

Influence of scanning strategies on microstructure and properties anisotropy of GH3536 alloy formed by laser powder bed fusion

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Abstract: The GH3536 (Hastelloy-X) nickel-based superalloy is increasingly applied in the aerospace industry due to its exceptional combination of excellent oxidation resistance and high-temperature strength. Laser powder bed fusion (LPBF) is an additive manufacturing (AM) technology for producing metallic components with complex shapes using layer-by-layer manufacture principle. The debate has long prevailed as to research on eliminating anisotropy in the forming of GH3536 alloy through LPBF technology. In this study, the anisotropy of microstructure and mechanical properties of GH3536 alloy formed by LPBF was investigated using different scanning strategies (0°, 90°, 67°, checkerboard, and contour). The scanning strategy was optimized to reduce the weaving differences between the horizontal and vertical directions of the microstructure of the LPBF formed GH3536 alloy, which in turn reduces the anisotropy of the properties in both directions. The results of the tensile specimens indicate that except for the horizontal specimens produced using the contour scanning strategy, the strength of all other specimens exceeds that of the vertical specimens. Additionally, differences in elongation are observed, demonstrating that the GH3536 alloy fabricated via laser powder bed fusion exhibits anisotropic properties. According to electron backscatter diffraction (EBSD) analysis, the grain boundary strengthening and geometrically necessary dislocations (GNDs) impede dislocation motion during tensile deformation along the horizontal direction. Consequently, this mechanism negatively affects both the tensile strength and ductility in that orientation. The anisotropy in tensile strength and plasticity is attributed to the different crack sensitivities in the two tensile directions. In addition, specimens molded using different scanning strategies exhibit varying degrees of anisotropy, strength, and elongation due to different degrees of texture strengthening, grain boundary strengthening, and dislocation strengthening effects. Regardless of the stretching direction, the combined tensile properties of the 0° and contoured specimens are the worst under the room temperature and 815 °C stretching conditions. The 67° specimens exhibit the best combined tensile properties. Therefore, the anisotropy of the mechanical properties of the LPBF formed GH3536 alloy can be positively mitigated by modulating the scanning strategy.

Keywords: GH3536 alloy; laser powder bed fusion; microstructure; mechanical properties; anisotropy

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1 Introduction

GH3536 alloy, also known as Hastelloy-X, is a solid solution strengthened nickel-based superalloy that primarily contains elements such as molybdenum, tungsten, and chromium. This alloy possesses a well-balanced combination of mechanical strength, high-temperature oxidation resistance, corrosion resistance, hot workability, and weldability between 600 °C and 900 °C. Consequently, it is widely used in components of gas turbine engines and high-temperature gas-cooled reactors (HTGR), particularly for manufacturing parts for aircraft engine combustion chambers^[1-6]. Laser powder bed fusion

(LPBF) is an additive manufacturing process for metals that enables the direct fabrication of complex components through the interaction of high-power lasers with metal powders. This technology boasts high design freedom, simplified processing, and improved forming quality. Due to its use of metal powders and near-zero waste, LPBF technology finds extensive application in fields such as, aerospace, medical, automotive, and mold manufacturing^[6-10].

Despite these attractive advantages, several technical issues still hinder the widespread application of LPBF technology on GH3536 alloys, mainly facing challenges such as porosity, crack defects, element segregation, and anisotropy behavior. Most researchers modulated the underlying process parameters to reduce internal defects and change the microstructure of alloys. Maria et al.^[11] found that laser power significantly affects the microstructure of GH3536 alloy. Under high laser power, the melt pool width increased, and the solidification microstructure exhibited a stronger preferred orientation. At the same time, lowering the laser scanning rate can avoid cracks and holes, and the densities of the specimens were increased from 77% to 99%. However, the elongation showed strong anisotropy in the horizontal direction (9%) and vertical direction (30%)^[12]. In addition, energy density is also an important factor that affects the structure of the alloy. Keshavarzkermani et al.^[13] found that when the line energy density was $0.25 \text{ J} \cdot \text{mm}^{-3}$, the LPBF-formed GH3536 alloy possessed a uniform melt pool and the smallest grain size. An increase in laser power (from 50 W to 300 W) led to increased melt pool depth, faster cooling rate, and more cellular structures observed in the melt pool. Elemental segregation of LPBF GH3536 alloy is also one of the research hotspots. Chen et al.^[14] discovered the significant micro-spatialization of Mo and Cr at columnar sub-grain boundaries in GH3536 alloy, which contributes to the formation of chain carbides and enhancement of room-temperature strength. Han et al.^[15] incorporated 3wt.% TiC particles into the GH3536 alloy, which successfully eliminated intergranular crack defects. As a result, they fabricated an LPBF GH3536 alloy with near-full density, achieving a remarkable 37% increase in yield strength.

Among many difficulties, anisotropy is an unavoidable phenomenon in the preparation process of laser powder bed fusion. The anisotropy inherent in the forming process serves as one of the primary contributors to the anisotropy behavior observed in alloys fabricated via additive manufacturing (AM). The layer-by-layer material deposition process and heat treatment lead to the formation of anisotropic columnar grain microstructures and ultimately to undesirable anisotropic Young's modulus, strength, and ductility of the materials^[16]. Kong et al.^[17] found that the Hastelloy-X by LPBF showed anisotropy in both mechanical and corrosion properties. Zhang et al.^[18] found that Hastelloy-X with different scanning strategies exhibited varying degrees of anisotropy. The scanning angle of 67° checkerboard scanning strategy exhibited the highest elongation rate. The scientists explained this discrepancy by pointing to the elongated columnar grains

and the {001} crystallographic structure along the building direction^[19]. Kaya et al.^[20] reported that the building direction significantly affected the microstructure, resulting in anisotropic mechanical properties in LPBF steels. Specimens with a $\langle 111 \rangle$ texture exhibited greater strength compared to those with a $\langle 001 \rangle$ texture. Evangelou et al.^[21] discovered that reducing the angles of rotation per layer could lead to a decrease in texture anisotropy and helped prevent the formation of keyhole porosity, resulting in finer and more uniform microstructures during the LPBF process. Dong et al.^[22] prepared the GH4169 alloy using LPBF in three distinct orientations: horizontal, vertical, and inclined. The vertical samples exhibited the lowest strength but the greatest elongation; the horizontal samples demonstrated higher strength but the least elongation; meanwhile, the inclined samples achieved the highest strength and relatively higher elongation. Wan et al.^[23] found that both grain orientation and crystal structure had an effect on the mechanical properties of LPBF-formed Inconel 718 alloy. The refinement of grain size compared to crystal orientation was responsible for the higher room temperature tensile and fatigue strengths of 0° specimens compared to 90° specimens.

Li et al.^[24] demonstrated that there was a trade-off between molten pool size and solidification conditions in terms of controlling texture intensity by adjusting the scanning speed. Specifically, altering the scanning speed modified the solidification conditions during the forming process, which subsequently affected the proportion of columnar crystals in the alloys. Salman et al.^[25] reported that the scanning strategy had negligible influence on phase formation and the type of microstructure established during LPBF processing. The scanning strategy considerably affected the characteristic size of cells and grains, which appeared to be the main factor determining the strength under tensile loading. There are fewer studies on the effect of scanning strategy on the anisotropy of mechanical properties of LPBF-prepared alloys. A comprehensive understanding of the mechanical property anisotropy between different scanning strategies and the reasons for this phenomenon is imperative.

This study employed five typical scanning strategies to fabricate GH3536 alloy using LPBF technology, investigating the impact of these strategies on the microstructural and mechanical anisotropy. Anisotropy is an orientation-dependent property, where the tensile properties along the deposition direction were contrasted against those perpendicular to it. Furthermore, the reasons behind mechanical anisotropy were also explored. Through research, a deeper insight into how different scanning strategies affect microstructure and mechanical properties can be obtained, providing guidance for the design of load-bearing components.

2 Materials and methods

This study employed GH3536 powder processed via atomization, supplied by the Institute of Metal Research, Chinese Academy of Sciences. Its chemical compositions are

listed in Table 1. The morphology and particle size distribution (PSD) of the powder were characterized using a Thermo scientific Apero 2C type scanning electron microscope and a Bettersize-2600 type laser particle size analyzer, respectively. As shown in Fig. 1(a), most particles are spherical, with some irregular (blue arrows) and satellite-like (red arrows) particles also present. The particle size distribution indicates that the

majority of powder particles falls within the size range of 19–44 μm [Fig. 1(b)].

Table 1: Chemical compositions of GH3536 powder

Element	Cr	Fe	Co	W	Mo	C	Ni
wt. %	21.75	18.5	1.5	0.6	9.0	0.08	Bal.

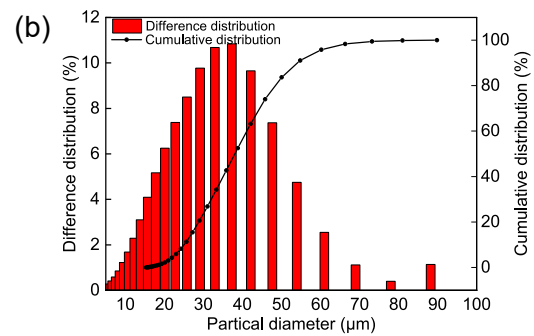
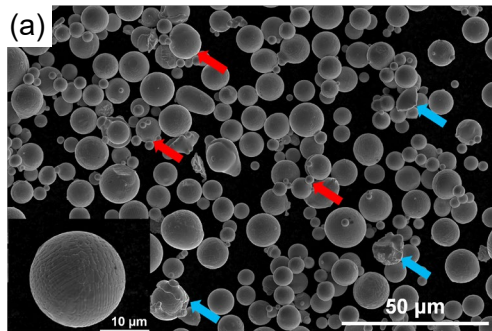


Fig. 1: Morphology (a) and particle size (b) of GH3536 powder used in LPBF process

The EP-M150 LPBF apparatus, utilizing a laser beam with a spot diameter of 60 μm , was employed to fabricate GH3536 alloy specimens. The process parameters were set as follows: laser power of 210 W, scanning speed of 1,000 $\text{mm}\cdot\text{s}^{-1}$, scan spacing of 100 μm , and layer thickness of 30 μm . Rectangular specimens with different scanning strategies in both horizontal and vertical orientations were prepared using this process. Five typical scanning strategies were selected [Figs. 2(a1) to (a5)]:

- (a1) Layer-to-layer angle of 0° , no direction change, with repetition on each layer;
- (a2) Layer-to-layer angle of 90° , 90° angle variation, repeated every 4 layers;
- (a3) Layer-to-layer angle of 67° , 67° angle variation, repeated every 360 layers;
- (a4) Checkerboard (CB) scanning strategy, each layer was divided into a 2×2 small checkerboard;

(a5) Contour (CT) scanning strategy, spiral scanning from the outer to the inner part of the layer, repeated every 4 layer.

After completing the scanning of each layer, an outer border scan was performed. The rectangular specimens were then cut off from the substrate using a precision line-cutting machine.

The specimens for microstructure characterization were cut from both horizontal and vertical rectangular specimens with dimensions of 16 mm $\times$ 16 mm $\times$ 50 mm [Fig. 2(b)]. X-ray diffraction (XRD, D8 Discover) with $\text{CuK}\alpha$ radiation was performed to identify phases of GH3536 alloy. The microstructure was examined by optical microscopy (OM, DM4M) and field emission scanning electron microscopy (SEM, Thermo scientific Apero 2C 15KV). Specimens for OM and SEM were successively ground using #180, #400, #1000, and #2000 grit SiC papers, polished by diamond paste and chemically etched using a CuCl_2 solution with a volume ratio of $\text{CuCl}_2\text{:HCl:C}_2\text{H}_5\text{OH}=1\text{:}2\text{:}2$. The crystallographic orientation and grain structure were

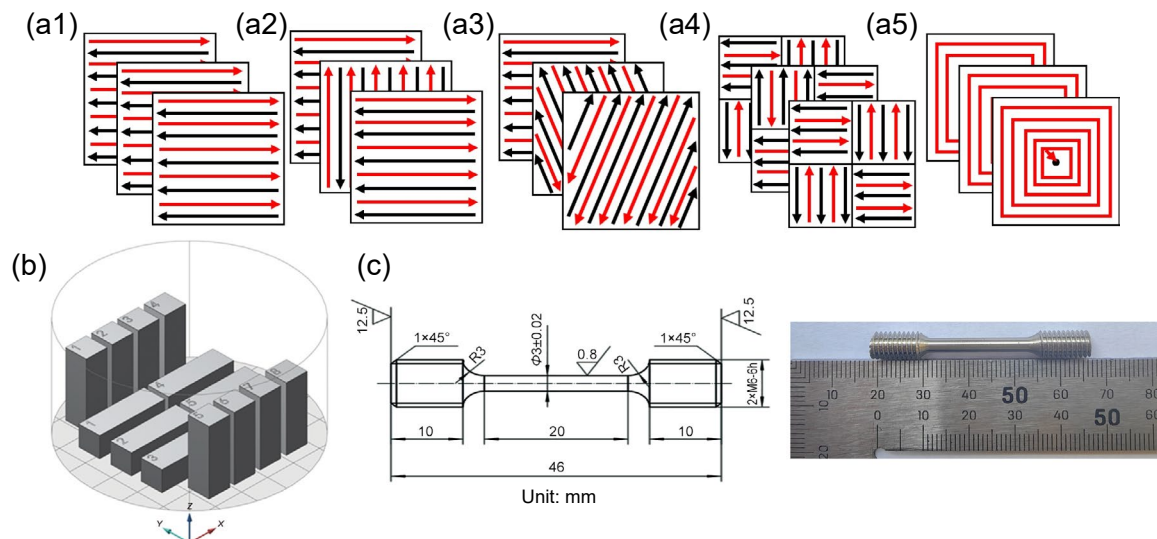


Fig. 2: Illustration of the five scanning strategies: (a1) 0° ; (a2) 90° ; (a3) 67° ; (a4) checkerboard; (a5) contour; (b) schematic of rectangular specimens; (c) diagrammatic sketch of tensile specimens

characterized by electron backscatter diffraction (EBSD, Thermo scientific Apero 2C, 20 KV) system mounted on SEM. Specimens for EBSD analysis were electro-polished in a solution of 10% perchloric acid.

The horizontal and vertical tensile specimens were machined from the rectangular specimens, as shown in Fig. 2(c). For the longitudinal specimens, the direction of tensile is parallel to the building direction, while for the horizontal specimens, the direction of tensile is perpendicular to the building direction. Tensile tests were performed by using an E45.105 universal testing machine with a strain rate of 0.00025 s^{-1} . After each test, the fracture morphology was inspected using SEM.

3 Results

3.1 Defects characterization

The relative densities of the specimens at 0° , 90° , 67° , checkerboard and contour structures are 96.37%, 98.25%, 98.91%, 97.46%, and 97.08%, respectively. Defects are the primary reason for the inability of the specimens to achieve complete density. Figure 3 illustrates the defects in polished specimens across their cross-sections. The internal defects of the five scanning strategies specimens were statistically analyzed using the Image-Pro Plus software, as depicted in Fig. 3(f). The results show that the defect density is inversely proportional to the relative density of the samples, with the 67° sample having the lowest density of internal defects ($\leq 0.05\%$), while the highest density of defects is found in the 0° and contour samples. The defects, including gas pores, cracks, and lack-of-fusion, are randomly distributed

within the specimens, with irregular shapes, occupying a small proportion. These defects might stem from powder spattering during the forming process, where some splashes larger than the layer thickness in the forming area result in unfused defects. Unlike unfused defects, the gas pore defects inside the specimens are small in size and have regular shapes. Gas pore defect occurs due to the incorporation of dissolved gases in the melt pool or gases released from the raw material of powders during the rapid solidification process^[26, 27]. In the LPBF process, temperature gradients lead to residual stress, causing cracks^[28, 29]. In this study, 0° , 90° , checkerboard, and contour samples exhibit micro-cracks. A preliminary assessment of the crack count in the samples reveals that the scanning strategy exerts a substantial influence on the density of micro-cracks. Specimens with scanning strategies of 0° and contour have higher micro-crack densities, which is attributed to the repeated thermal cycling caused by these strategies, leading to residual stress^[30, 21]. In contrast, the thermal stress in the specimens formed by scanning strategies of 90° , 67° , and checkerboard patterns is released. Consequently, only a few micro-cracks appear and higher forming quality can be achieved.

3.2 Phase analysis and microstructures

The XRD patterns of the five scanning strategies specimens are shown in Fig. 4. The strong diffraction peaks at (111), (200), and (311) crystal planes illustrate that all specimens consist of γ -phase, indicating the scanning strategy has no effect on the phase constitution of GH3536 alloy. The relative peak intensities of typical crystal planes show a significant change

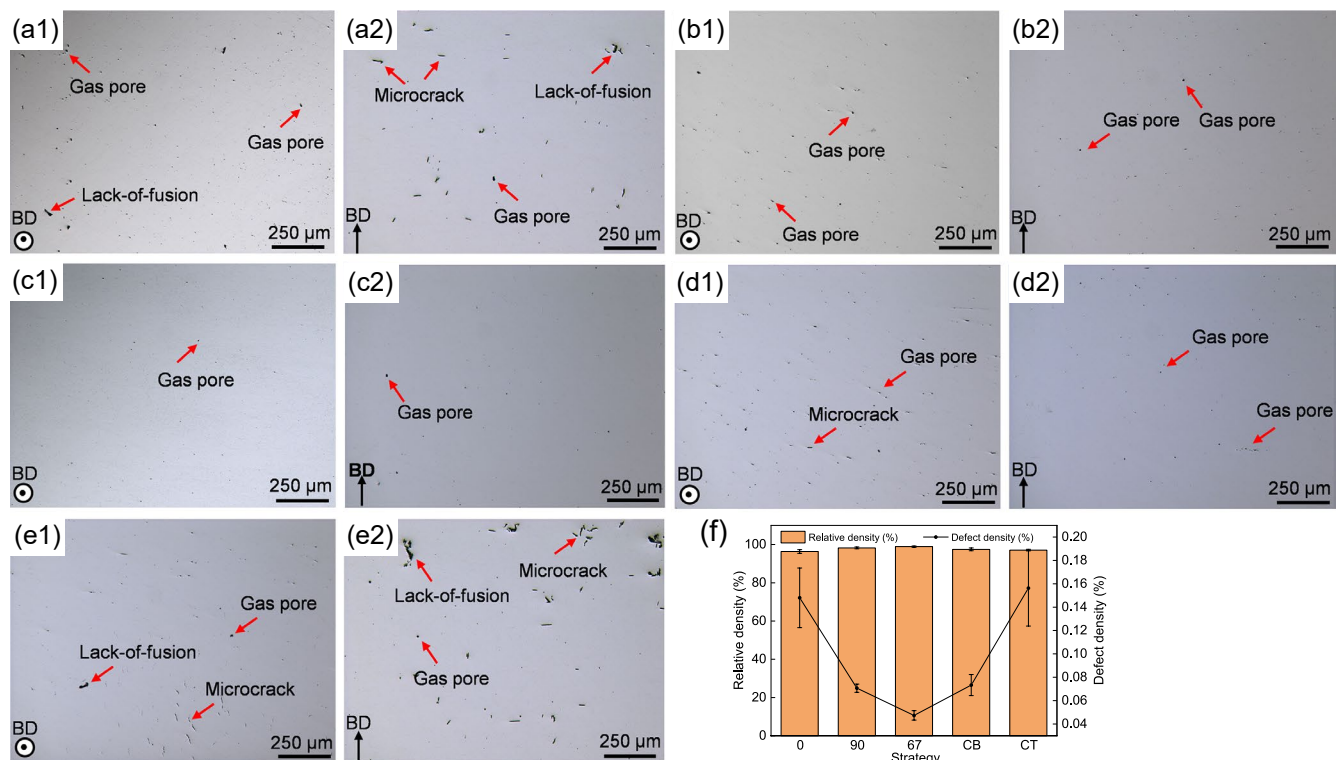


Fig. 3: Optical micrographs of horizontal and vertical specimens: (a1-a2) 0° ; (b1-b2) 90° ; (c1-c2) 67° ; (d1-d2) checkerboard; (e1-e2) contour; (f) porosity and microcrack

with the variations in the scanning strategy, demonstrating the dependency of the crystallographic texture on the scanning strategy. It should be noted that among the five scanning strategies employed for the GH3536 alloy, the (200) diffraction peaks exhibit a notably higher relative intensity when compared to the (111) and (311) crystallographic diffraction peaks, ultimately establishing themselves as the predominant growth orientation of the crystal. It can be considered that LPBF is helpful to the (200) crystal plane due to the directional

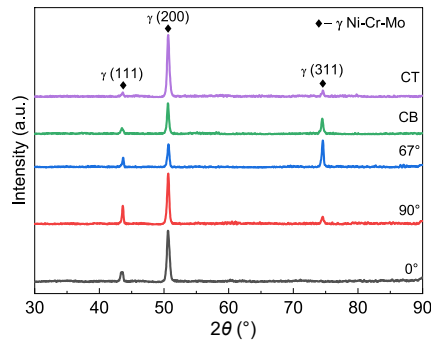


Fig. 4: XRD patterns of GH3536 alloys prepared by LPBF

heat flux and thermal gradient^[32]. In the next step, EBSD will be used to study the crystallographic texture, which will be discussed in the subsequent sections.

As can be seen from the Fig. 5, regardless of the scanning strategy employed, both horizontal and vertical directions exhibit typical sub-grain microstructures. The horizontal direction is composed of cellular structures; while the vertical direction consists of columnar and fine cellular grains. Unlike the microstructures produced by traditional manufacturing methods, such as forging, that the sub-grain structure is formed by dislocation cells. In the SEM images, the melt pool boundary (MPB), delineated by the white dotted line, is clearly visible apart from the sub-grain structure. The morphology of the melt pool exerts a substantial influence on solidification behaviors and the orientation of grain growth by impacting the critical solidification parameter, namely, the thermal gradient (G). Due to a higher thermal gradient G generated by high-energy beam irradiation during metal AM processes, epitaxial grain growth is usually more favorable than what is observed in conventional manufacturing processes^[33-35].

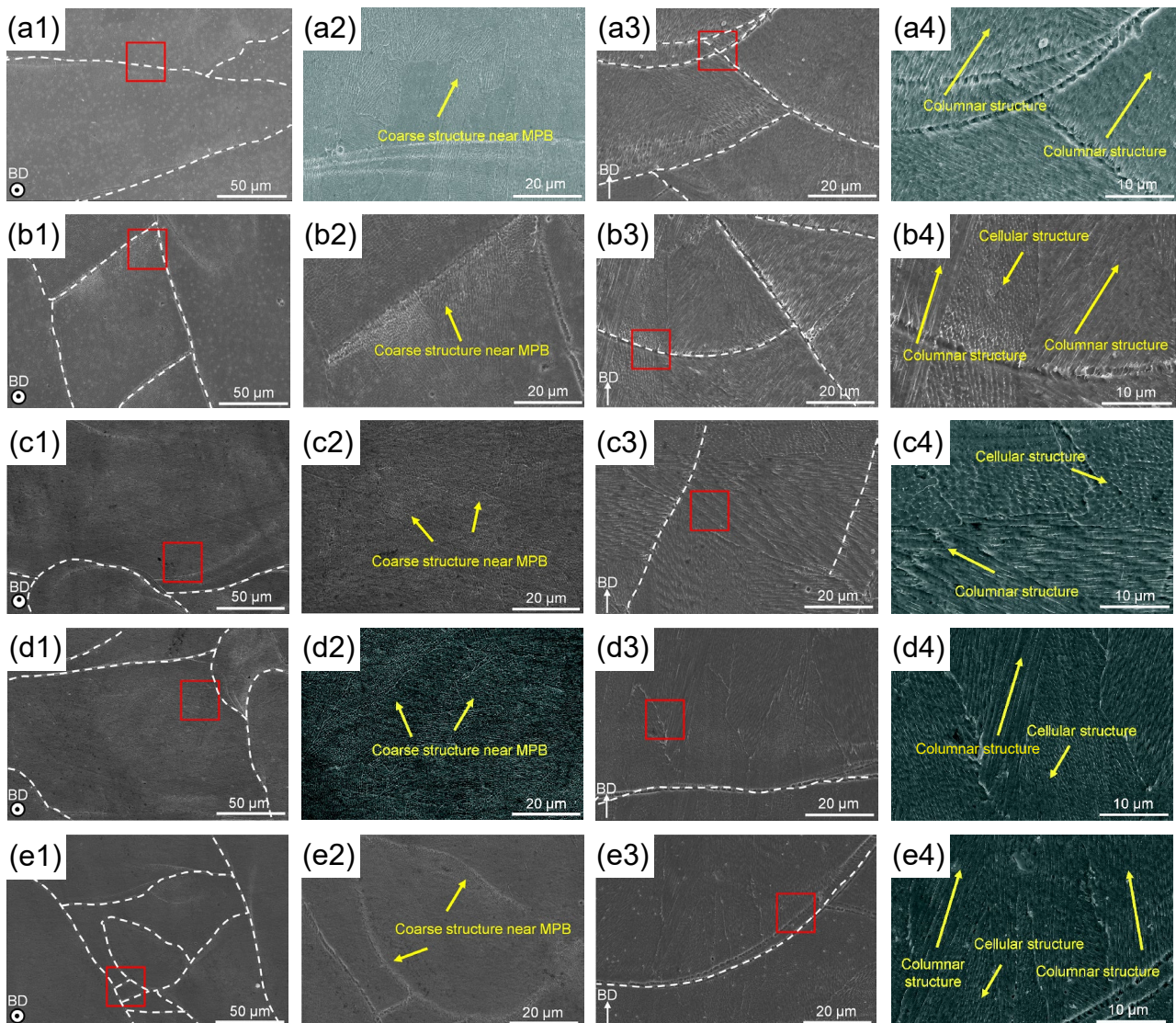


Fig. 5: SEM micrographs for horizontal specimens: (a1-a2) 0°; (b1-b2) 90°; (c1-c2) 67°; (d1-d2) checkerboard; (e1-e2) contour; and vertical specimens: (a3-a4) 0°; (b3-b4) 90°; (c3-c4) 67°; (d3-d4) checkerboard; (e3-e4) contour

3.3 Grain morphology and crystallographic texture

The morphology and texture of grains in specimens using different scanning strategies were investigated by EBSD. As observed in Fig. 6, two distinct grain morphologies exist within the horizontal direction of the specimens: columnar and equiaxed grains. The additive manufacturing process is akin to welding, where columnar crystals initially grow perpendicular to the melt pool boundary and eventually form equiaxed crystals along the centerline of the scanning track^[36]. The transformation from columnar crystals to equiaxed crystals (CET) is notably evident in the 90° specimens [Figs. 6(a1), (b1)], whereas the grain distribution in the 67°, checkerboard (CB) and contour (CT) specimens [Figs. 6(c1), (d1), (e1)] appears disordered. Vertically, the specimens are characterized mainly by columnar grains, with only a few fine grains scattered throughout. Large columnar grains can grow through several

pools in the forming direction due to the exsolution caused by partial remelting of the previously solidified layer. When the thermal flow direction of adjacent pools is similar to that of the previous pool's crystallographic orientation, the exsolution will form across the entire pool boundary due to the much lower energy for crystal growth compared to nucleation energy^[37].

Regardless of the scanning strategies employed, preferential orientations of $\langle 001 \rangle$ and $\langle 101 \rangle$ exist in the horizontal direction due to the competitive growth mechanism between grains. This phenomenon is related to the preferred growth trend and thermal flow direction due to the face-centered cubic metals. When the thermal flow direction forms a smaller angle with the crystallographic preferred orientation, the grains with the preferred orientation grow more rapidly, while the growth of other grains is inhibited. As shown in the corresponding $\{100\}$ pole figures (Fig. 7), the strength of the texture varies with changes in the scanning strategy, with the highest strength observed in the 0° specimen^[38].

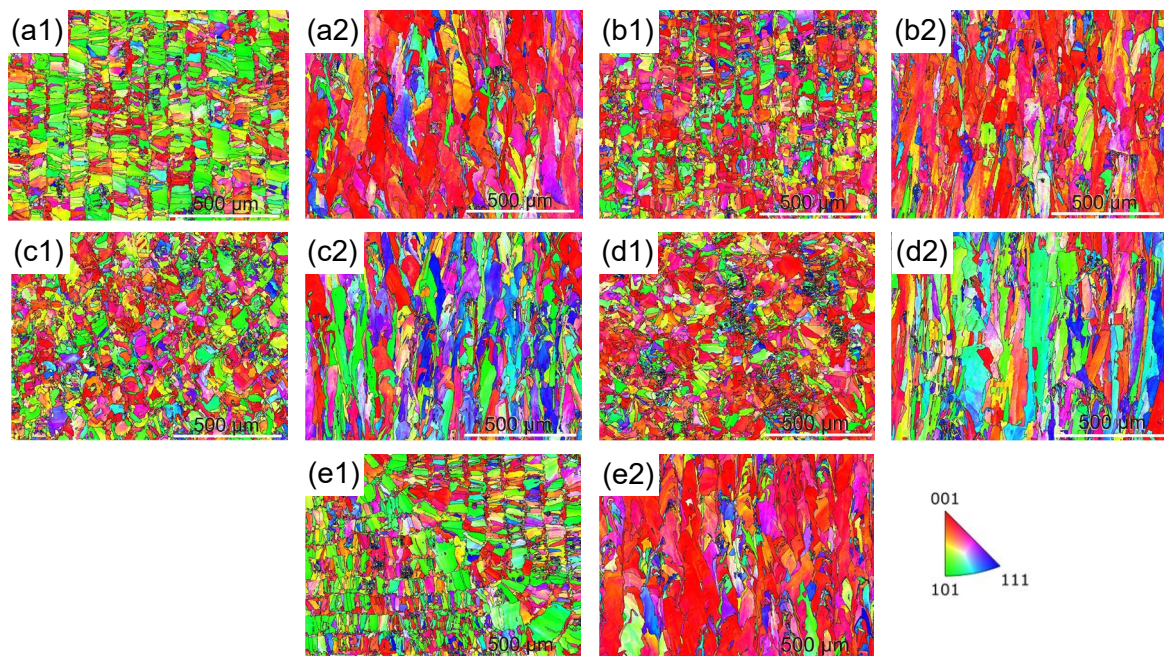


Fig. 6: IPF maps of horizontal specimens: (a1) 0°; (b1) 90°; (c1) 67°; (d1) CB; (e1) CT; and vertical specimens: (a2) 0°; (b2) 90°; (c2) 67°; (d2) CB; (e2) CT

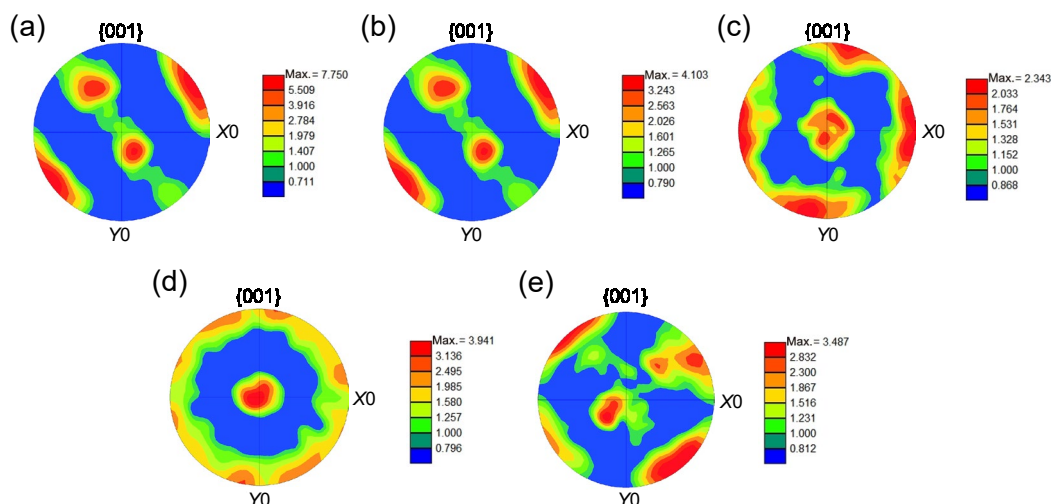


Fig. 7: PF maps of horizontal specimens: (a) 0°; (b) 90°; (c) 67°; (d) CB; (e) CT

3.4 Tensile properties and fracture appearance

Figures 8(a) and 9(a) show the stress-strain curves for tensile tests conducted at room temperature and 815 °C in horizontal and vertical directions. Regardless of the scanning strategy used, the specimens tested horizontally exhibit higher yield strength (YS) and ultimate tensile strength (UTS), and a lower elongation (δ) compared to those tested vertically. To compare the effects of different scanning strategies on tensile performance, Figs. 8(b) and (c) and Figs. 9(b) and (c) display the average YS, UTS, and δ for horizontal and vertical specimens under room temperature and 815 °C conditions. At room temperature, for horizontal specimens, the 0° and contour (CT) specimens exhibit lower strength and elongation. When employing the 90° and checkerboard (CB) scanning strategies, a notable rise in strength is observed, accompanied by the highest elongation values. The disparity between these two strategies in terms of their effects on tensile properties is relatively minor. In the horizontal specimens, the 67° scanning strategy shows the highest tensile strength.

In vertical specimens, the specimen with a 67° orientation exhibits the highest ultimate tensile strength. The tensile strength of specimens obtained using the 90° and checkerboard scanning strategies shows a slight decrease. The yield strengths of the specimens, excluding that produced using the 67° scanning strategy, are roughly the same. Furthermore, the specimens by the 0° and contour scanning strategies exhibit the lowest elongation. While, the elongation values for the specimens produced by the other three strategies are relatively similar. Under 815 °C conditions, for horizontal specimens, the elongation of the 0° and contour specimens is lower, and that of the other three scanning strategy specimens is almost the same.

In vertical specimens, the 0° and contour specimens exhibit the lowest elongation, while that of the other three scanning strategy specimens is relatively high. The other performance indicators follow a similar trend as those at room temperature conditions. Comparison of the tensile results among the specimens under various scanning strategies reveals that the scanning strategy significantly impacts the tensile properties of specimens.

To evaluate the comprehensive performance of specimens with various scanning strategies, anisotropy in tensile properties was compared, as summarized in Figs. 8(d) and 9(d). The research findings indicate that the GH3536 alloy fabricated through LPBF shows significant anisotropy in tensile properties. Under room temperature conditions, the anisotropy in strength and elongation of the 0° specimen is relatively small, while that of the contour strategy results in greater anisotropy for the ultimate tensile strength and elongation. Among the other three scanning strategies, notable differences are observed in the anisotropy of strength metrics, except for elongation. At 815 °C, samples scanned with the 67° strategy exhibit minor variations across all indices. The checkerboard-scanned samples show small differences in ultimate tensile strength and the contour-scanned samples show small differences in elongation, the remaining scanning strategies exhibit substantial variations in performance metrics. By comparing the tensile properties under different scanning strategies and their impact on the anisotropy of the specimens, it is recommended to adopt a 67° scanning strategy.

Figures 10 and 11 show the fracture morphology of the tensile specimens at room temperature and 815 °C, analyzing both horizontal and vertical directions. The fracture surfaces of the 90° and 67° specimens exhibit ductile pits, whereas the fracture surfaces of the checkerboard and contour specimens

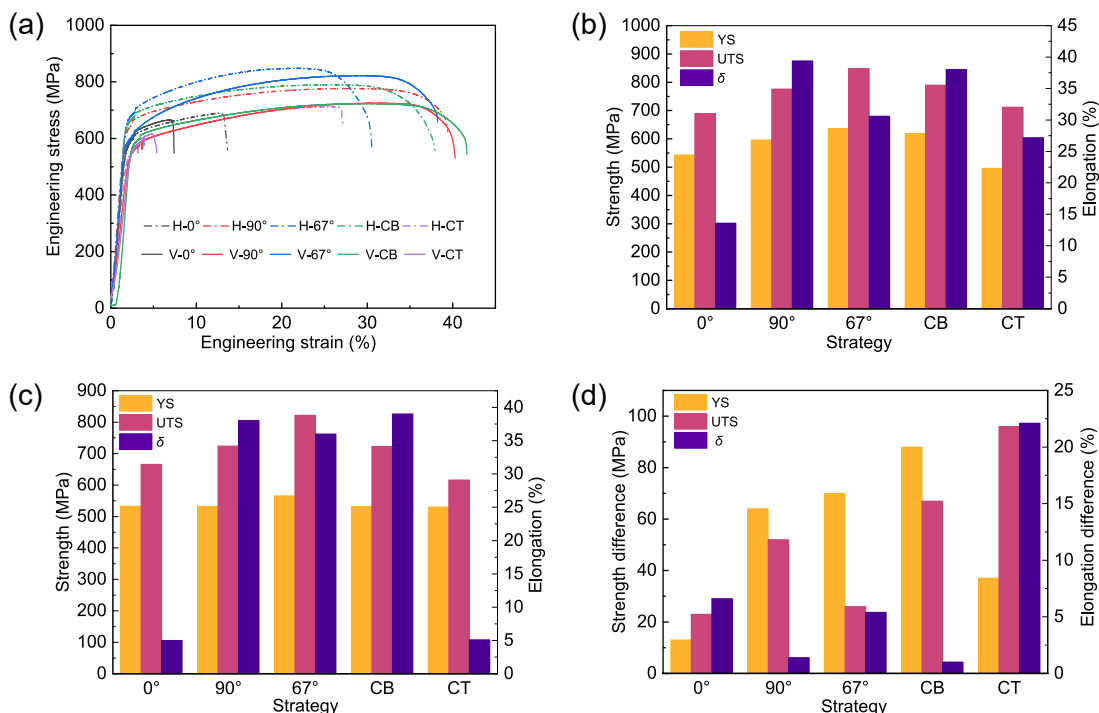


Fig. 8: Tensile stress-strain curves of horizontal (H) and vertical (V) specimens at room temperature (a), tensile properties of horizontal specimens (b), tensile properties of vertical specimens (c), and tensile anisotropy (d)

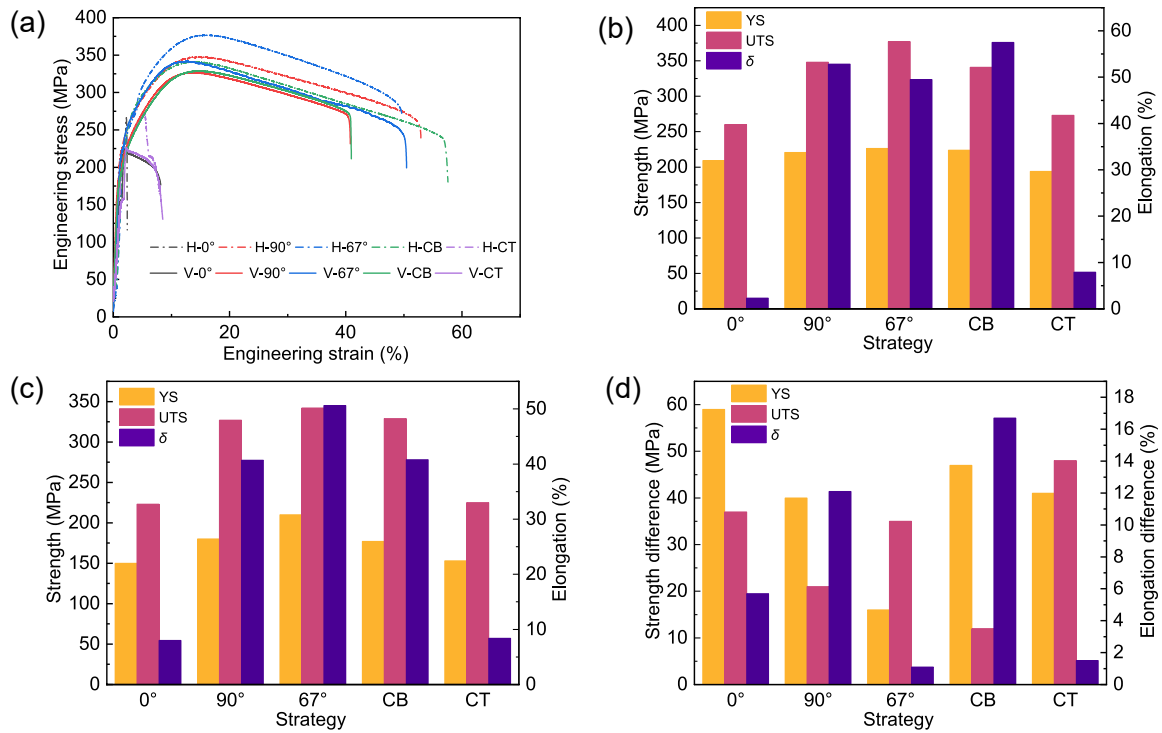


Fig. 9: Tensile stress-strain curves of horizontal (H) and vertical (V) specimens at 815 °C (a), tensile properties of horizontal specimens (b), tensile properties of vertical specimens (c), and tensile anisotropy (d)

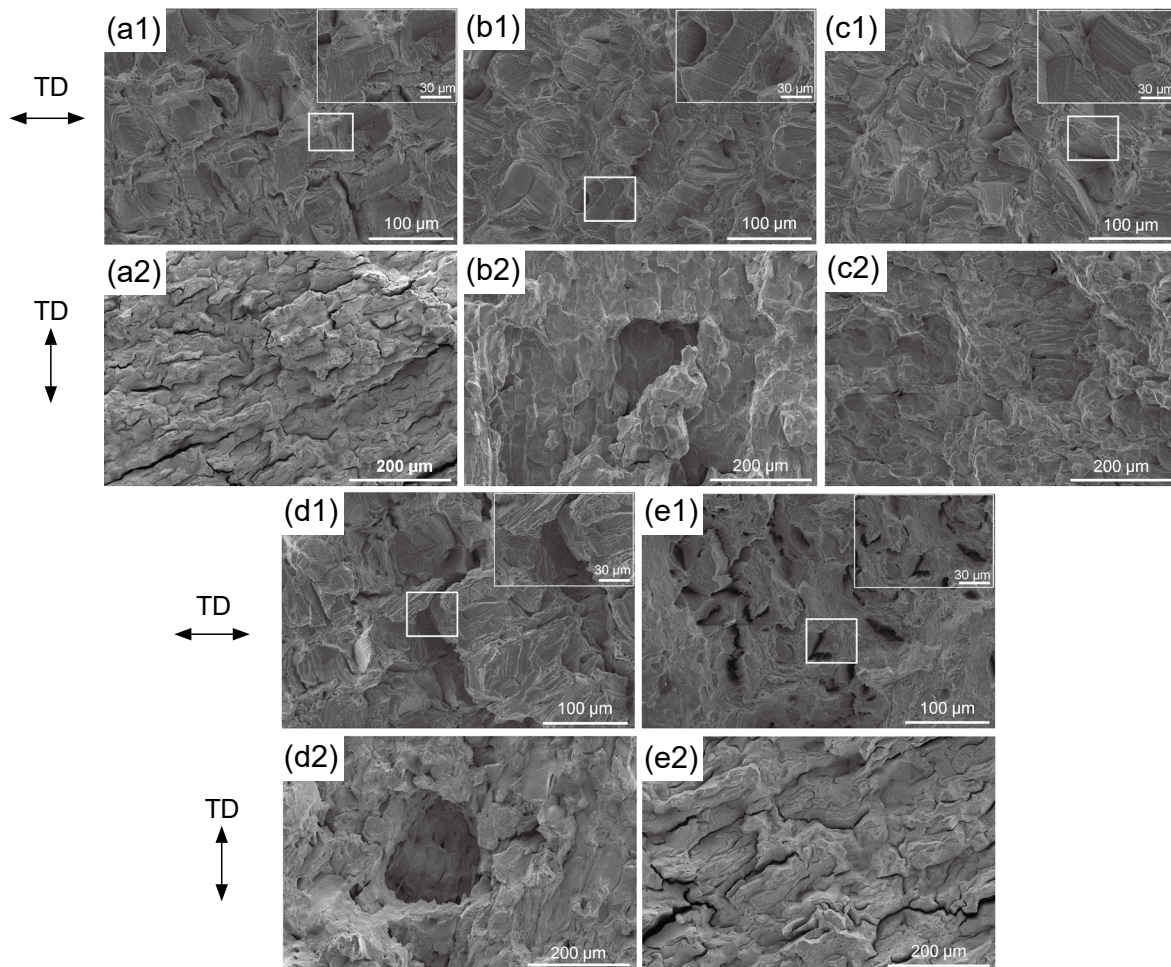


Fig. 10: Tensile fracture morphologies of specimens at room temperature. Horizontal specimens: (a1) 0°; (b1) 90°; (c1) 67°; (d1) CB; (e1) CT; vertical specimens: (a2) 0°; (b2) 90°; (c2) 67°; (d2) CB; (e2) CT (TD represents tensile direction)

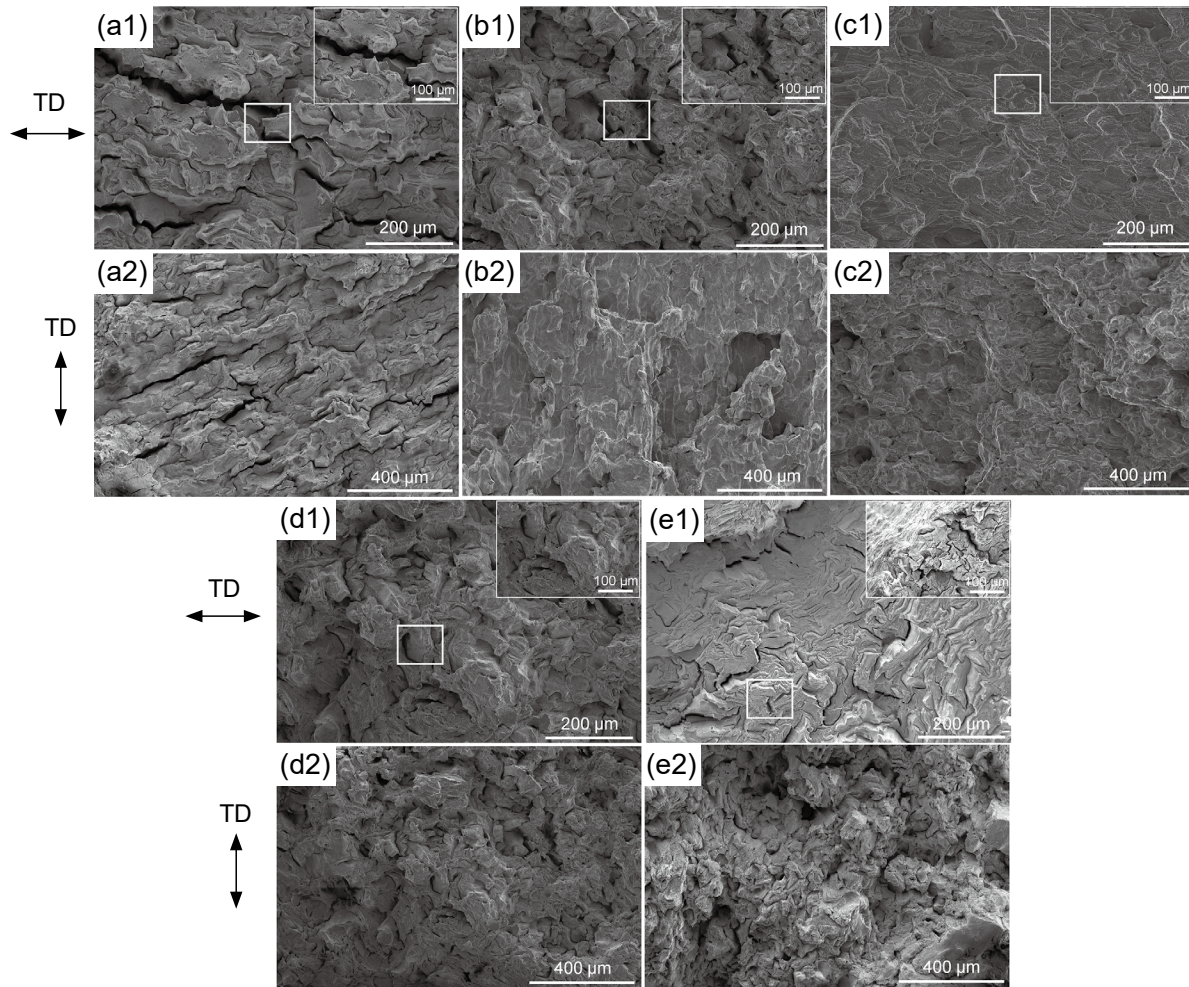


Fig. 11: Tensile fracture morphologies at 815 °C. Horizontal specimens: (a1) 0°; (b1) 90°; (c1) 67°; (d1) CB; (e1) CT; vertical specimens: (a2) 0°; (b2) 90°; (c2) 67°; (d2) CB; (e2) CT

show no obvious ductile pitting structures. Instead, they contain numerous defects such as cracks and cavities. In the remaining four horizontal specimens, as illustrated in Figs. 10(b1–e1), several strip-like features and numerous small ductile dimples are observable. This phenomenon is attributed to the relatively weaker metallurgical bonding between the columnar grains^[39]. Consequently, following fracture, these strip-like features persist in the vertical specimens, as indicated in Figs. 10(a2–e2). Regardless of the scanning strategy used, a large number of isotropic ductile dimples with sizes in the hundreds of nanometers are observed, exhibiting a ductile fracture mode.

4 Discussion

From Figs. 8 and 9, it can be observed that altering the scanning strategy has an obvious impact on the tensile strength and elongation of GH3536 alloy. Specifically, defects within the alloy significantly affect its mechanical properties. Studies have shown that pores and cracks within the test specimen reduce the tensile properties, leading to rapid material failure^[40, 41]. However, in this experiment, the proportion of defects within the specimen is less than 0.2% [Fig. 3(f)], which is a limited amount and insufficient to influence the results of this experiment. Micro-cracks are the key cause of plastic degradation

when evaluating tensile properties, especially in horizontal specimens. When the tensile direction is perpendicular to the micro-crack direction, stress concentration occurs easily at the micro-crack tip, leading to localized yielding and crack propagation^[42]. Among various scanning strategies, the 0° and contour specimens exhibit the highest micro-crack densities, resulting in the lowest elongations in 0° horizontal specimens. Conversely, the specimens with a scanning angle of 67° exhibit the lowest micro-crack density, showing the highest tensile strength and a good elongation. For vertical specimens, when the micro-crack direction is parallel to the tensile direction, its impact on tensile strength and elongation is minimal. Therefore, for the same scanning strategy, horizontal specimens consistently exhibit higher tensile strength and elongation compared to vertical specimens. As a result, the presence of high-density micro-cracks negatively impacts the tensile properties of horizontal specimens, ultimately giving rise to anisotropy.

GH3536 alloy exhibits pronounced anisotropy in its tensile properties, which is attributed to texture-strengthening, grain boundary strengthening, and dislocation strengthening^[43, 44]. During plastic deformation, polycrystalline materials require the simultaneous activation of five independent slip systems in each grain. Consequently, through Taylor's theory, it can be

understood that the anisotropic behavior of GH3536 alloy is a result of the differential contribution of these strengthening mechanisms to the overall deformation. Taylor factor was used to evaluate the texture-strengthening effect^[45]. The Taylor factors for the slip systems parallel and perpendicular to $\{111\}$ and $\langle 110 \rangle$ were calculated for the horizontal and vertical specimens, respectively, as shown in Figs. 12 and 13. The relationship between strength (σ_s) and Taylor factor (M) is shown in Eq. (1):

$$\sigma_s = M \cdot \tau \quad (1)$$

where τ represents the critical shear stress, which is the same for all grains in an alloy with the same composition^[46]. According to Eq. (1), the Taylor factor influences the yield strength. However, this study found that horizontal specimens, despite having a lower Taylor factor under a 67° scanning strategy, exhibit unexpectedly high strength. The Taylor factors for the vertical specimens are comparable to those of the checkerboard and contour types, yet their strength differs

significantly. Therefore, texture strengthening cannot fully explain the differences in tensile properties.

Another strengthening mechanism affecting the tensile strength of the GH3536 alloy is grain boundary strengthening. The EBSD results were statistically analyzed using the Aztec Crystal software, as shown in Fig. 13. Specifically, the relationship between strength and grain size is expressed using the Hall-Petch equation:

$$\sigma_s = \sigma_0 + k d^{-1/2} \quad (2)$$

where σ_0 and k are constants, d represents the grain size. It indicates that reducing the grain size helps to enhance the strength of the alloy. Based on the statistical results of grain sizes in the horizontal specimens [Fig. 14(a)], the grain sizes obtained from the 0° and contour scanning strategies are larger than those from the 67° scanning strategy. Tensile testing results indicate that specimens employing the 67° scanning strategy demonstrate superior strength compared to those

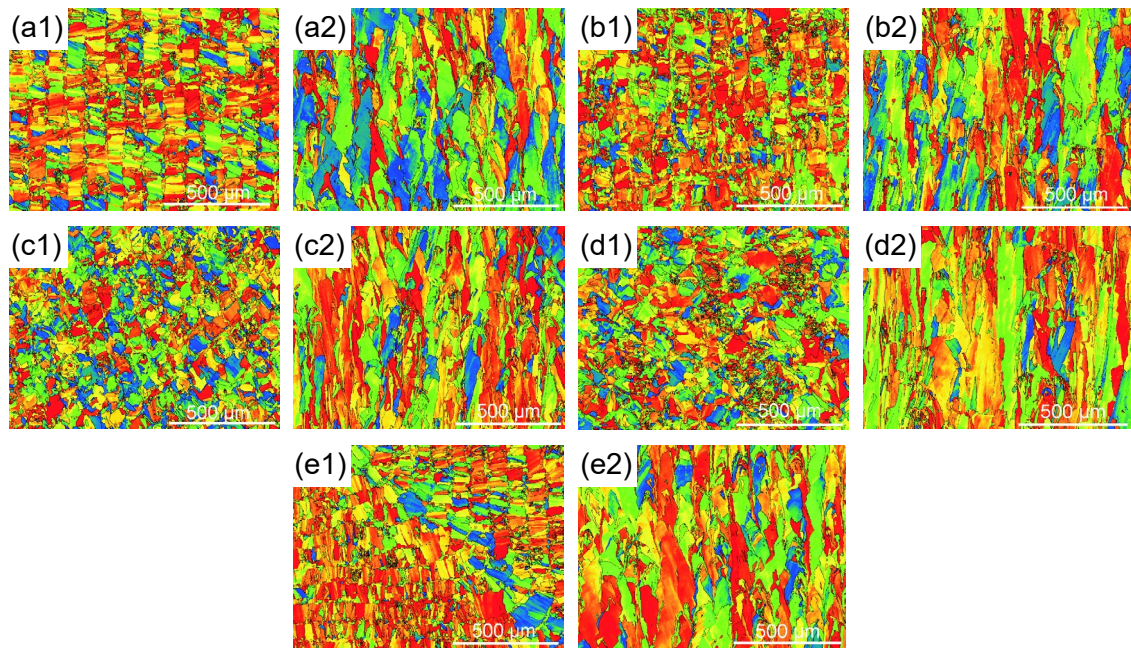


Fig. 12: Taylor factor maps and corresponding histograms calculated using orientation imaging microscopy for horizontal and vertical specimens: (a1-a2) 0° ; (b1-b2) 90° ; (c1-c2) 67° ; (d1-d2) CB; (e1-e2) CT

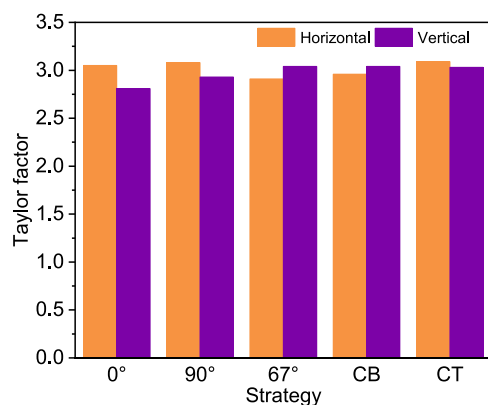


Fig. 13: Taylor factor statistics for samples formed by different scanning strategies

utilizing 0° and 90° , checkerboard and contour scanning methods, aligning with the Hall-Petch equation's prediction results on the relationship between yield strength and statistical grain size data. Vertical specimens exhibit similar trends in yield strength variation across scanning strategies, with the correlation between yield strength and average grain size providing additional support for the Hall-Petch relationship.

The aspect ratio of the long axis dimensions of columnar grains is notably larger than that of the short axis. This implies that a greater number of grain boundaries impede dislocation movement during horizontal stretching, leading to increased strength. Exploiting this feature, anisotropy in strength was identified in the GH3536 alloy. Results reveal that the aspect ratio of elongated grains influences the yield strength

within a specific range [Fig. 14(b)]. Therefore, grain boundary strengthening not only influences strength under varied scanning strategies but also plays a role in specific strengths observed in different stretching orientations.

Figures 15 and 16 show the Kernel average misorientation (KAM) maps and the corresponding histograms obtained using

the Aztec Crystal software, which can be used to evaluate dislocation density. The higher the KAM value, the higher the dislocation density. However, the KAM method only considers geometrically necessary dislocations (GNDs) in the microstructure, i.e., the actual dislocation density exceeds the KAM values. However, due to the hindrance effect of

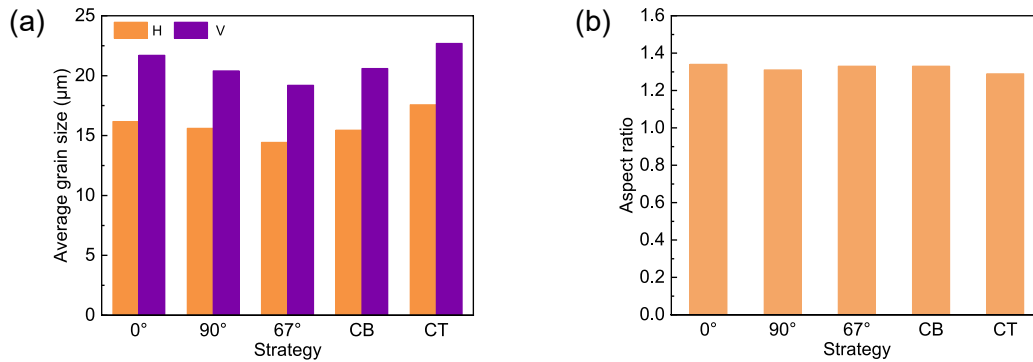


Fig. 14: Analysis of average grain size from different directions (a) and aspect ratio of elongated grains along vertical cross section (b)

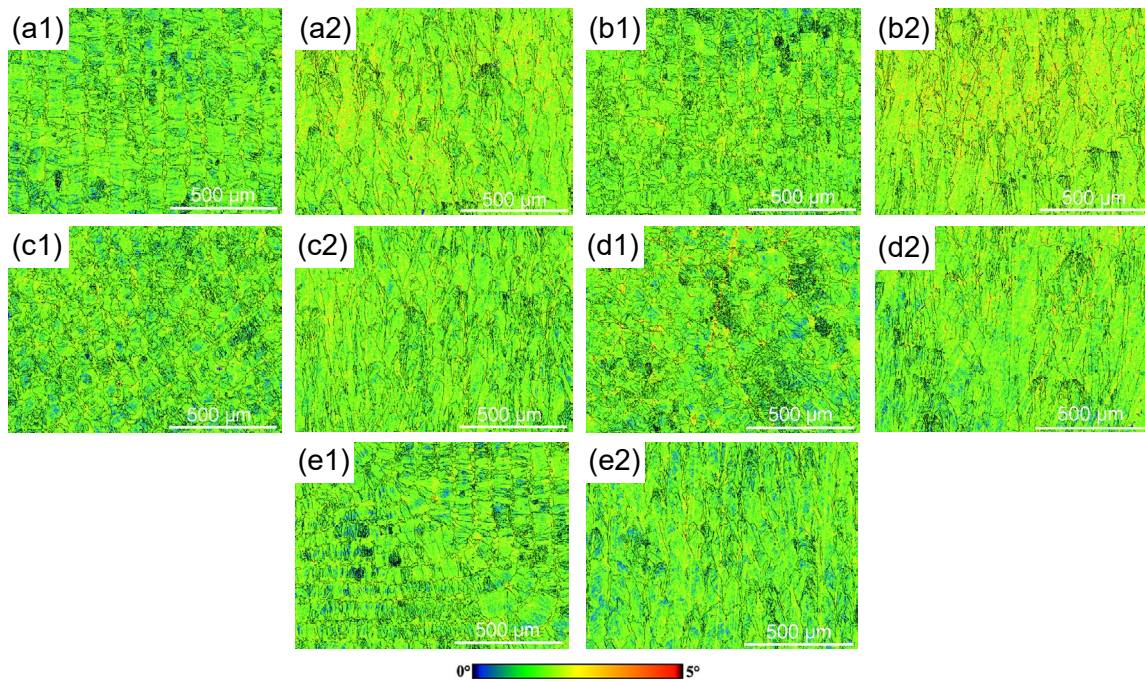


Fig. 15: KAM maps and corresponding histograms for horizontal and vertical specimens: (a1-a2) 0°; (b1-b2) 90°; (c1-c2) 67°; (d1-d2) CB; (e1-e2) CT

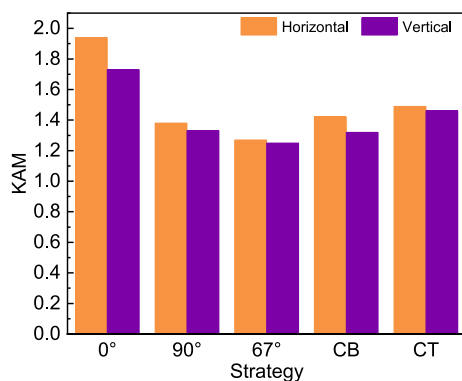


Fig. 16: Statistical plots of KAM values of samples with different scanning strategies

GND density, the KAM value can also represent the level of dislocation strengthening^[47-49]. The statistical analysis indicates that the highest KAM values occur in the 0° and contour scanning strategies, but their horizontal and vertical specimens exhibit the lowest strength, suggesting that variations in strength among scanning strategies are not solely attributes to the changes of dislocations. Additionally, horizontal specimens demonstrate greater KAM values than vertical ones under the same scanning strategy, showing that they possess higher tensile strength due to increased dislocation density, which enhances resistance to slip. In conclusion, dislocation density is another factor contributing to the strength anisotropy.

5 Conclusions

In this study, the effects of employing different scanning strategies during laser powder bed fusion (LPBF) on the microstructure and mechanical properties of the GH3536 superalloy were investigated. The following conclusions are reached:

(1) All specimens of the GH3536 alloy processed by LPBF consist of a single γ phase, with both cellular and columnar grains observed in horizontal and vertical directions. Tensile tests demonstrate that strength and elongation vary with scanning strategies. In view of the analysis of the microstructure and mechanical properties of the alloys formed by different scanning strategies, the 67° scanning strategy is recommended for laser powder bed fusion forming of GH3536 alloy.

(2) At room temperature, the specimens with 90° and checkerboard scanning strategies exhibit the highest elongation, while the 67° scanning strategy shows the highest strength. For the vertical specimens, the specimen with a 67° scanning strategy exhibits the highest strength, whereas the specimens with 0° and contour scanning strategies show the lowest elongation. At 815°C , for the horizontal specimens, the yield strength and elongation of the specimens with 0° and contour strategies is the lowest. In the vertical specimens, the specimen with a 0° scanning strategy has the lowest elongation. Similar to horizontal specimens, the tensile strength and elongation of vertical specimens are also affected by changes in scanning strategy.

(3) Compared to vertical specimens, horizontal ones exhibit slightly higher yield strength, but lower tensile strength and elongation. These results indicate that the mechanical properties of the GH3536 alloy formed by LPBF show anisotropy. Detailed examination reveals that the interplay among texture strengthening, grain boundary strengthening, and dislocation strengthening mechanisms within the alloy results in anisotropic mechanical properties.

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Conflict of 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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