder hoppers and configuring the process parameters.

Prior to the build, the manufacturing chamber was evacuated to a high vacuum, the electron beam was calibrated, and the powder bed was preheated to a target temperature to mitigate residual stresses. The specimens were then built layer-by-layer through the selective melting of the powder bed. Upon completion, the build chamber underwent a controlled cooldown, after which the specimens were extracted from the surrounding unmelted powder cake and cleaned. To meet the precise dimensional tolerances required for fracture mechanics testing, the loading pin holes and the starter notch were introduced via subsequent machining operations.

A key aspect of this research was the investigation of mechanical anisotropy. To this end, specimens were produced in different building orientations relative to the main building axis (Z-axis). As visible in Fig. 2, two primary configurations were manufactured:

- Horizontal Orientation: The specimen main plane was oriented perpendicularly to the build plate (X-Y plane), meaning the build direction (Z) laid in the crack growth plane. These specimens were named H-H specimens.
- Vertical Orientation: The specimen main plane was oriented parallel to the build plate (e.g., in the X-Z plane). In this case, two distinct notch directions were further investigated to probe different crack propagation paths relative to the layered microstructure: one where the crack advanced parallel to the build direction and another where it advanced perpendicular to it. The former were labelled V-V specimens, while the latter were labelled V-H specimens.

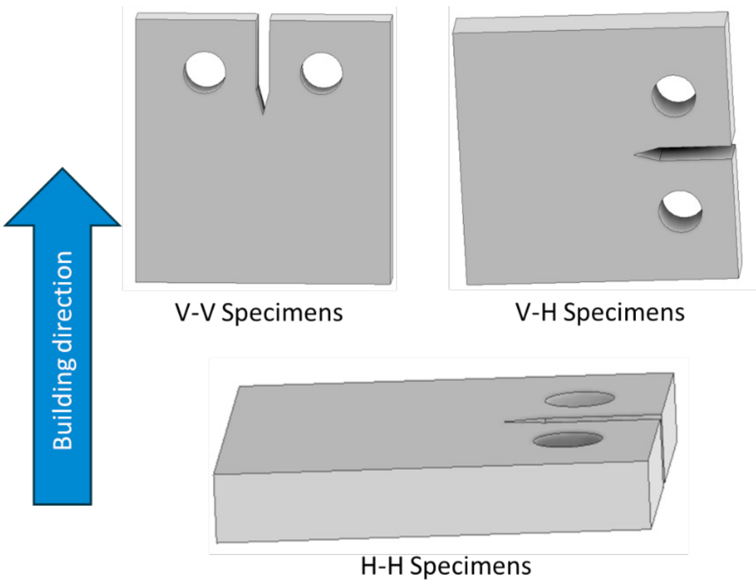

Fig. 2. Different building directions for the specimens.

For the fatigue crack growth (FCG) tests, a servohydraulic machine, controlled by a computer, was used to carry out experimental runs on CT specimens. For the experimental tests, a load ratio of 0.1 was considered. The other experimental conditions were a loading frequency of 30 Hz with a sinusoidal waveform, and the tests were carried out at room temperature. Moreover, a compliance method was implemented to evaluate the crack length. According to this method, the crack opening displacement was measured through a double cantilever mouth gage, and then this measure was correlated to the crack length using some relations. The value was controlled using an optical microscope with a magnification of 40x.

3. Results

The FCG behaviour of the EBM-manufactured Ti6Al4V specimens for the three distinct build orientations is presented in Fig. 3. The data is plotted as the crack growth rate per cycle, da/dN, as a function of the applied stress intensity factor range, ΔK, on a log-log scale.

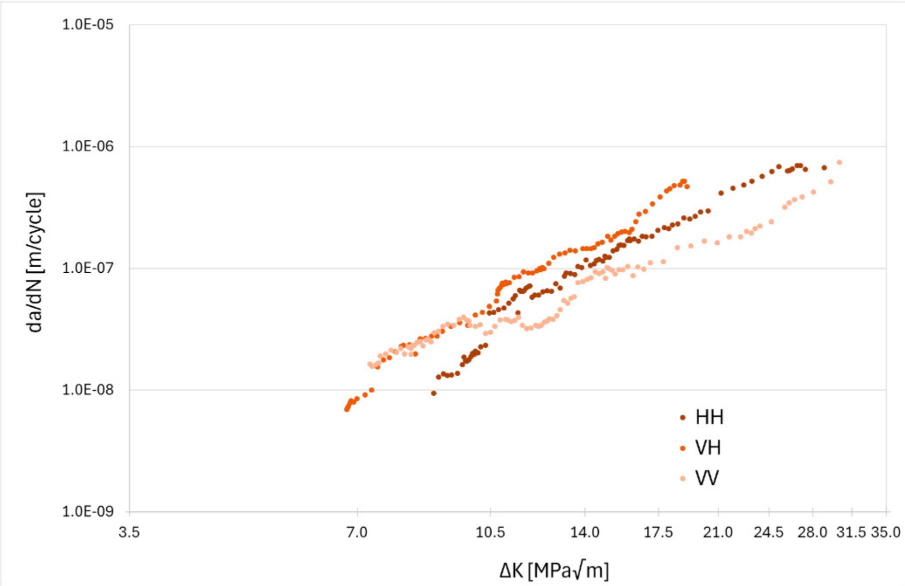

Fig. 3. FCG graphs for the tested specimens.

A clear trend is observable for all three configurations (HH, VH, and VV), where the crack growth rate increases with an increasing ΔK. This behaviour is consistent with the established Paris Law for stable fatigue crack propagation. However, it is evidenced the significant influence of build orientation on the material resistance to fatigue. The VV configuration (Vertical build, Vertical crack propagation) demonstrated a superior performance, exhibiting the lowest crack growth rates across the entire ΔK range tested. This indicates a significantly higher resistance to fatigue crack propagation compared to the other orientations. Furthermore, within the linear Paris regime, the VV curve presents the lowest slope. This implies that the crack growth rate in this orientation is less sensitive to increments in the stress intensity factor range.

In contrast, the HH (Horizontal build, Horizontal propagation) and VH (Vertical build, Horizontal propagation) configurations exhibited higher crack growth rates at the same ΔK, indicating lower fatigue resistance. Their performance was broadly similar, particularly in the near-threshold region. However, at ΔK values exceeding approximately 15 MPa √ m, the HH configuration consistently showed the highest da/dN, marking it as the orientation with the lowest resistance to fatigue crack growth in this study.

Fig. 4 displays a representative SEM micrograph of the fracture surface from the HH specimen, captured within the stable crack growth region at 200x magnification. The fracture morphology is complex and topographically rough, characterised by the presence of large, relatively flat facets, indicative of a transgranular, quasi-cleavage fracture mechanism. Numerous secondary cracks are visible, running parallel to the main fracture plane, contributing to the rapid crack advancement. Additionally, some spherical particles can be distinctly noted, likely a lack of fusion defect from the EBM process. Such defects act as stress concentrators and facilitate crack coalescence, further accelerating the fatigue crack growth rate.

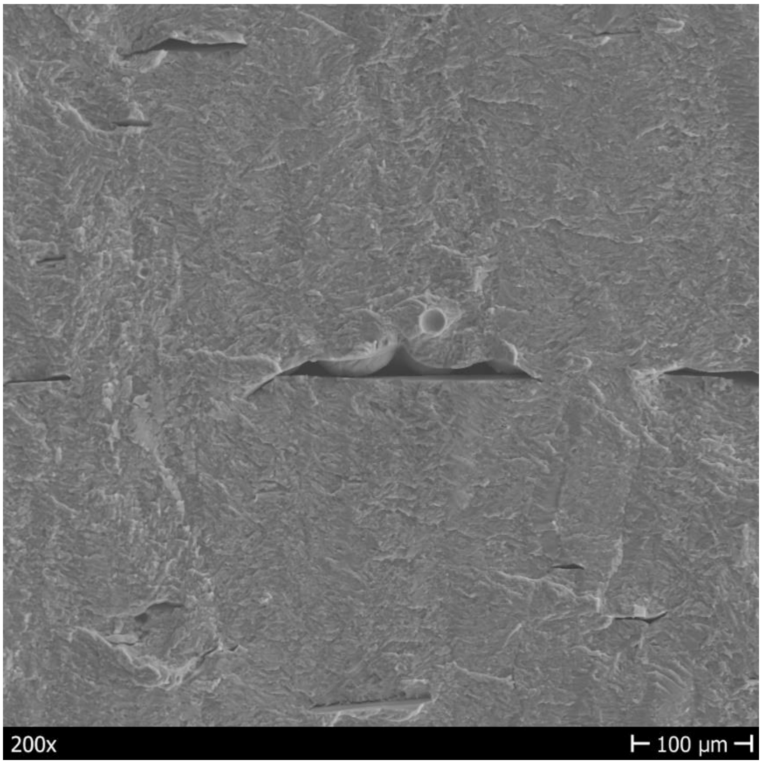

Fig. 4. Fracture surface of HH specimen.

4. Conclusion

In this study, the influence of build orientation on the fatigue crack growth (FCG) behaviour of Ti6Al4V fabricated by Electron Beam Melting (EBM) was systematically investigated. The experimental results unequivocally demonstrated that the EBM-processed material exhibits a significant mechanical anisotropy, leading to profoundly different levels of resistance to fatigue crack propagation depending on the orientation of the crack relative to the build direction.

The specimen built and tested in the vertical orientation (VV), where the crack propagated parallel to the columnar grain structure, exhibited a markedly superior fatigue performance. This configuration yielded the lowest crack growth rates and showed the least sensitivity to increases in the stress intensity factor range. The HH configuration was identified as the least damage-tolerant. Fractographic analysis of the HH specimen revealed that its poor performance was governed by a low-energy, transgranular quasi-cleavage fracture mechanism, exacerbated by the presence of process-induced defects like lack of fusion defects.

These findings have critical implications for the design and manufacturing of fatigue-critical components using EBM. The orientation of a part during the build process is not a negligible parameter but a crucial design choice that dictates the final component service life and structural integrity.

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