



Systematic study of the interplay between laser beam shape, energy input, and hatch spacing in PBF-LB/M of Ti-6Al-4V: experiments and numerical modeling[☆]

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ABSTRACT

Programmable laser beam shaping tailors the spatial irradiance distribution in laser powder bed fusion (PBF-LB/M), enabling control over melt-pool geometry and defect formation. However, the coupled effects of beam shape, hatch spacing (track overlap), and energy input on densification and microstructural development remain insufficiently understood. Accordingly, Ti-6Al-4V is studied using single-track experiments, cube builds, and 3D transient multiphysics simulations across three ring-type beam profiles ranging from relatively core-weighted to strongly ring-dominated. Single tracks spanning a power–speed matrix (linear energy density, P/v) quantified melt-pool width, depth, and molten area and mapped stability regimes (fragmentation, necking, stable) and transition thresholds with increasing energy input. Cube specimens mapped relative density versus beam mode, areal energy density $AED_h = P/(v \cdot h)$ (J/mm^2), hatch spacing h , and geometric ratios h/d (d : effective beam diameter) and W/h (W : melt-pool width). Near-full density ($\sim 99.9\%$) was achieved for all profiles at $AED_h \geq 2.8\text{--}3.0 J/mm^2$; relatively more core-weighted profiles reached this at lower AED_h , whereas ring-dominated profiles required higher input to suppress lack-of-fusion. Density dropped when $h/d \geq 1$, while $W/h \geq 1.2$ preserved high density. Microstructure and Vickers microhardness ($HV_{0.2}$) were assessed across AED_h . All conditions exhibited martensitic α' microstructures, and microhardness remained $\approx 360\text{--}395 HV_{0.2}$, converging once near-full density was reached. Simulations showed that ring-dominated density loss arises from insufficient inter-track remelting depth (cusp formation) despite lateral overlap, requiring higher overlap ratios for full fusion. Thermal gradients (G) and solidification rates (R) placed all cases in the columnar growth regime; higher G/R in more core-weighted profiles is consistent with stronger grain continuity than the more refined ring-dominated structures.

1. Introduction

Laser-based powder bed fusion of metals (PBF-LB/M) is an established additive manufacturing technology increasingly used for producing complex, high-performance components, particularly in aerospace, biomedical, and automotive sectors [1,2]. The process

selectively melts a pre-spread powder layer using a focused laser beam, enabling near-net-shape fabrication with fine microstructures and robust properties. Most commercial systems use single-mode Gaussian beams with spot sizes of $\sim 30\text{--}120 \mu m$ because of their high focusability and stable, well-defined profiles. However, their strongly center-peaked irradiance distribution concentrates energy near the spot center and

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reduces irradiance toward the periphery. The resulting steep spatial gradient promotes strong thermal gradients and directional melt-pool flow, increasing sensitivity to parameter fluctuations [3,4]. Insufficient energy input promotes lack-of-fusion (LoF), whereas excessive peak intensity can trigger keyholing, vaporization, spatter, and balling [5,6]. These instabilities constrain the usable processing window, especially at high scan speeds or large hatch spacing, where overlap and remelting become difficult to maintain [7,8]. Overall, process stability is primarily controlled not only by total energy input, but also by how energy is distributed within the melt pool. This has motivated growing interest in beam-profile engineering to redistribute irradiance, stabilize melt-pool dynamics, and expand the processing window beyond conventional Gaussian beams [5,9].

Laser beam shaping has therefore emerged as a promising strategy to improve melt-pool stability in PBF-LB/M. A range of non-Gaussian profiles (e.g., annular/ring, elliptical, and flat-top) has been investigated, including implementations based on Mode-selectable multi-Mode fiber architectures that redistribute power between concentric Modes [10,11]. Compared with Gaussian beams, these profiles can reduce peak intensity, modify thermal gradients, widen melt pools, and improve track uniformity. Numerical studies in AlSi10Mg [12], Ti-6Al-4V [13], and AISI 316 L [14] suggest that ring-type beams can redistribute heat, often lowering peak temperatures and modifying thermal gradients compared with Gaussian beams, depending on the parameter set. Sinha et al. [15] showed that tailored irradiance can regulate melt-pool dimensions, cooling rates, and solidification in AlSi10Mg, while experiments indicate that beam-profile effects depend strongly on the selected energy conditions [16,17]. Bauch et al. [10,18] reported reduced surface defects and porosity, and improved stability in copper using ring-type beams, while Pérez-Ruiz et al. [19] correlated beam shape and scan speed to transitions between LoF and keyhole porosity in IN718. Because porosity acts as a stress concentrator and degrades tensile and fatigue performance [20,21], conventional parameter optimization has been widely used to suppress defects [22,23]. Beyond densification, shaped beams can also influence microstructure by modifying melt-pool geometry and the local thermal field. Beam-shape effects on melt-pool behaviour, thermal response, and microstructure have been reported, together with related comparison metrics [9,24–26], but their link with hatch-spacing-dependent densification, microstructure and hardness remains less explored for Ti-6Al-4V. Cazzolano et al. [27] reported that increasing ring contribution in IN718 produced shallower, wider melt pools and promoted vertically aligned dendritic growth while maintaining comparable density and hardness. Esmailzadeh et al. [28] tailored irradiance in Ti-6Al-4V using a spatial light modulator and showed that reduced cooling rates promoted β to $\alpha + \beta$ transformation rather than α' martensite, indicating a direct beam-shape influence on phase kinetics.

Despite growing interest, the coupling between irradiance distribution, hatch spacing (track overlap), and energy input remains insufficiently understood, particularly from an integrated experimental–numerical perspective [12,29]. This coupling is critical because beam shape changes melt-pool width and penetration depth, so the same nominal energy input can produce different inter-track remelting, defect states, and microstructures [9,30]. Most studies compare Gaussian and ring-type beams mainly via outcomes (e.g., porosity, melt-pool shape) [10,31], whereas fewer quantify these effects using geometric overlap metrics directly linked to track-to-track bonding [32]. While volumetric energy density and other absolute metrics are widely used, they do not explicitly capture differences in effective spot size, irradiance spread, or melt-pool geometry, limiting interpretability when comparing beam profiles under nominally identical settings [33,34]. Normalized descriptors such as the areal energy density $AED_h = P/(v h)$ (J/mm^2) [35,36], the normalized hatch spacing h/d (with d the effective beam diameter), and the overlap ratio W/h (with W the melt-pool width) provide a more physical description because they link energy input to melt-pool geometry and inter-track

remelting [37,38]. However, systematic experimental studies using these descriptors remain scarce. This gap is particularly evident for Ti-6Al-4V, where shaped-beam studies remain limited [28,29], and these rarely isolate the combined influence of hatch spacing and energy input under energy-normalized conditions.

Unlike conventional PBF-LB/M parameter-optimisation studies, which mainly identify suitable combinations of laser power, scan speed, and hatch spacing for a fixed beam profile, the present work examines how the spatial distribution of laser energy changes the interpretation of these parameters. The central contribution of this study is therefore the development of a beam-shape-dependent process-design framework for Ti-6Al-4V, in which AED_h , normalized hatch spacing h/d , and melt-pool overlap ratio W/h are used together to compare different irradiance profiles on a geometry-aware basis. To the best of the authors' knowledge, this combination of single-track experiments, cube densification mapping, microstructural characterisation, and validated 3D multiphysics simulation has not been systematically applied to ring-type beam profiles in Ti-6Al-4V PBF-LB/M. This enables dense-processing limits to be interpreted in terms of beam size, melt-pool geometry, inter-track remelting, and LoF susceptibility, rather than by energy input alone.

Specifically, this study investigates how ring-type beam profiles, ranging from relatively core-weighted to strongly ring-dominated, respond to variations in hatch spacing and energy input during Ti-6Al-4V PBF-LB/M. Single-track experiments quantify melt-pool geometry and stability transitions from fragmentation/necking to stable tracks with increasing energy input, while cube specimens map relative density as a function of AED_h and hatch-related ratios. Microstructural characterization and microhardness measurements assess the corresponding material response across beam profiles and energy levels, clarifying how beam profile and hatch spacing jointly influence densification. A validated 3D transient multiphysics model simulates melt-pool evolution and track-to-track interactions. Extracted thermal fields, solidification parameters (G , R), and overlap geometries provide mechanistic links between irradiance profile, densification limits, and microstructural characteristics.

2. Materials and Methods

2.1. Materials

The experiments in this work are conducted using gas-atomized Ti-6Al-4V Grade 5 powder supplied by Höganäs Germany GmbH (Goslar, Germany). The powder was delivered with a nominal particle size range of 15–53 μm .

2.2. PBF-LB/M system and beam intensity distributions

Experiments are conducted on an EOS M290 (EOS GmbH, Krailling, Germany; $250 \times 250 \times 325$ mm³ build volume) equipped with an nLIGHT AFX programmable fiber laser (nLIGHT, Inc., Camas, WA, USA). The AFX unit replaces the standard ytterbium fiber laser and provides Mode-selectable irradiance distributions (Modes 0–6), enabling active control of the radial intensity profile. The beam Mode can be selected through the laser control software and does not require mechanical adjustment of the optical components. In the present experiments, however, dynamic Mode switching within an individual scan track or during the exposure of a given specimen was not used. Instead, each specimen/parameter condition was fabricated using one selected beam Mode (Mode 4, 5, or 6) to isolate the influence of the beam profile. Each AFX beam Mode is defined by a prescribed power partition between the central core and surrounding ring (edge), allowing systematic evaluation of melt-pool response to different radial irradiance distributions. During parameter selection, the Mode-dependent maximum available laser power is considered, and conditions are chosen as close as practical to the maximum optical output. Across Modes 0–6, the maximum

available power varies approximately from 367 W (Mode 0) to 981 W (Mode 6). In this work, three AFX beam modes (Modes 4–6) were selected to focus on ring-type irradiance distributions, ranging from relatively core-weighted to strongly ring-dominated profiles, where hatch-spacing/overlap effects are expected to be most pronounced. Modes 0–3, representing more core-weighted or near-Gaussian distributions, were not included because they have been addressed in prior mode-screening studies [29,34]. The present work extends the analysis by systematically incorporating hatch spacing and energy-normalized overlap descriptors and therefore concentrates on the ring-type regime while keeping the experimental matrix tractable.

Laser beam profile measurements were performed at a laser power of up to 200 W using a CCD camera (SP928, Ophir Spiricon Europe GmbH, Germany). To protect the sensor, the beam was attenuated using an LBS-300 beam splitter, directing approximately 0.01% of the incident radiation to the CCD, followed by two neutral density filters providing a total attenuation of ND4 (Ophir Spiricon Europe GmbH, Germany). The resulting beam intensity distributions were extracted along the major beam axis and normalized with respect to the maximum measured intensity $I_{\max}$, such that the plotted relative intensity corresponds to $I/I_{\max}$. The normalized radial intensity profiles of the beam-shaping Modes investigated are presented in Fig. 1. The corresponding beam diameters, D , calculated using the method described in a previous study [10], are listed in Table 1.

2.3. Design of experiments

To evaluate beam-profile effects on single-track stability, melt-pool geometry, and cube densification under comparable energy input, three beam profiles (Modes 4–6) were studied in both single-track experiments and subsequent cube builds. A systematic matrix of laser power (600 and 700 W), scan speed (900–1500 mm/s), and hatch spacing was selected to span representative low- to high-energy regimes for each mode. For single tracks, 139 scans were produced using the same power-speed matrix across modes, and the resulting melt-pool geometry was used to interpret overlap-dependent behavior in the cube study. Cube specimens were fabricated to map relative density as a function of areal energy density $AED_h = P/(v h) (J/mm^2)$ and overlap ratios h/d and W/h , where h is hatch spacing, d the effective beam diameter, and W the melt-pool width. Hatch spacing was varied from ~ 100 to $220 \mu m$ based on the achievable melt-pool width for each mode to ensure comparable overlap conditions. The selected cube conditions

were subsequently used to assess microstructural development and microhardness trends across modes and energy/overlap regimes.

To quantify energy input and enable fair comparison across beam modes, two metrics were used. LED is used to index single-track experiments because hatch spacing is not defined for a single scan line; differences in effective beam footprint between modes are therefore evaluated through the measured melt-pool dimensions and subsequent overlap descriptors. The linear energy density (LED) is defined as:

$$LED = \frac{P}{v} [J/mm] \quad (1)$$

where P is the laser power (W) and v is the scan speed (mm/s).

Because density and melt-pool overlap are strongly influenced by the energy delivered per unit area, the AED_h based on hatch spacing was also evaluated:

$$AED_h = \frac{P/v}{h} [J/mm^2] \quad (2)$$

Where P/v is the linear energy density (J/mm) and h is the hatch spacing (mm). Dividing by h converts line energy to an areal energy input (J/mm^2) because a scan length of 1 mm nominally covers an area of $h \times 1 mm^2$. Accordingly, cube densification is indexed using AED_h together with h/d and W/h , since these descriptors capture hatch-controlled overlap, inter-track remelting, and LoF sensitivity.

The final process matrix (summarized in Table 2) includes all tested combinations for Modes 4, 5, and 6, covering a consistent LED range of 0.44–1.17 J/mm and an AED_h range of 2.10–4.55 J/mm^2 , enabling analysis of densification mechanisms, hatch-spacing effects, and overlap-dependent stability. All other parameters, including layer thickness, shielding gas, and build environment, were kept constant to isolate the influence of beam shape and energy input.

2.4. Specimen preparation and characterization methods

After fabrication, specimens were characterized to quantify the resulting density, microstructure, and microhardness. Single-track specimens were characterized first. Top-surface images were acquired using a Keyence VHX-5000 (KEYENCE Corporation, Osaka, Japan) at $50 \times$ magnification to classify track stability into fragmentation, necking, and stable regimes. Representative tracks spanning the investigated energy range were then sectioned perpendicular to the scan direction to reveal melt-pool cross-sections, from which melt-pool width, depth, molten cross-sectional area, and heat-affected-zone (HAZ) depth were quantified. Cube samples were then prepared by cutting at mid-height in a plane perpendicular to the build direction using a Discotom 6 machine, followed by cold mounting in epoxy resin using a ClaroCit kit (Struers GmbH, Willich, Germany). The embedded samples were ground and polished using a Tegramin-30 (Struers GmbH), with grinding performed using SiC papers from 80 to 2000 grit and polishing carried out using DIADUO-2 suspensions (9, 3, and $1 \mu m$) as well as OP-S and OP-U suspensions to obtain a mirror finish for porosity visualization. Surface features and microstructural contrasts were developed by etching the polished samples in Kroll's solution (5 vol% HNO_3 , 2 vol% HF) for 10–12 s, followed by neutralization in a $CaCl_2$ bath and ultrasonic cleaning in acetone. Optical microscopy and 3D laser scanning confocal microscopy (VK-X160K, Keyence Corporation, Osaka, Japan) were used for visualization and high-resolution, non-contact surface and morphological analysis. Microstructural characterization was performed using a ZEISS scanning electron microscope (SEM) under backscattered electron imaging (BSD1) at 15 kV accelerating voltage and a working distance of approximately 8.6 mm. Vickers microhardness (HV0.2) was measured using a Qness microhardness tester (Qness GmbH, Golling an der Salzach, Austria), with 25 indents recorded per specimen along the build direction and averaged to obtain the final hardness values.

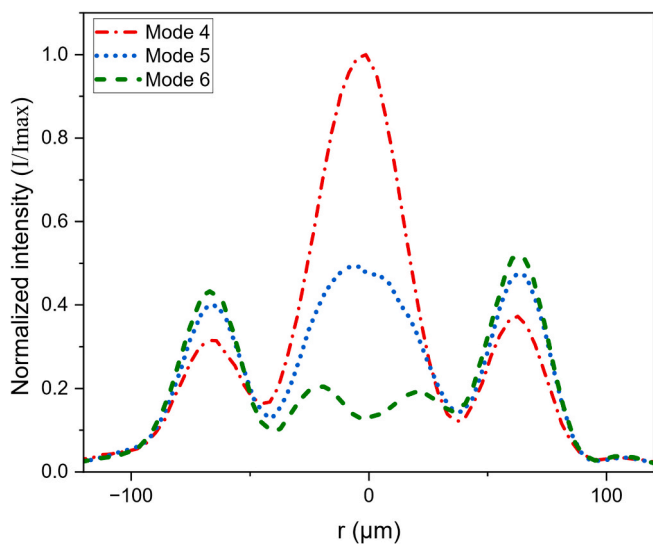


Fig. 1. Radial beam-intensity profiles for the three investigated beam Modes, shown as relative irradiance $I/I_{\max}$ as a function of radial distance r .

Table 1
AFX beam profiles (Modes 4–6).

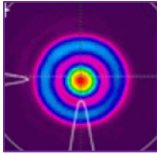
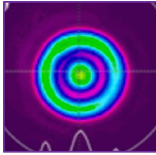
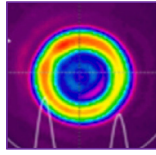
2D Beam Profile	Mode 4	Mode 5	Mode 6
			
Power ratio (Ring/Core)	72/28	82/18	89/11
Beam Diameter (μm) ($D_{0.1, \text{eq}}$)	163.4	178.6	177.6

Table 2
General processing parameters used in this study.

Parameter	Values
Machine	EOS M290 with nLIGHT AFX laser-1000
Beam Modes	4, 5, 6
Laser power (W)	600, 700
Scan speed (mm/s)	900–1500 (Mode-dependent combinations)
LED range (J/mm)	0.44–1.17
Hatch spacing (μm)	102–222 (Mode-specific combinations; selected based on melt-pool overlap)
AED _h range (J/mm ²)	2.10–4.55
Layer thickness (μm)	60
Build environment	Ar, O ₂ < 0.1%

2.5. Numerical modeling

A three-dimensional transient multiphysics model coupling heat transfer and fluid flow was developed to investigate the influence of different laser beam intensity distributions on melt-pool evolution and track overlap. The simulations were performed using the finite element method (FEM) in COMSOL Multiphysics® (COMSOL AB, Stockholm, Sweden) version 6.3. The computational domain consisted of a 60 μm thick powder layer on a solid Ti-6Al-4V substrate, discretized using a mesh with a maximum element size of 20 μm in the melt-pool region to resolve steep thermal gradients (see Fig. 2(a)). To accurately represent the experimental beam shapes, the laser heat input was not modeled as a standard Gaussian source but was calibrated using an exponentially decaying volumetric heat source that accounts for the specific power partition between the core and ring. The source term, Q_{laser} , is defined as a superposition of two Gaussian distributions:

$$Q_{\text{laser}} = \left[\frac{\beta \eta P}{\pi \delta r_c^2} \exp\left(-\frac{(x^2 + y^2)^2}{r_c^2}\right) + \frac{(1 - \beta) \eta P}{4\pi \delta R r_r} \exp\left(-\frac{((x^2 + y^2) - R_r)^2}{r_r^2}\right) \right] \exp\left(-\frac{|z|}{\delta}\right) \quad (3)$$

Here, η is the absorption coefficient used to calibrate the model, β represents the intensity split between the central Gaussian and the outer ring, P is the laser power, x and y are the coordinates of the beam center, r_c is the core Gaussian radius, r_r is the ring Gaussian distribution radius, R_r is the ring radius, $|z|$ is the absolute value of the z -coordinate, and δ is the laser optical penetration depth. The optical penetration depth represents an effective parameter accounting for multiple scattering and absorption within the powder bed rather than the true optical

penetration depth of solid Ti-6Al-4V. Fig. 2(b) shows the normalized laser beam intensity profiles for Mode 4, Mode 5, and Mode 6 in three dimensions using Eq. (3).

The model solves the conservation equations for mass, momentum (Navier-Stokes), and energy, incorporating temperature-dependent thermophysical properties for Ti-6Al-4V. Fluid flow within the melt pool is driven by buoyancy, solidification drag (Carman-Kozeny), and Marangoni convection, modeled via a temperature-dependent surface tension coefficient $\frac{d\gamma}{dT}$. Heat losses due to radiation, convection, and evaporation are applied at the boundaries, with recoil pressure effects approximated through an evaporative heat loss term (see [Supplementary Material for details](#)).

The numerical model was validated by comparing predicted melt-pool dimensions with experimental cross-sections (Fig. 3). The simulations reproduced the mode-dependent trends in melt-pool geometry, with Mode 4 exhibiting deeper pools (higher D/W) and Mode 6 showing shallower pools at comparable widths. The mean absolute error was 2.1% for melt-pool width and 3.7% for depth, supporting the model fidelity for analyzing beam-shape effects.

The protruding feature observed above the original surface in some experimental cross-sections corresponds to the solidified track crown/bead formed by melt redistribution and free-surface deformation during solidification. The present model does not resolve free-surface deformation above the powder layer and therefore does not capture this track crown protrusion. Instead, the model was calibrated and validated against subsurface melt-pool dimensions, namely width and depth, which are the relevant quantities for inter-track remelting and densification analysis. Simulating track crown morphology and surface roughness would require a dedicated free-surface tracking scheme, such as a volume-of-fluid or level-set method, and is therefore identified as a future model extension.

3. Results and Discussion

3.1. Single tracks analysis

This section systematically investigates the influence of spatial energy redistribution on melt-pool formation using single tracks produced with Mode 4, Mode 5, and Mode 6 beam profiles over a linear energy range of 0.35–1.2 J/mm. Fig. 4 shows representative top-view morphologies together with corresponding cross-sectional melt-pool shapes,

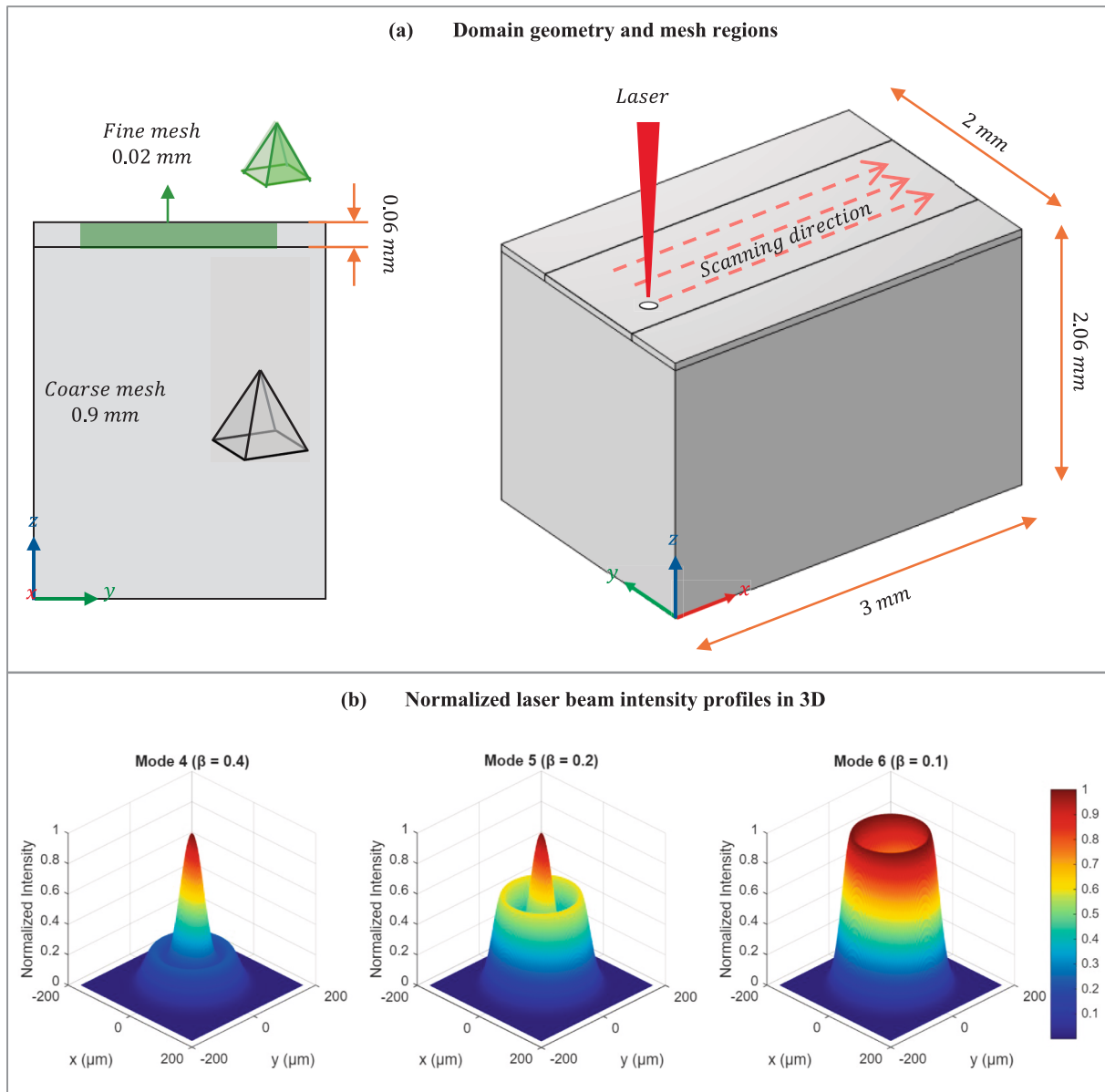


Fig. 2. (a) Domain geometry and mesh regions. The simulation domain comprises a powder layer and a substrate, with a refined mesh for the region of interest and a coarser mesh elsewhere. The fine mesh region is highlighted with green. (b) Normalized laser irradiance distributions used in the analytical heat-source model for Modes 4–6.

revealing three characteristic stability regimes: (i) an unstable fragmentation regime marked by periodic beads and track break-up with under-melted or balling-type cross sections, (ii) a transitional necking regime characterized by continuous but locally constricted tracks, and (iii) a stable conduction regime exhibiting smooth, continuous tracks and regular melt-pool geometry. These regimes reflect the competition between melt volume, wetting/anchoring, and capillary stability: at low energy input, insufficient melting and incomplete wetting promote discontinuity (LoF tendency), whereas increasing energy improves wetting and stabilizes continuous tracks; the transitional regime is consistent with capillary (Plateau–Rayleigh-type) necking preceding stabilization or breakup. Similar melt-track classifications and interpretations have been reported in single-track literature [29,39].

Following the regime classification in Fig. 4 (fragmentation, necking, and stable), Fig. 5 compares representative single-track cross sections produced with Mode 4, Mode 5, and Mode 6 while systematically increasing the linear energy density, LED (0.46–1.17 J/mm). For all three Modes, increasing energy input enlarges the molten region,

reflected by progressive increases in melt-pool width and depth. However, the melt-pool shape evolves differently between beam Modes: Mode 4 tends to produce deeper pools (higher D/W), whereas Mode 6 produces wider and flatter pools, with Mode 5 showing intermediate behavior. Although the comparison is performed at the same nominal linear energy density for each level, LED equalizes only the energy delivered per unit scan length and does not account for differences in effective beam footprint and intensity distribution between Modes. Therefore, the consistent geometric ordering observed at each energy level reflects differences in spatial energy delivery (i.e., redistribution of the same nominal energy over different beam profiles/areas), rather than differences in the LED itself, providing the geometric basis for the stability trends identified in Fig. 4. In addition, several conditions exhibit a rounded and locally constricted melt-pool profile with reduced lateral anchoring, consistent with a balling-prone morphology linked to capillary-driven necking rather than any keyhole-type behavior. Excessive melt-track convexity or crown height is generally undesirable because it can increase surface roughness and disturb powder spreading

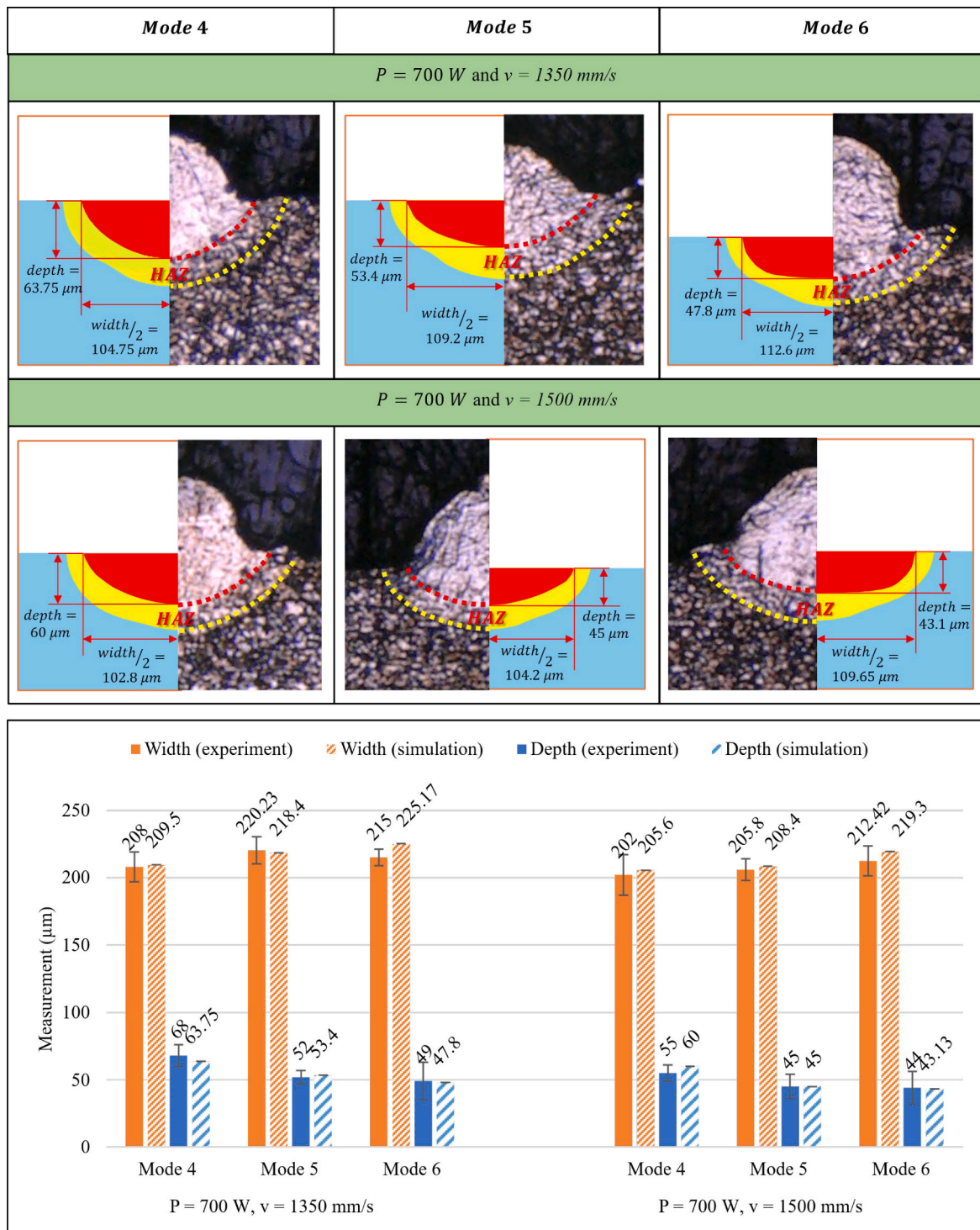


Fig. 3. Comparison between experimentally measured and numerically predicted melt pool geometry for different beam Modes (Mode 4, Mode 5, and Mode 6) at a laser power of 700 W and scan speeds of 1350 mm/s and 1500 mm/s. The cross-sectional optical micrographs show the experimentally measured melt pool profiles, overlaid with the corresponding numerically predicted melt pool boundaries. The bar chart summarizes the quantitative comparison of melt pool width and depth obtained from experiments and simulations, demonstrating good agreement across all beam Modes and processing conditions.

in subsequent layers. Within the present parameter space, this can be controlled by maintaining a stable conduction-mode melt pool with sufficient wetting and lateral anchoring. This requires avoiding low-energy necking/balling conditions, selecting an appropriate energy input and scan speed, and maintaining sufficient inter-track overlap through hatch-spacing control. Beam-profile selection also contributes to convexity control by balancing penetration and lateral spreading:

core-weighted profiles enhance anchoring, whereas ring-dominated profiles promote wider/flatter melt pools but require sufficient energy and overlap to avoid shallow remelting and LoF. Similar instability mechanisms, including reduced wetting, capillary-driven necking/balling, and beam-shape-dependent melt-pool spreading, were also discussed in our previous single-track study on beam-shaped PBF-LB/M Ti-6Al-4V [29].

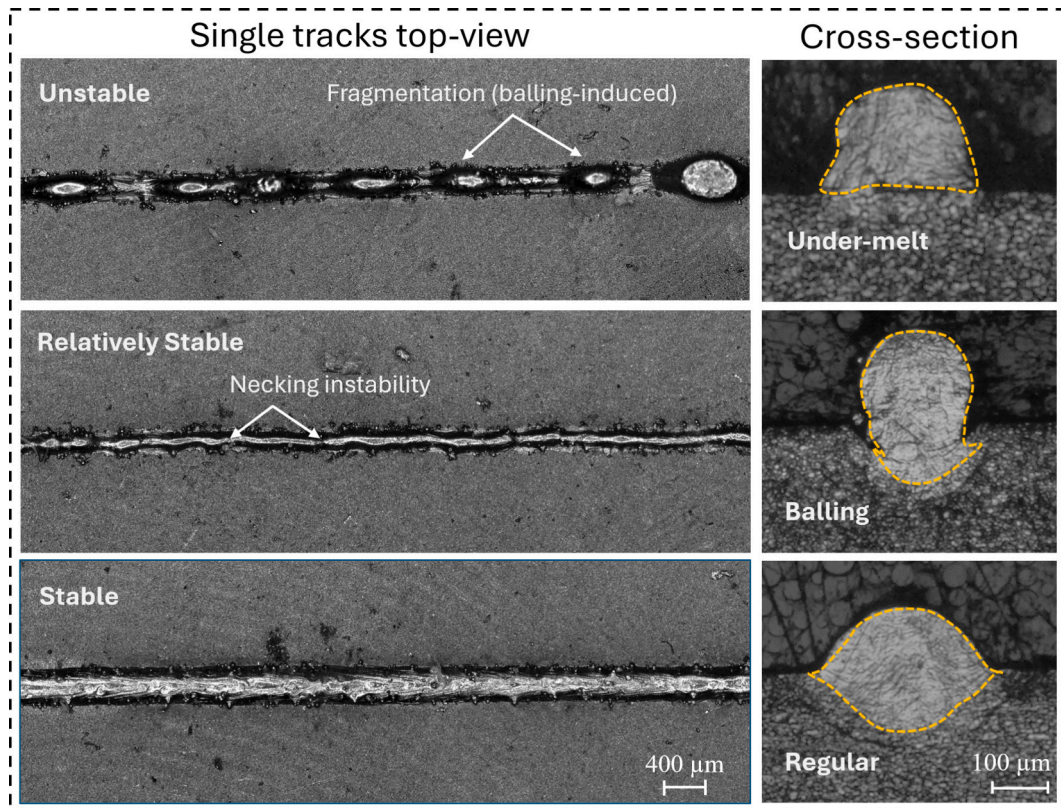


Fig. 4. Representative single-track top-view morphologies and corresponding cross-sections showing stability regimes (fragmentation, necking, stable conduction). Images are shown for illustration of the classification only.

Continuous tracks are achieved at different energy thresholds for the three Modes: Mode 4 becomes stable at ≥ 0.58 J/mm, whereas Mode 5 and Mode 6 require ≥ 0.80 J/mm to form regular tracks. Across the examined conditions, the heat-affected zone (HAZ) can be clearly distinguished from the molten pool in the cross sections and shows a similar extent for all beam Modes. Its depth remains approximately 34–38 μm , with no obvious or systematic variation attributable to beam Mode. This is expected in conduction-Mode PBF-LB/M because the sub-solidus thermal field is primarily governed by heat diffusion in the solid (set mainly by the material's thermal diffusivity and interaction time), so beam-profile differences are largely smoothed out away from the melt pool. At higher inputs (>0.9 J/mm), the melt pools become noticeably larger and deeper, suggesting increased remelting and a higher likelihood of continuous bonding; however, no clear keyhole features were identified for any of the investigated beam Modes within the studied range. To quantify these beam-shape-dependent trends over the full parameter set, Fig. 6 summarizes the evolution of melt-pool width, depth, aspect ratio (D/W), and molten cross-sectional area as a function of LED for Modes 4–6. The observed trends highlight that melt-pool width increases nonlinearly with energy input, whereas depth increases more steeply at higher energies, leading to a systematic rise in D/W and molten area. These quantitative metrics provide a consistent basis to compare penetration versus spreading-dominated behavior among the three beam Modes.

3.2. Effect of beam profiles on the relative density of cubes

In PBF-LB/M, achieving high density depends not only on how much energy is supplied, but also on how well neighboring melt tracks overlap and bond [40,41]. This becomes particularly important for non-Gaussian beam profiles, which redistribute irradiance relative to the standard Gaussian. Accordingly, densification is evaluated using physically meaningful, geometry-aware metrics rather than conventional

volumetric energy density. AED_h is used to capture the combined influence of energy input and hatch spacing, density–hatch spacing curves quantify the hatch-driven melt-pool bonding behavior [42,43], the normalized spacing h/d reveals a universal overlap threshold relative to the optical beam width, and the geometric overlap ratio W/h describes the melt-pool interpenetration required to suppress LoF defects. Together, these descriptors provide a beam-profile-aware framework for comparing Modes 4–6 under energy-normalized conditions.

Fig. 7 presents representative cross-sectional micrographs illustrating how porosity evolves as the AED_h varies for the three beam Modes investigated. These micrographs provide an intuitive starting point for understanding the densification mechanism before moving into the quantitative analysis. At high $\text{AED}_h = 3.1\text{--}4.55$ J/mm², the investigated beam modes produce nearly pore-free structures with relative densities exceeding 99.95%, indicating that melt-pool penetration is sufficient and that adjacent scan tracks sufficiently remelt into one another. As AED_h is reduced, isolated pores begin to appear, reflecting the onset of insufficient overlap and reduced inter-track bonding. At the lowest energy levels, these isolated pores develop into characteristic LoF defects, typically elongated along the scan direction, an established indicator of inadequate melt-pool depth and weak fusion between neighboring tracks. The level of sensitivity to decreasing AED_h differs markedly across the three beam Modes. Mode 4, which exhibits a comparatively strong central intensity peak, maintains high density across the largest energy interval due to its deeper and more stable melt pool. Mode 5 shows earlier pore initiation, consistent with its moderately softened core intensity. Mode 6 (ring-dominated) deteriorates fastest because reduced central irradiance produces shallower melt pools that fall below the penetration threshold at higher energy levels. This interpretation is consistent with the single-track observations (Figs. 4–6) and is schematically demonstrated in Fig. 8, which contrasts penetration-dominated versus lateral-spreading melt pools arising from the different irradiance redistributions. The observed behavior is largely

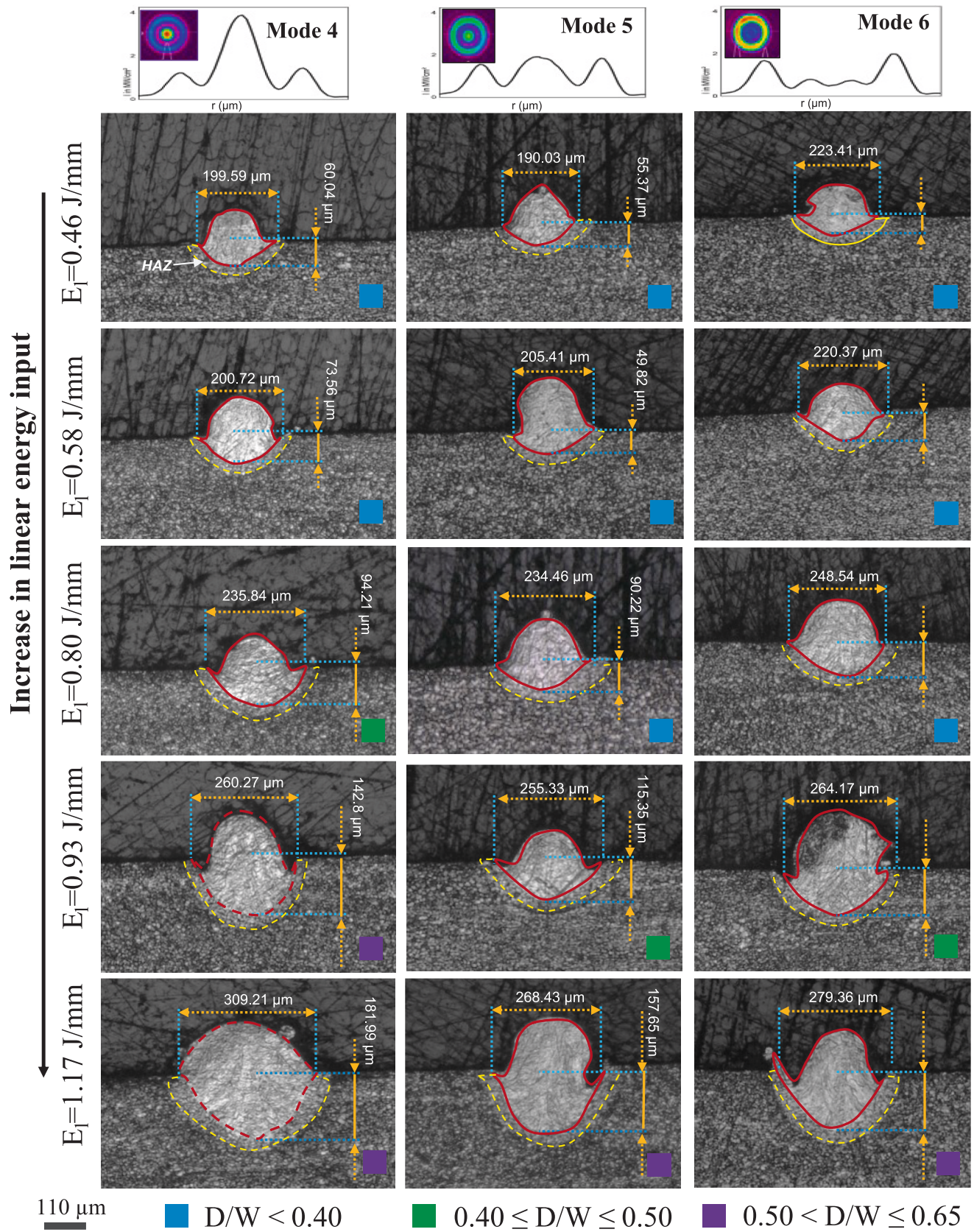


Fig. 5. Representative single-track cross-sections for Modes 4–6 at identical linear energy densities (0.46–1.17 J/mm), showing melt-pool geometry and aspect ratio D/W (depth/width) with increasing energy input.

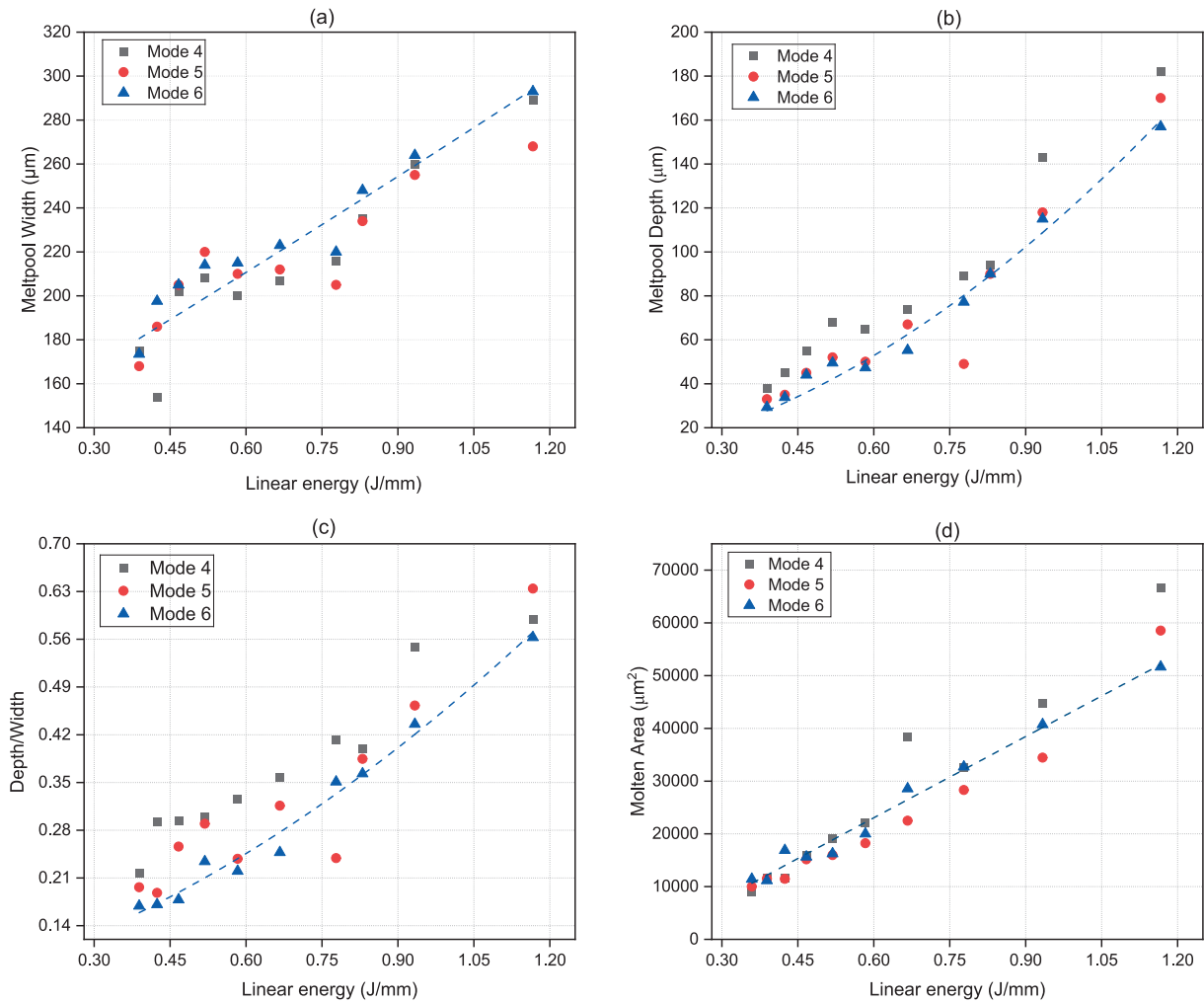


Fig. 6. Quantitative dependence of single-track melt-pool geometry as a function of LED for Modes 4–6: (a) melt-pool width, (b) melt-pool depth, (c) depth-to-width ratio (D/W), and (d) molten cross-sectional area. A fit is provided for Mode 6 only to serve as a reference guide and to avoid overfitting multiple trendlines across Modes.

consistent with the melt-pool physics reported in prior beam-shaping studies with different materials. Galbusera et al. [44] observed that profiles with diminished central irradiance exhibit reduced penetration and therefore require higher power to achieve comparable remelting. Pérez-Ruiz et al. [19] reported a material-dependent critical irradiance threshold, below which insufficient remelting causes newly deposited tracks to overlap only partially with the previous track, promoting lack-of-fusion. A similar low-energy/low-overlap transition is observed in the present Mode 6 conditions at low AED_h . Similarly, Bauch et al. and Wischeropp et al. [10,45] showed that ring-dominated or weak-core beam profiles can narrow the effective process window, particularly when hatch spacing or scan speed is increased, as both parameters exacerbate melt-pool shallowing and reduce overlap. Taken together, these micrographs visually reaffirm that densification is directed by how each beam Mode deposits energy into the melt pool. Beam profiles with a higher central intensity (Mode 4) form deeper and more tolerant melt pools, enabling high density over a wider range of hatch spacing and energy inputs. In contrast, ring-dominated profiles (Mode 6) inherently produce shallower melt pools and therefore require higher AED_h to prevent LoF defects. These qualitative observations align directly with the quantitative analysis that follows, where differences between the beam Modes become evident through the AED_h , h/d , and W/h relationship.

The results observed in Fig. 7 are quantitatively confirmed by the relationship between density and the areal energy input, as shown in

Fig. 9. Across all Modes, density increases steeply with AED_h in the low-energy region, demonstrating that LoF is the dominant defect mechanism when insufficient energy is delivered per unit area. A clear transition occurs at $\text{AED}_h \approx 2.8\text{--}3.0 \text{ J/mm}^2$, above which all Modes approach $\sim 99.9\%$ density and the curves plateau. Beyond this threshold, additional energy provides little further benefit because the melt pool is already sufficiently deep and wide to consistently remelt adjacent tracks. At this point, both melt-pool depth and lateral width surpass the minimum overlap needed for full fusion, leading to a stable plateau in densification. Beam-shape-dependent differences are most pronounced in the low- AED_h regime: Mode 4 reaches a given density at the smallest AED_h , followed by Mode 5, while Mode 6 consistently requires the highest AED_h to suppress LoF defects. This ordering reflects the relative energy concentration of the beam profiles. Profiles with relatively stronger central intensity (e.g., here Mode 4) generate higher local peak temperatures and more robust track remelting, while ring-dominated profiles (Mode 6) distribute energy more broadly and thus require higher total energy to achieve comparable densification. At sufficiently high AED_h , the energy input becomes sufficient to stabilize melt-pool formation and track overlap for all beam Modes, so differences in beam shape have a reduced impact, and the densification responses converge. Together, the cross-sectional micrographs and AED_h curves establish a clear and consistent picture: densification in PBF-LB/M of Ti-6Al-4V is controlled primarily by the balance between melt-pool geometry and inter-track overlap, and beam shape influences this balance

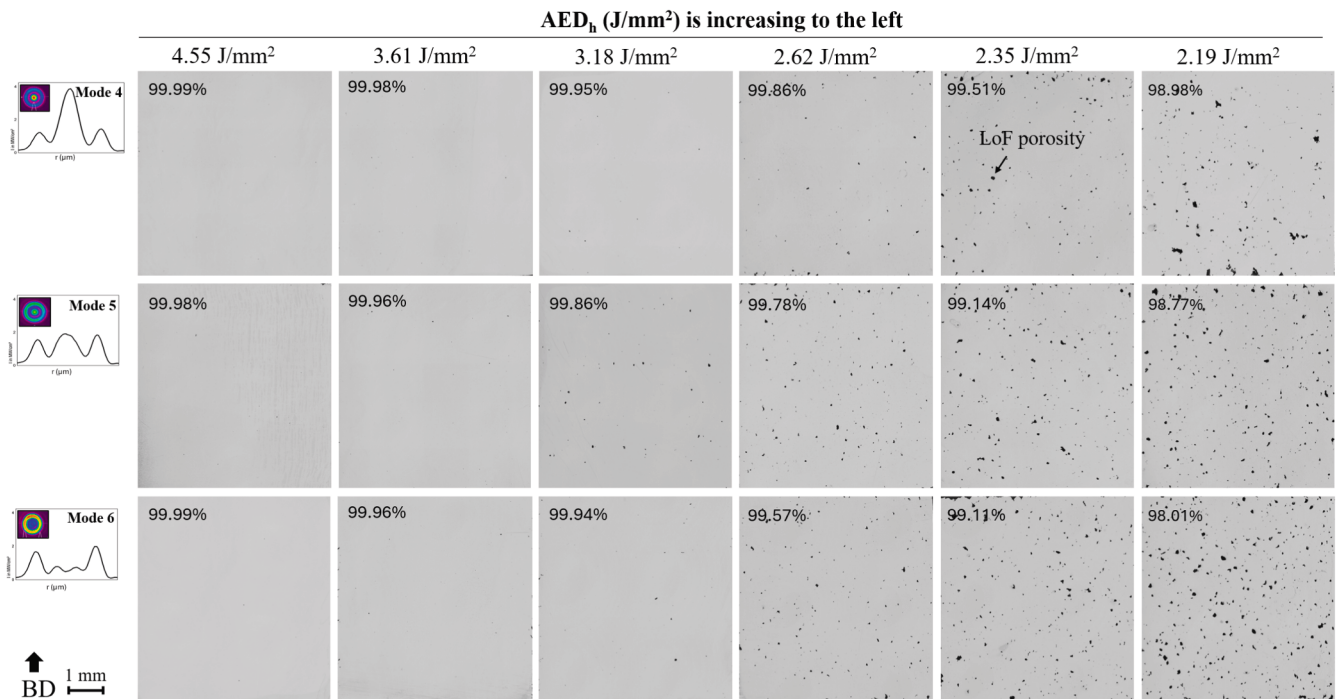


Fig. 7. Optical micrographs illustrate how porosity evolves with increasing hatch spacing for Modes 4, 5, and 6. High densities (>99.95%) are obtained at small hatch values, while larger spacings lead to isolated pores and finally LoF defects.

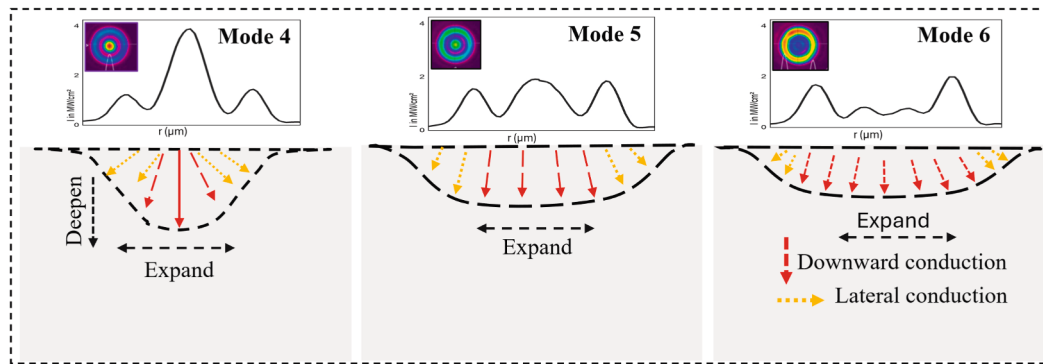


Fig. 8. Schematic comparison of the three beam Modes showing how their irradiance profiles shape the melt pool. Mode 4's relatively strong central peak drives deeper melt pools, Mode 5 produces moderately deep pools with balanced energy spread, and Mode 6's ring-dominated profile leads to shallower pools with stronger lateral heat flow. These differences explain their distinct overlap requirements and densification behavior observed in this study.

mainly at low energy input. The subsequent analysis builds on this foundation by examining the role of hatch spacing, normalized hatch spacing (h/d), and geometric overlap ratio (W/h) to further elucidate how beam profile and energy distribution shape the process window for stable, fully dense manufacturing.

Fig. 10 quantifies the evolution of relative density with increasing hatch spacing for the three beam Modes at different LEDs. At small hatch spacings, all Modes maintain high density because adjacent tracks still share a common thermal field, allowing sufficient lateral remelting and consolidation. As the spacing grows, however, the lateral melt-pool overlap is progressively eroded, and density begins to fall once the inter-track overlap region becomes insufficient to remelt the boundary between neighboring tracks, producing shallow cusps and LoF [46]. The onset of densification loss varies across the beam Modes, as evidenced by the distinct trends observed for Modes 4, 5, and 6 in **Fig. 10(a–c)**, respectively. Mode 4 consistently offers a broad spacing tolerance, reflecting its wider thermal footprint and more persistent sidewall

remelting. Mode 5 behaves intermediately, while Mode 6 shows the earliest densification loss due to its more rapidly cooling periphery and reduced lateral melt-pool extent. Increasing LED shifts all curves toward larger spacing, indicating that additional energy enhances the thermal wake around each track, but the relative ranking of the beam profiles remains unchanged, showing that beam-shape-dependent melt-pool geometry rather than absolute power drives spacing sensitivity. These trends become clearer when the data are expressed in terms of normalized hatch spacing h/d (normalized by beam diameter), shown in **Fig. 10(d)**. A common threshold becomes evident across all three beam Modes such that, as long as the normalized hatch spacing remains below roughly $h/d \approx 1$, adjacent melt pools overlap sufficiently, and high density is maintained. Once h/d exceeds this limit, the density decreases sharply because the lateral melt-pool width is no longer large enough to bridge the spacing between tracks. Although this transition is universal, the allowable h/d varies slightly among the Modes. Mode 4 sustains full density at the largest normalized spacing, Mode 5 shows an intermediate

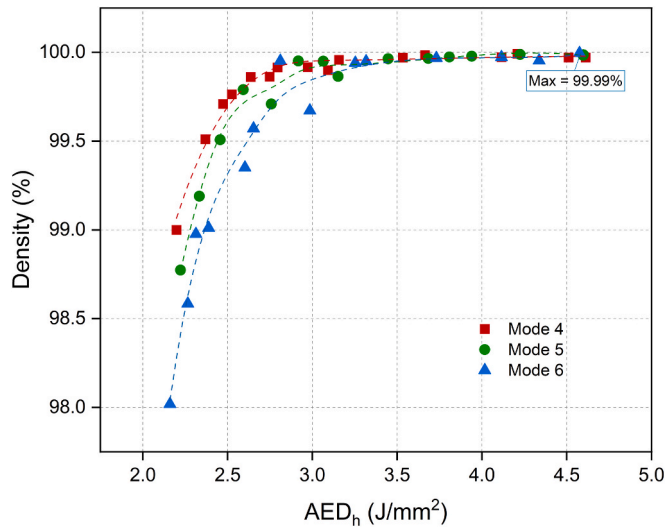


Fig. 9. Relative density as a function of areal energy input AED_h , for Modes 4, 5, and 6. Density increases rapidly at low AED_h due to suppression of LoF defects, with all Modes converging toward $\sim 99.9\%$ density above $\sim 2.8\text{--}3.0\text{ J/mm}^2$. Mode 4 reaches a given density at the lowest AED_h , followed by Mode 5 and Mode 6, reflecting the progressively broader lateral energy distribution of beam profiles.

tolerance, and Mode 6 exhibits the earliest decline, reflecting its shallower and more laterally distributed melt pool. These trends indicate that hatch-spacing tolerance depends not only on melt-pool depth but also on lateral thermal diffusion and sidewall remelting, both of which are strongly influenced by beam-shape-dependent irradiance distributions. Maintaining $h/d \lesssim 1$ therefore represents a practical guideline for stable, fully dense processing under energy-normalized conditions.

Before discussing the experimental melt-pool width-to-hatch-spacing (W/h) trends (Fig. 12), a schematic (Fig. 11) is provided to clarify how melt-pool geometry primarily influences track-to-track bonding. The schematic illustrates adequate, marginal, and insufficient track interaction for relatively core-weighted and strongly ring-dominated profiles and links these conditions to continuous bonding versus LoF gaps. Hatch spacing sets the center-to-center track spacing, whereas W/h expresses bonding (overlap) potential by comparing melt-pool width with hatch spacing [42,46,47]. The effectiveness of track bonding depends not only on W/h but also on melt-pool penetration at the inter-track boundary, which controls whether cusps/unfused regions persist. Relatively core-weighted profiles tend to provide greater remelting depth at the track boundary (more robust bonding) at a given W/h , whereas ring-dominated profiles can yield shallower penetration at the inter-track region, increasing susceptibility to LoF even at similar hatch spacing. With this geometric context, Fig. 12 quantitatively shows how density evolves as a function of the melt-pool width-to-hatch-spacing ratio W/h for the three beam Modes. $W/h = 1$ corresponds to tracks that only touch (0% overlap), $W/h > 1$ indicates positive overlap, and $W/h < 1$ represents a gap where LoF defects are

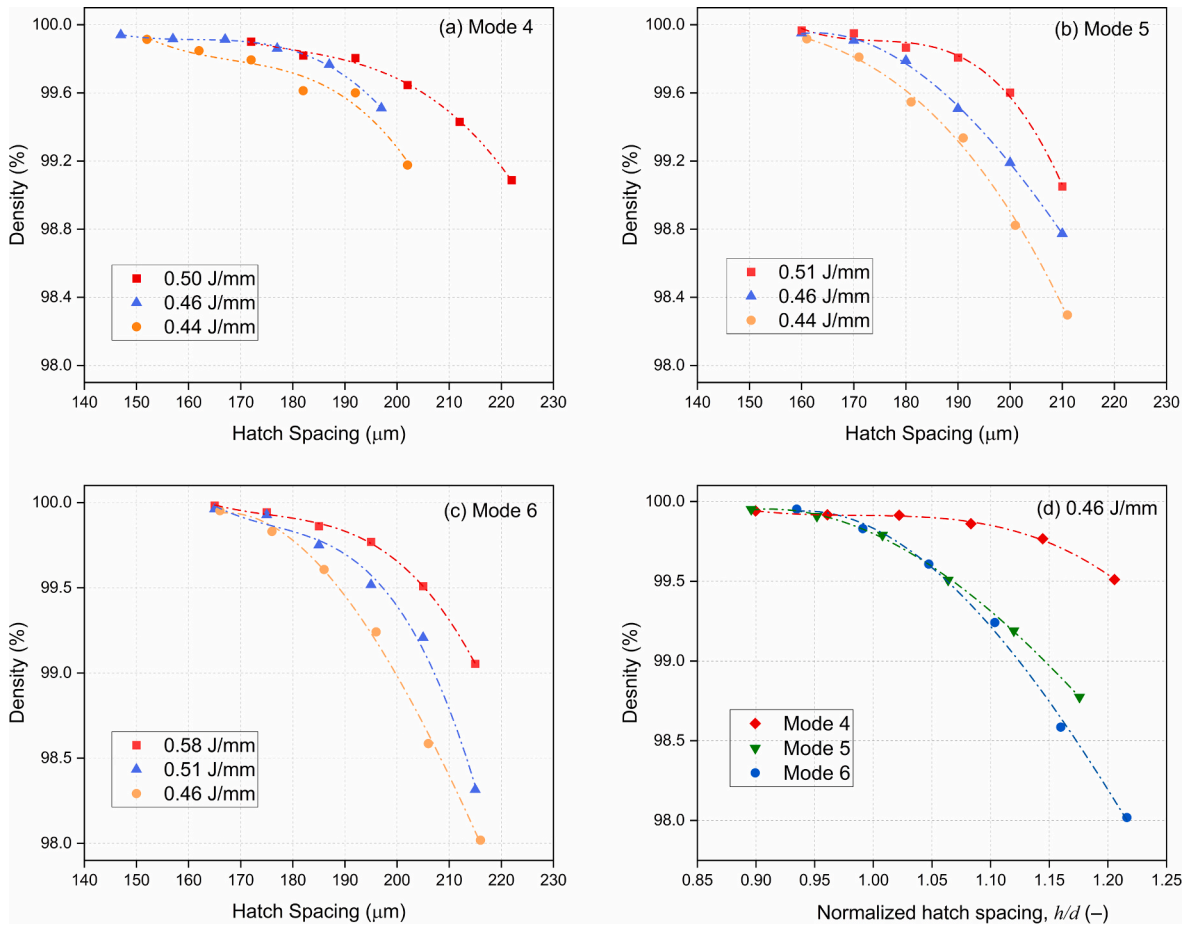


Fig. 10. Density as a function of hatch spacing for Modes 4, 5, and 6 at different linear energy densities. Density decreases as spacing increases, with Mode 4 tolerating the largest hatch values, Mode 5 showing moderate sensitivity, and Mode 6 losing density earliest. The normalized plot (hatch spacing/beam diameter, h/d) reveals a common threshold near $h/d \approx 1$, beyond which LoF porosity rapidly increases.

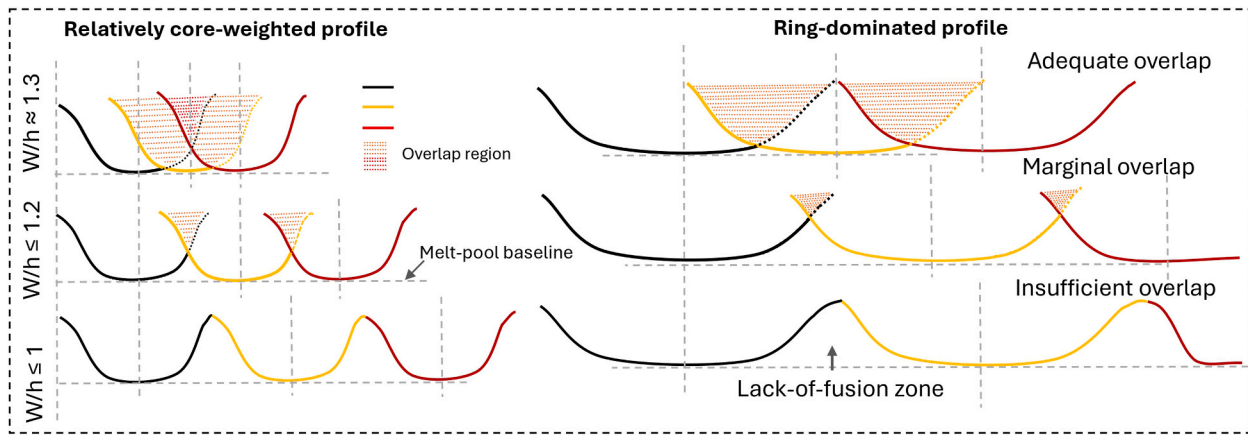


Fig. 11. Schematic comparison of melt-pool overlap for relatively core-weighted and ring-dominated beam profiles across three illustrative regimes. Shaded regions indicate effective inter-track bonding.

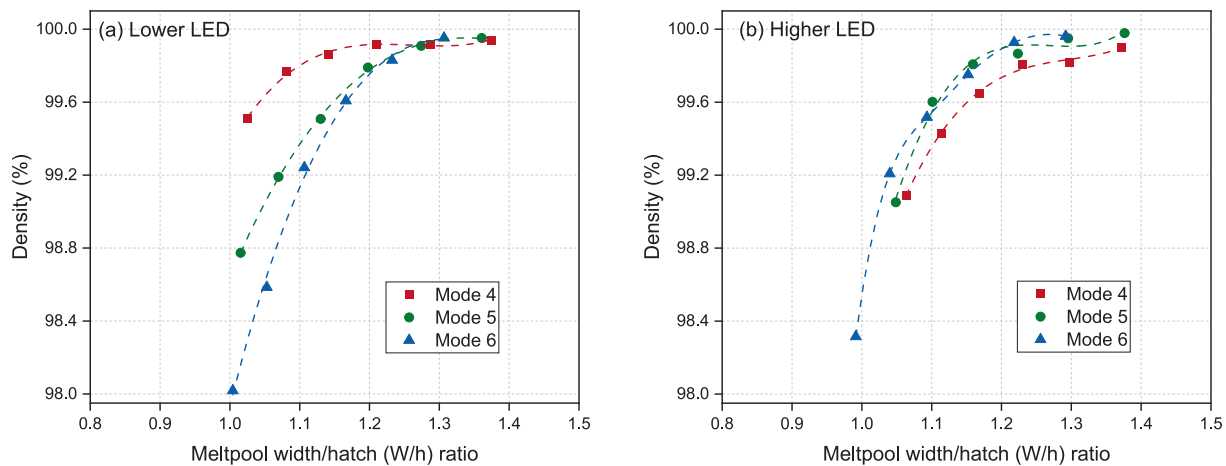


Fig. 12. Relative density versus melt-pool width-to-hatch-spacing ratio (W/h) for Modes 4–6 at low and high LED. Density rises as overlap increases and levels off around $W/h \approx 1.15$ – 1.25 . At low LED, Mode 4 reaches high density with the least overlap, while Mode 6 needs the most; at high LED, the Modes converge and achieve $\geq 99.9\%$ density in the same W/h range.

expected. Across all Modes, density increases systematically with increasing W/h . At low W/h ($\approx \leq 1.1$), all Modes exhibit reduced density due to insufficient inter-track remelting. A pronounced “knee” appears around $W/h \approx 1.15$ – 1.25 , beyond which density approaches a plateau and further W/h yields diminishing returns. The multiphysics simulations (Section 3.4.2) rationalize this transition by showing cusp formation and reduced inter-track remelting at low W/h . This geometric threshold is consistent with the porosity evolution observed in the micrographs and with the normalized hatch-spacing limit of $h/d \approx 1$ identified earlier.

The required W/h varies with both beam Mode and energy input. Under lower LED, the three Modes diverge in their tolerance to reduced overlap. Mode 4 reaches $\geq 99.7\%$ density at the lowest W/h (≈ 1.05 – 1.12), Mode 5 requires slightly higher W/h (≈ 1.12 – 1.18), and Mode 6 requires the highest W/h (≈ 1.18 – 1.25) to suppress LoF, consistent with reduced penetration robustness in ring-dominated profiles. These differences align well with the beam-dependent melt-pool width trends: centrally concentrated profiles generate deeper and more robustly penetrating tracks, whereas ring-shaped profiles produce shallower bonding interfaces, making them more sensitive to spacing variations. Although Mode 6 can produce wider pools, it also requires a higher W/h . Therefore, the allowable hatch spacing $h = W/(W/h)$ does not necessarily increase and depends on the measured W for each mode. At higher LED, all curves shift modestly to the left and their separation

reduces. With increased energy input (higher LED), all Modes reach $\geq 99.9\%$ density once $W/h \approx 1.15$ – 1.25 is achieved, and the curves nearly collapse onto each other. This convergence indicates that sufficiently high energy input can partially offset beam-profile differences by increasing melt-pool robustness and stabilizing inter-track bonding. Overall, the W/h analysis provides a practical geometry-based guideline for dense PBF-LB/M processing: maintaining $W/h \geq 1.20$ generally ensures stable densification across all beam Modes, whereas Mode 6 and/or low-energy conditions may require $W/h \approx 1.25$ – 1.30 to fully suppress LoF defects.

3.3. Microstructure

To complement the densification analysis, cross-sections were examined to assess how beam Mode and AED_h affect melt-pool morphology and α' lath/packet structure in PBF-LB/M Ti-6Al-4V. Optical and SEM images allow comparison of solidification features and refinement associated with mode-dependent melt-pool geometry and cooling conditions. Fig. 13 presents representative microstructural images for Modes 4–6 at four AED_h levels spanning LoF-prone to fully dense conditions. Although the overall appearance is similar, differences emerge in the apparent prior- β features. Differences in spacing and long-range continuity become apparent with changing beam Mode and AED_h , consistent with changes in melt-pool geometry and solidification

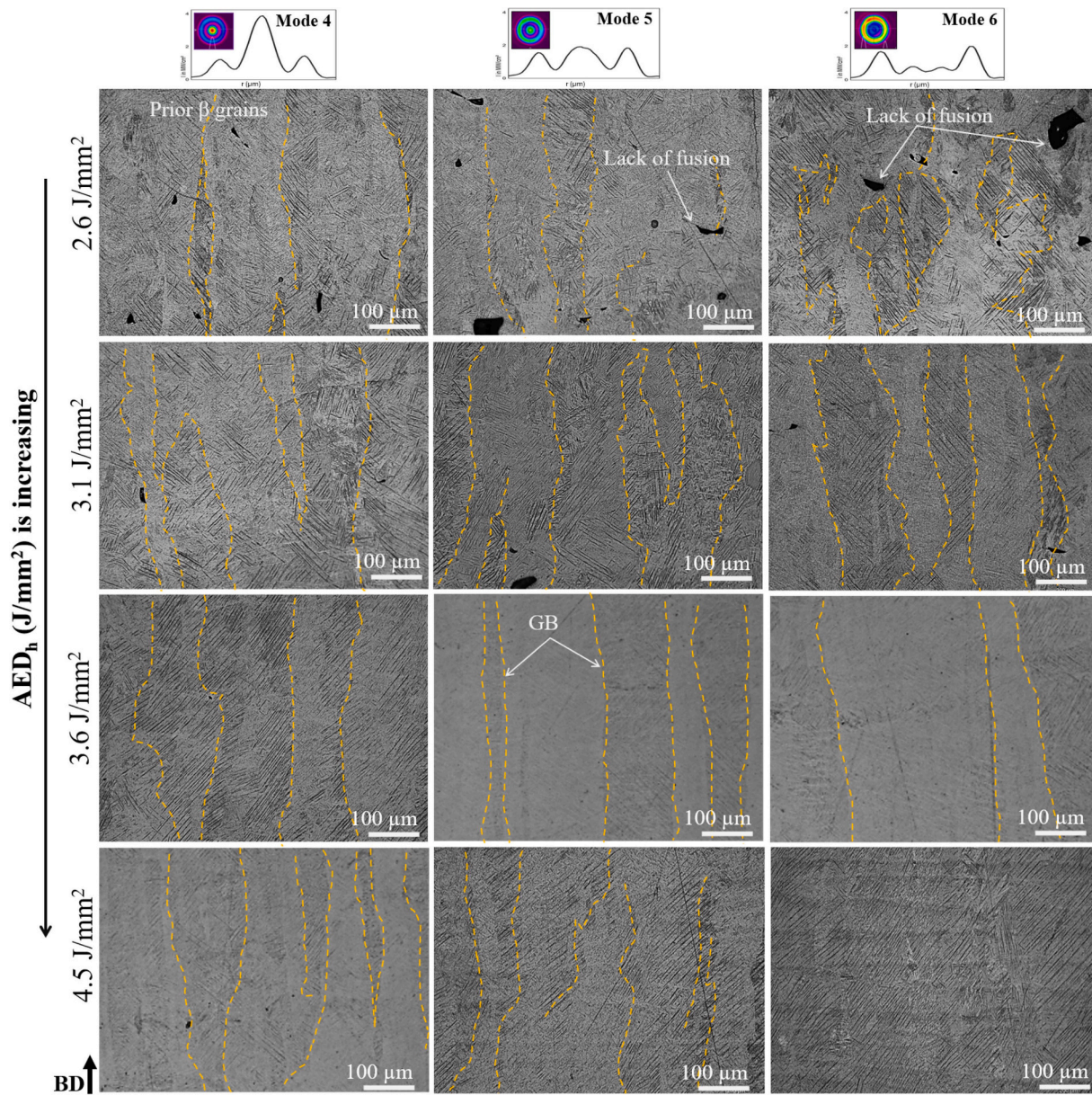


Fig. 13. Cross-sectional microstructures for Modes 4–6 at increasing AED_h . Dashed yellow lines indicate prior- β grain boundaries to highlight differences in grain continuity and width. At low AED_h , Mode 5 and especially Mode 6 show disrupted prior- β features with isolated LoF, whereas Mode 4 remains more uniform. With increasing AED_h , prior- β features become wider and more continuous, and LoF disappears across all Modes, indicating improved melt-pool stability even for ring-dominated profiles.

conditions. The micrographs suggest mode and AED_h dependent variations in the apparent continuity and spacing of prior- β features, particularly under LoF-prone conditions. However, these observations are qualitative, and crystallographic orientation is not quantified here. It should be noted that the microstructural analysis in this study is based on optical microscopy and SEM observations, supported by simulated thermal gradients and solidification rates. Detailed EBSD characterisation was not included in this experimental matrix because the main focus was to isolate the coupled effects of beam profile, energy input, and hatch spacing on densification, inter-track remelting, and melt-pool overlap behaviour. However, the previous beam-shaping study on PBF-LB/M Ti-6Al-4V included EBSD analysis and showed that laser beam profiles can influence crystallographic texture, grain alignment, and orientation-dependent microstructural development [34]. Therefore, the SEM-based observations reported here are discussed in relation to those EBSD-based findings, while a dedicated EBSD analysis of the

present hatch-spacing matrix is planned as a future extension.

At the lowest AED_h (≤ 2.6 J/mm²), mode-to-mode differences are most evident, with LoF-related discontinuities interrupting the apparent prior- β framework. Mode 4, with its higher central irradiance, produces comparatively deeper melt pools and therefore generates more continuous and elongated prior- β grains aligned with the build direction. Grain boundaries remain well-defined, and the α' lath structure is dense and uniform. In Mode 5, the prior- β features appear more segmented, with local interruptions that coincide with occasional LoF defects. Mode 6 shows the higher disruption, with frequent LoF, interrupted boundaries, and locally distorted prior- β columnar patterns under shallow, ring-dominated melting. These features confirm that insufficient penetration and reduced thermal gradients inhibit stable directional grain growth at low AED_h . At the transition regime (3.1–3.5 J/mm²), the microstructure becomes more uniform. Mode 4 rapidly transitions to a uniform columnar prior- β structure with minimal defects, consistent

with its ability to maintain stable melt pools even at moderate energy input. Mode 5 likewise stabilizes, showing straighter prior- β columns and reduced grain segmentation, indicating recovery of consistent thermal gradients. Mode 6 improves more gradually as continuity increases and LoF decreases, although prior- β features remain finer and less continuous, consistent with shallower ring-dominated melt pools. At the highest AED_h ($\approx 3.6\text{--}4.5\text{ J/mm}^2$), all three Modes show dense microstructures with minimal porosity and broadly similar columnar prior- β features. The α' martensitic laths are uniformly distributed, and grain boundaries exhibit smooth, uninterrupted columnar growth. Although the three Modes appear superficially similar at this stage, subtle distinctions persist. At higher AED_h, Mode 6 also develops more continuous prior- β features, and α' laths extend more smoothly across etch-defined boundaries (e.g., Mode 6 at 4.5 J/mm^2 in Fig. 13). This increased continuity of the prior- β columns and smoother α' lath connectivity across etch-defined boundaries is consistent with wider and deeper melt pools at higher energy input, which enhance remelting and stabilize the conditions required for continuous directional growth.

High-magnification SEM images from representative conditions were analyzed to compare microstructural responses across beam Modes. Overall, no major phase differences were observed: equilibrium $\alpha + \beta$ colonies were absent, retained β plates were not detected, and grain-boundary α films were not resolvable, indicating that all samples transformed fully to martensite during rapid cooling. Fig. 14 shows representative α' martensitic morphologies. While all Modes exhibit the α' martensitic microstructure typical of PBF-LB/M Ti-6Al-4V, subtle yet systematic differences in lath morphology are evident, consistent with beam-Mode-dependent solidification conditions. Mode 4 shows the most developed α' laths ($\approx 1.5\text{--}3\text{ }\mu\text{m}$ long, $\approx 0.2\text{--}0.5\text{ }\mu\text{m}$ thick), with secondary refinement in the inter-lath regions, consistent with deeper melt pools and more directional heat flow. Mode 5 displays mostly refined α' microstructure consisting of short, densely packed laths ($\sim 0.8\text{--}1.8\text{ }\mu\text{m}$, $0.15\text{--}0.25\text{ }\mu\text{m}$ thick). Only occasional long laths extend across prior- β boundaries, implying localized directional gradients, but overall, the structure is more uniform than in Mode 4. Mode 6 shows the most uniformly refined martensite, characterized by short laths ($\approx 0.6\text{--}1.5\text{ }\mu\text{m}$) with minimal directional alignment, consistent with shallower melt

pools and increased lateral heat dissipation associated with ring-like irradiance. Despite similar overall phase constitution, these variations illustrate how subtle changes in beam power distribution influence the formation of α' laths, packet refinement, and martensite morphology. A recent study on relatively core-weighted (Mode 3) and ring-dominated (Mode 6) profiles reports comparable trends in prior- β morphology and α' martensite refinement, in agreement with these results [34].

3.4. Numerical results and Discussion

3.4.1. Melt pool evolution and thermal fields

Transient numerical simulations were conducted to evaluate melt-pool evolution and the thermal response for the three beam Modes. Fig. 15 shows the simulated temperature–time histories at a representative subsurface point beneath the scan track for Modes 4–6 at 700 W and scan speeds of 1500 and 1350 mm/s. In all cases, temperature rises rapidly as the laser passes, followed by rapid cooling and a slower decay dominated by heat conduction into the surrounding material. Despite identical laser power, the beam Modes produce distinct peak temperatures and cooling trajectories. Mode 4 consistently produces higher peak temperatures, exceeding the evaporation threshold, whereas Mode 6 results in much lower peak temperatures, remaining closer to the liquidus temperature. Mode 5 shows intermediate behavior. Reducing the scan speed from 1500 to 1350 mm/s increases the interaction time, leading to higher peak temperatures and longer thermal residence for all Modes.

The differences in thermal histories are directly reflected in melt pool morphology, as shown in Figs. 16 and 17. Mode 4 generates a long and deep melt pool with the highest peak temperature, indicating strong energy localization and efficient penetration. In contrast, Mode 6 produces a wider but shallower melt pool with reduced penetration depth and melt pool length, consistent with its lower peak temperatures and more distributed energy input. Mode 5 again shows intermediate melt pool characteristics.

The higher peak temperatures and elongated melt pool observed for Mode 4 suggest increased susceptibility to evaporation-driven effects, whereas Mode 6 promotes a thermally milder processing regime. This

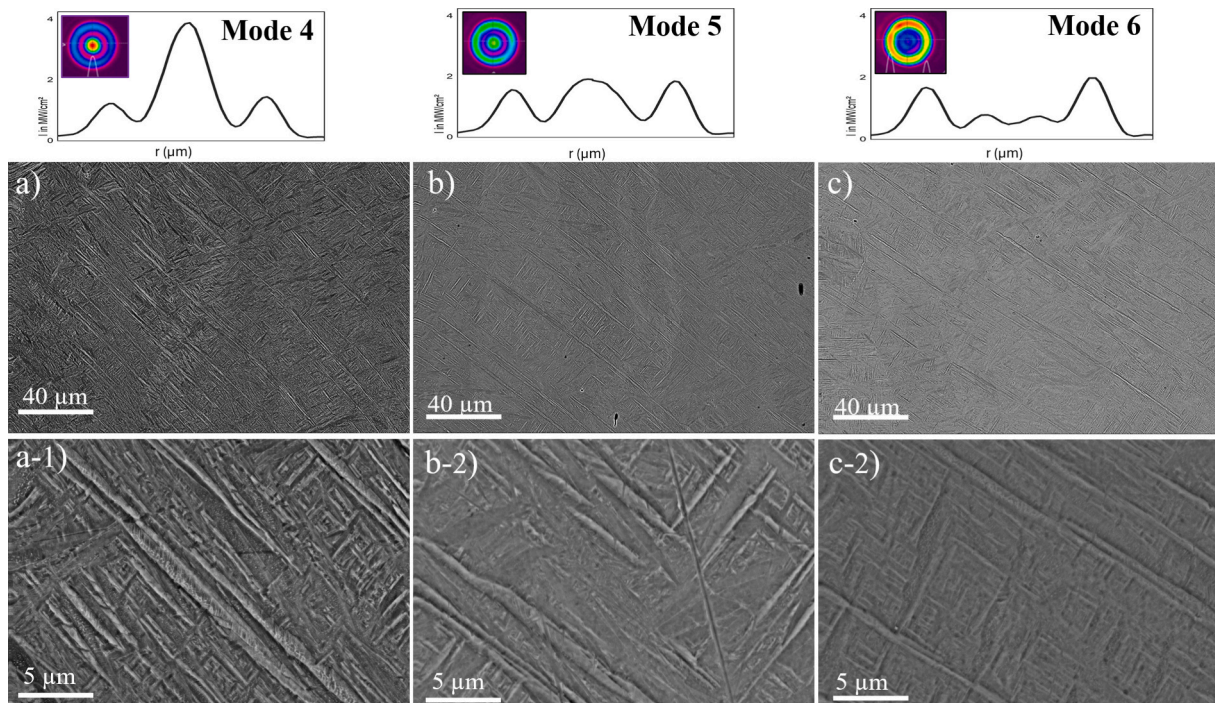


Fig. 14. SEM micrographs illustrating α' martensitic lath morphology for Modes 4–6.

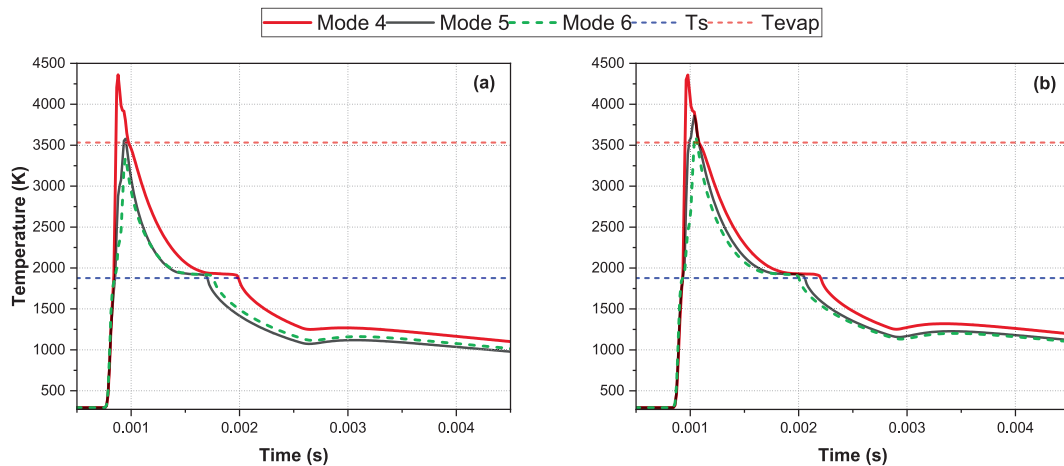


Fig. 15. Transient temperature histories extracted from the numerical simulations for Modes 4, 5, and 6 at a laser power of 700 W and scan speeds of (a) 1500 mm/s and (b) 1350 mm/s. The dashed horizontal lines indicate the solidus temperature (T_s) and evaporation temperature (T_{evap}), highlighting differences in peak temperature and thermal residence time among the beam Modes. The secondary temperature rise observed at later times corresponds to heat conduction from the deposition of the adjacent third track, which does not exceed the solidus temperature.

also suggests that beam shaping may be important in the keyhole-transition regime. Although keyhole conditions were not specifically targeted here, the higher peak temperatures predicted for the more core-weighted Mode 4 indicate closer proximity to evaporation- or keyhole-prone behaviour, whereas the ring-dominated Mode 6 reduces peak temperature and may delay this transition. A systematic study of this regime, including more core-weighted/Gaussian-like profiles, is therefore identified as future work. Related beam-profile-dependent track-stability transitions were discussed in our previous single-track study [29]. Overall, the combined thermal and geometric analyses demonstrate that beam shaping strongly influences melt pool evolution by modifying peak temperature, thermal gradients, and penetration behavior, which are critical for melt pool stability and subsequent solidification.

3.4.2. Hatch spacing and track overlap

Hatch spacing and track overlap play a critical role in determining inter-track bonding and the formation of LoF defects in PBF-LB/M. While hatch spacing is commonly selected based on single-track melt pool width, the effective overlap between adjacent tracks is strongly influenced by melt pool geometry, penetration depth, and thermal accumulation effects, all of which are beam-Mode dependent. In this study, the overlap ratio W/h , where W is the experimentally measured melt pool width, and h is the hatch spacing, is used as a primary metric to correlate numerical predictions with experimentally observed relative density.

Multi-track numerical simulations consisting of three consecutive scan tracks were performed for Modes 4, 5, and 6 under representative process conditions. The second track was selected for quantitative analysis, as it experiences a quasi-steady thermal environment influenced by both preceding and subsequent tracks. Fig. 18 presents cross-sectional views of the three-track configurations at a representative overlap ratio of $W/h \approx 1.2$, corresponding to the transition region in the experiments where density begins to deviate from the plateau for the more overlap-sensitive conditions (notably Mode 6 at low LED). Although the model does not explicitly predict porosity, it captures the experimentally observed Mode ranking and hatch-spacing sensitivity through simulated penetration and inter-track remelting behavior. Mode 4 exhibits the deeper melt-pool penetration and partial remelting of the adjacent tracks. Although partial overlap is achieved laterally, regions of limited remelting are still observed near the inter-track boundaries at this overlap ratio. This explains the experimentally observed reduction in relative density from 99.90% to 99.09% for Mode

4 as the hatch spacing increases from 172 μm to 222 μm at a scan speed of 1350 mm/s. The simulations indicate that, despite the high penetration capability of Mode 4, insufficient lateral fusion can occur when the hatch spacing exceeds a critical threshold.

For Mode 5, the simulations reveal a more balanced melt pool geometry, characterized by moderate penetration depth and wider lateral spread. At comparable overlap ratios ($W/h \approx 1.2$), Mode 5 achieves partial remelting of neighboring tracks; however, the remelt depth is shallower than that observed for Mode 4. This reduced penetration leads to a narrower fusion zone between adjacent tracks, increasing sensitivity to hatch spacing. Experimentally, this behavior manifests as a decrease in relative density from 99.97% to 99.05% as hatch spacing increases from 160 μm to 210 μm at 1350 mm/s, consistent with the numerically predicted reduction in overlap robustness. Mode 6 demonstrates the weakest inter-track remelting. As illustrated in Fig. 18, the melt pool produced by Mode 6 is wide but shallow, resulting in limited penetration into the previously solidified tracks. Even at identical overlap ratios, the simulations show partial remelting at the track boundaries, particularly near the lower regions of the melt pool. This behavior explains the pronounced sensitivity of Mode 6 to hatch spacing, as evidenced by the experimental density reduction from 99.96% to 98.32% for hatch spacings between 165 μm and 215 μm at 1350 mm/s. Although Mode 6 exhibits the largest melt pool width and theoretically sufficient lateral overlap ($W/h > 1$), the LoF defects persist due to insufficient remelting depth, indicating that for ring-dominated beam Modes, lateral overlap alone is insufficient to guarantee defect-free fusion without adequate penetration depth.

The influence of scan speed further amplifies these trends. At the higher scan speed of 1500 mm/s, reduced energy input per unit length leads to shallower melt pools for all beam Modes, increasing the sensitivity to hatch spacing. This effect is particularly pronounced for Mode 6, where experimental densities fall below 98.1% at the largest hatch spacing despite maintaining similar overlap ratios. The numerical simulations confirm that reduced penetration and weaker thermal accumulation at higher scan speeds limit the remelting of adjacent tracks, thereby increasing the likelihood of LoF defects. Overall, the combined numerical and experimental results demonstrate that the overlap ratio W/h , while useful, is insufficient as a standalone criterion for hatch spacing selection. Melt pool penetration depth and inter-track remelting behavior, both of which are strongly regulated by beam intensity distribution, must be considered concurrently. Modes with higher core energy concentration (Mode 4) provide greater tolerance to increased hatch spacing, whereas ring-dominated Modes (Mode 6) require tighter

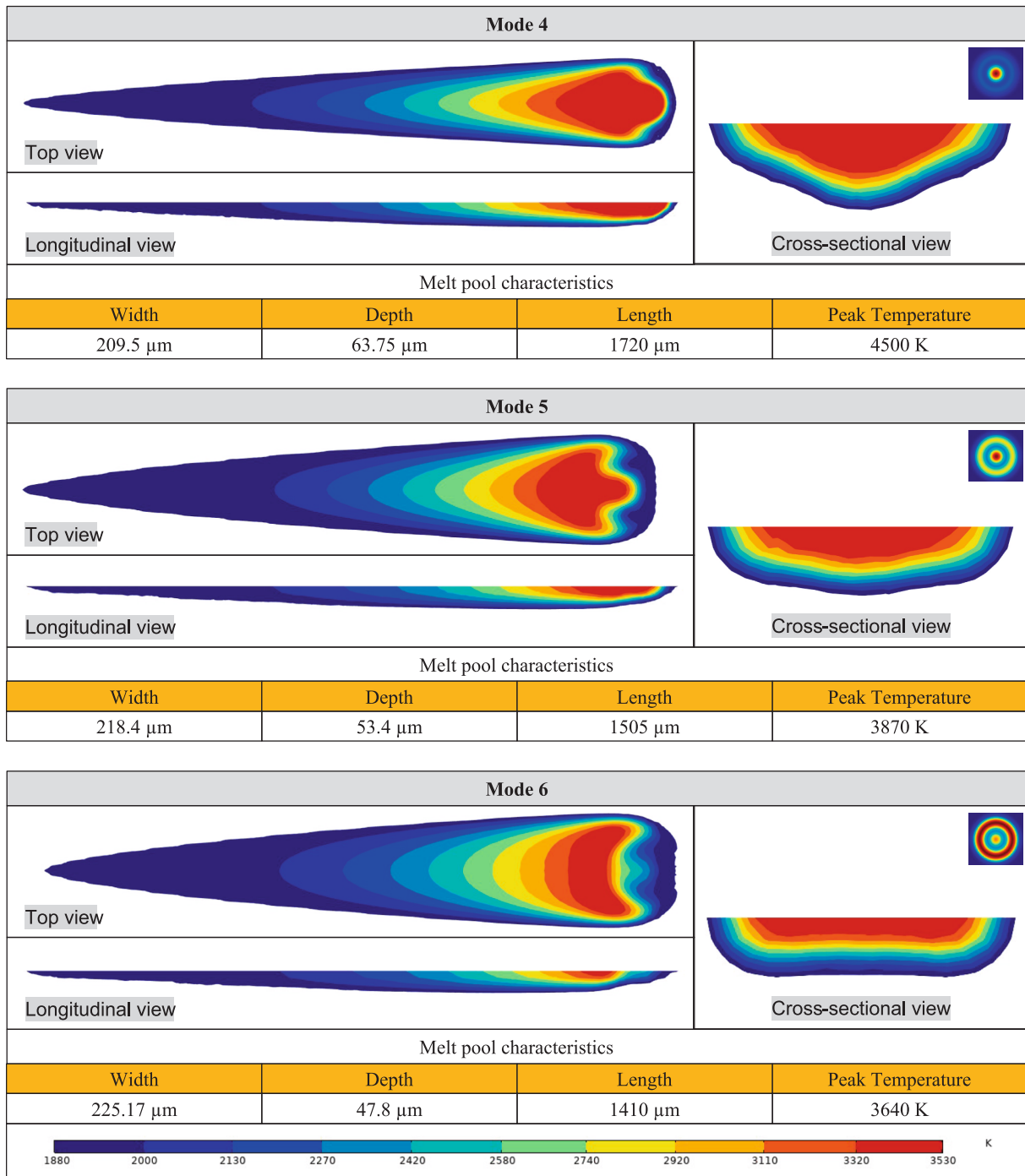


Fig. 16. Numerically predicted three-dimensional melt pool morphologies, corresponding top views, and longitudinal cross-sectional views for Modes 4, 5, and 6 at a laser power of 700 W and a scan speed of 1350 mm/s. The table summarizes the corresponding melt pool width, depth, length, and peak temperature, illustrating the influence of beam Mode on melt pool geometry and thermal intensity.

hatch spacing to achieve comparable densification.

3.4.3. Solidification conditions and microstructure control

To interpret the experimentally observed microstructures, the thermal gradient (G) and solidification rate (R) were evaluated along the solid–liquid interface within the mushy zone. The G and R values were extracted from the numerical simulations using an *iso-surface* defined by $T = T_L$, as illustrated in Fig. 19. The thermal gradient, defined as the magnitude of the temperature gradient normal to the solidification front ($G = |\nabla T|$), and the solidification rate were calculated as $R =$

$v_{\text{spot}} \left(\frac{\nabla T_x}{|\nabla T|} \right)$, where v_{spot} is the laser scanning speed and ∇T_x is the thermal gradient component along the scanning direction, representing the local velocity of the advancing solidification front.

To assess the influence of beam shaping on microstructure formation, G and R values were extracted at multiple cross-sectional and longitudinal locations along the melt pool tail (i.e., where the final microstructure is determined) for two processing conditions: 700 W at 1350 mm/s (High LED) and 1500 mm/s (Low LED). The extracted data were then plotted on the Ti-6Al-4V solidification map [48] based on Hunt's columnar-to-equiaxed transition (CET) theory [49].

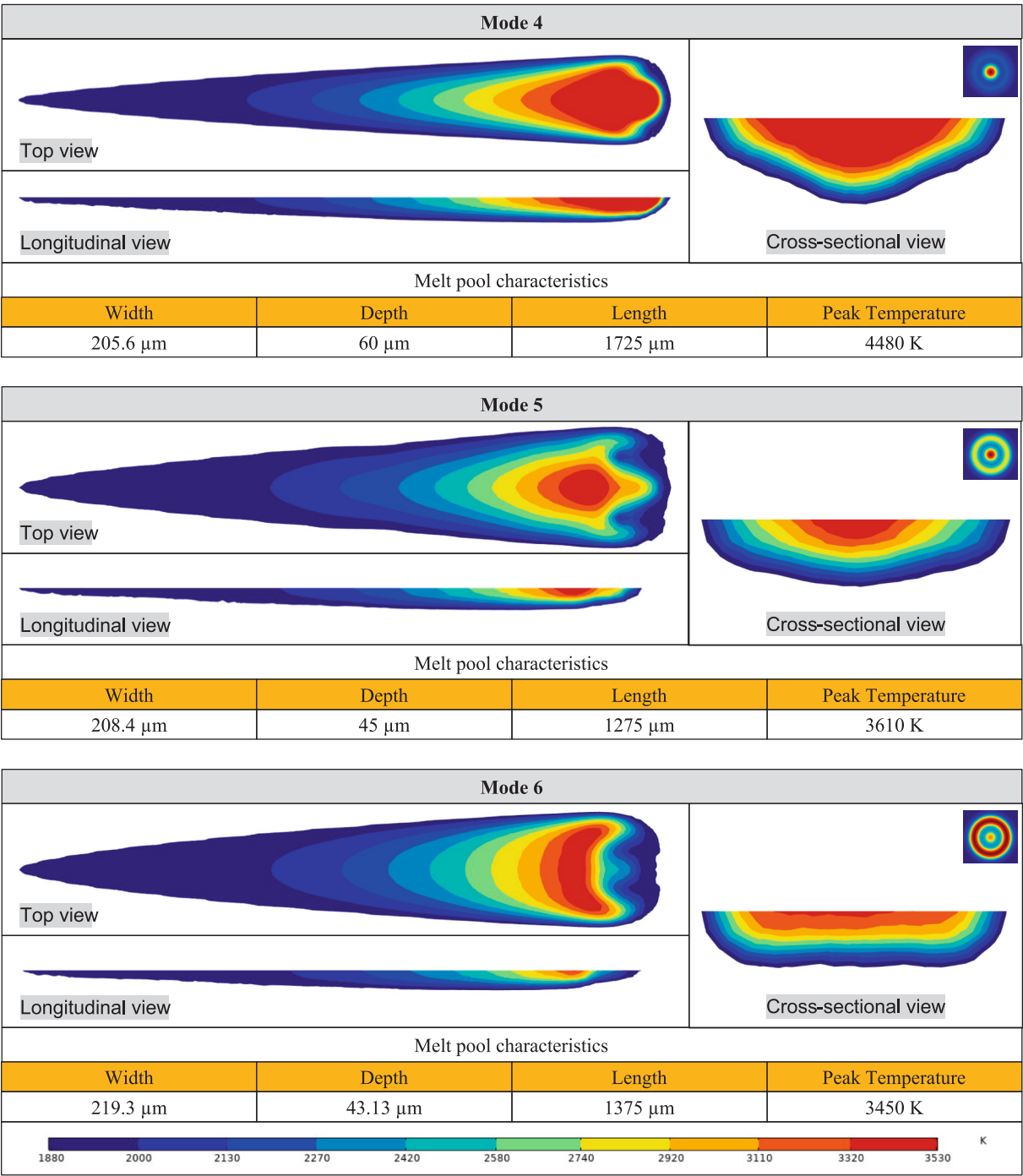


Fig. 17. Numerically predicted three-dimensional melt pool morphologies, corresponding top views, and longitudinal cross-sectional views for Modes 4, 5, and 6 at a laser power of 700 W and a scan speed of 1500 mm/s. The table summarizes the corresponding melt pool width, depth, length, and peak temperature, illustrating the influence of beam Mode on melt pool geometry and thermal intensity.

Fig. 20 presents the distributions of G and R at different cross-sectional locations of the melt pool for the High and Low LED conditions across the three beam shaping Modes. For all beam Modes and processing conditions, the simulated data cluster within a relatively narrow region characterized by high thermal gradients ($G \sim 10^3\text{-}10^4$ K/mm) and moderate solidification rates ($R \sim 10^1\text{-}10^2$ mm/s). These conditions correspond to cooling rates ($G \bullet R$) on the order of $10^5\text{--}10^6$ K/s and lie well within the columnar solidification regime of the $G\text{--}R$ map. As a result, columnar growth dominates the solidification behavior in all cases, with predicted columnar fractions ranging from 95% to 99%. Mixed morphologies remain limited, and fully equiaxed

solidification is not predicted under any of the investigated conditions, which agrees with the experimental absence of fully equiaxed zones in the bulk microstructure.

Despite this overall trend, mode-dependent differences in the G/R ratio are observed. Mode 4 tends to exhibit higher thermal gradients and G/R , indicating conditions that are more favorable for directional epitaxial growth. This is qualitatively consistent with the experimental micrographs, where Mode 4 appears to show more continuous prior- β features and comparatively coarser α' laths. In contrast, Mode 6 shows lower thermal gradients and a broader distribution of cooling conditions, particularly near the melt-pool periphery. The associated reduc-

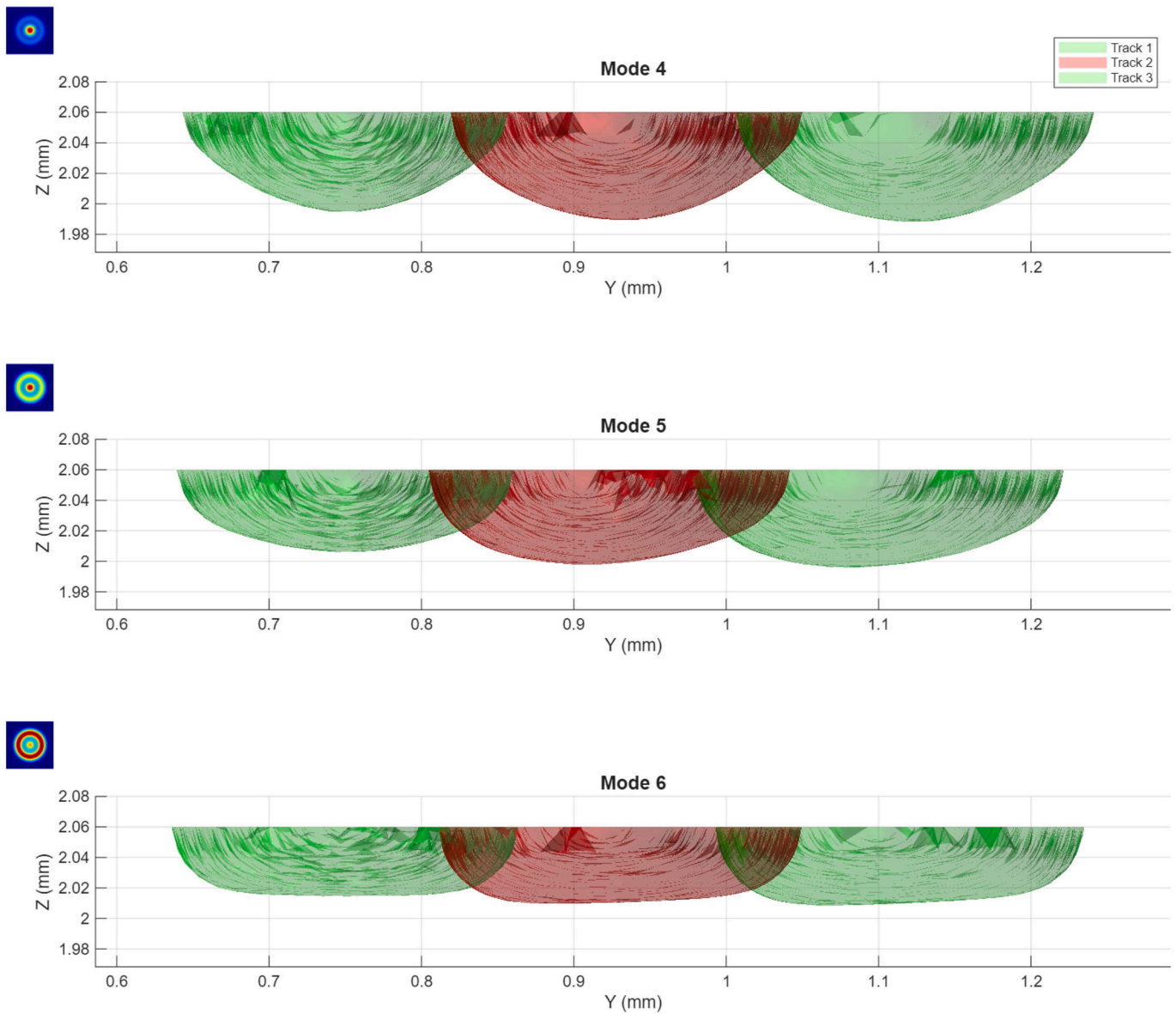


Fig. 18. Cross-sectional views of three consecutive melt tracks obtained from multi-track numerical simulations for Modes 4, 5, and 6 at a laser power of 700 W and a scan speed of 1350 mm/s. The central red region represents the second track, while the adjacent green regions correspond to the preceding and subsequent tracks. An overlap ratio of $W/h \approx 1.2$ is applied in all cases. Despite identical overlap ratios, insufficient remelting is observed near the inter-track boundaries, indicating an increased susceptibility to LoF defects. The extent of remelting and penetration varies with beam Mode, consistent with the experimentally observed reduction in relative density at comparable hatch spacings.

tion in G may reduce the tendency for strictly directional growth, consistent with the comparatively refined and less continuous martensitic lath structure observed for Mode 6. Mode 5 shows intermediate behavior between these two cases.

Complementing the cross-sectional view, Fig. 21 shows the G and R distribution taken from longitudinal sections along the melt pool centreline. Unlike the tight clustering seen in the cross-sections, the longitudinal data form a distinct curve spanning a wider range of solidification rates. This trajectory represents the progression from the bottom of the melt pool up toward the trailing surface. At the deepest point of the melt pool (low R), thermal gradients are at their peak, providing the strongest driving force for initial epitaxial growth aligned with the build direction. As solidification proceeds upward along the tail, the solidification rate R increases toward the laser scanning velocity, while G progressively decreases.

Superimposed iso-cooling-rate lines in Fig. 21 indicate that cooling rates vary significantly along this longitudinal path, decreasing from

very high rates ($> 10^6 K/s$) at the pool bottom to lower rates near the surface. Comparing the Modes longitudinally, Mode 4 maintains slightly steeper thermal gradients over a larger portion of the pool depth compared to Mode 6, further reinforcing the conditions for the more strongly directional, continuous columnar growth observed experimentally in Mode 4 samples. In conclusion, the numerical simulations indicate that for the Ti-6Al-4V parameters investigated, laser beam shaping does not alter the fundamental solidification mechanism; all conditions remain far from the CET boundary. Instead, beam shaping modulates the local G and cooling rates within the columnar regime. The high-intensity core of Mode 4 maximizes the G/R ratio, promoting stable, elongated grains. Conversely, the ring-shaped energy distribution of Mode 6 reduces peak thermal gradients and promotes a wider variation in local cooling conditions, leading to the observed refinement and interruption of the columnar microstructure without inducing a transition to equiaxed growth.

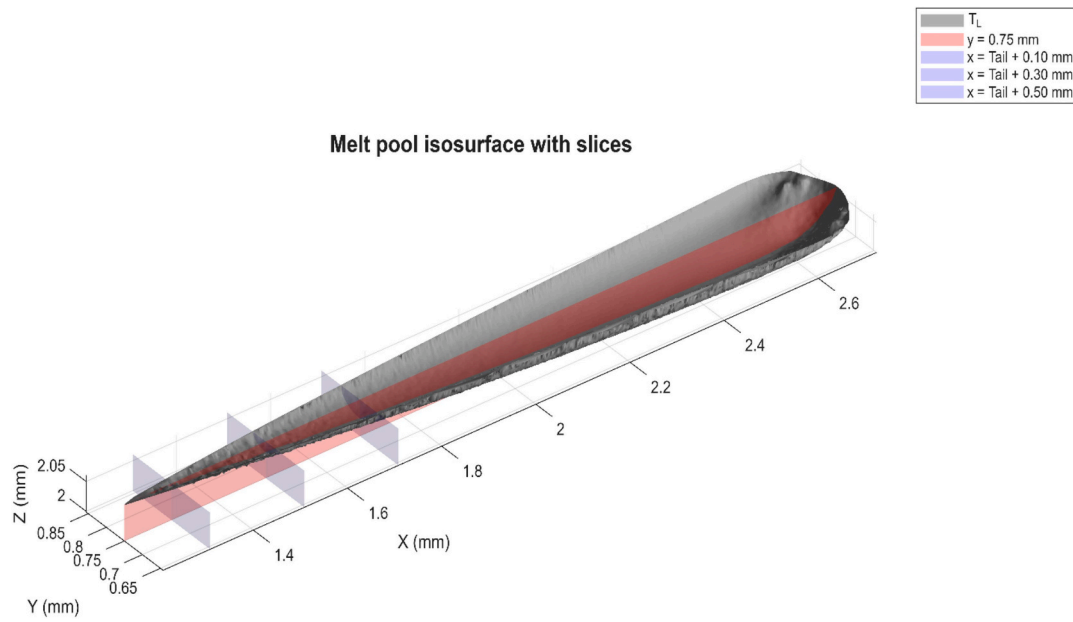


Fig. 19. Schematic of the melt pool iso-surface used to extract G and R values. The iso-surface is defined by the condition $T = T_L$, corresponding to the solid-liquid interface. The slices along the X and Y directions indicate the locations used for cross-sectional and longitudinal data extraction for CET analysis.

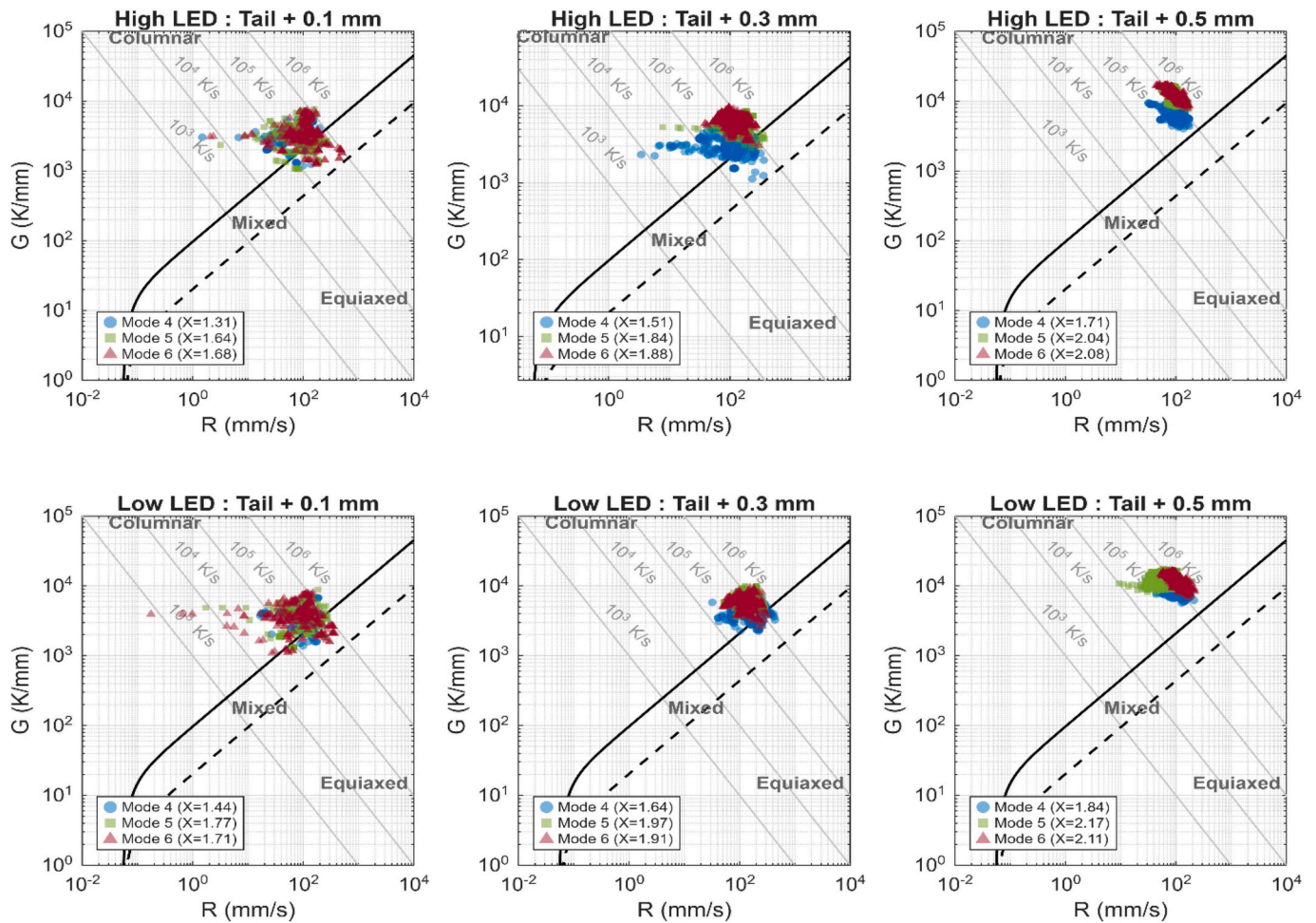


Fig. 20. Solidification maps showing G versus R extracted from numerical simulations for three laser beam shaping Modes (Mode 4, Mode 5, and Mode 6). Results are shown for High LED (top row) and Low LED (bottom row) conditions at different spatial locations along the melt pool. Solidification regime boundaries and iso-cooling-rate lines are superimposed. All conditions lie predominantly within the columnar growth regime, with no transition to fully equiaxed solidification.

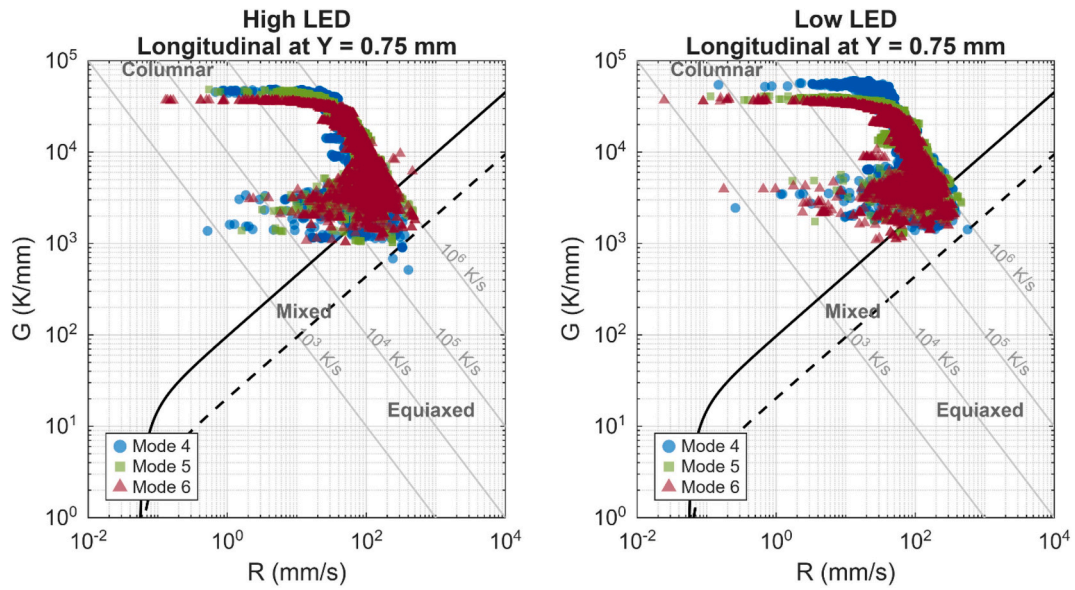


Fig. 21. Solidification maps showing G versus R obtained from numerical simulations for three laser beam shaping Modes (Mode 4, Mode 5, and Mode 6). Results are shown for High LED (left) and Low LED (right) conditions at the longitudinal cross-section ($Y = 0.75$ mm) along the melt pool. Solidification regime boundaries and iso-cooling rate lines are superimposed.

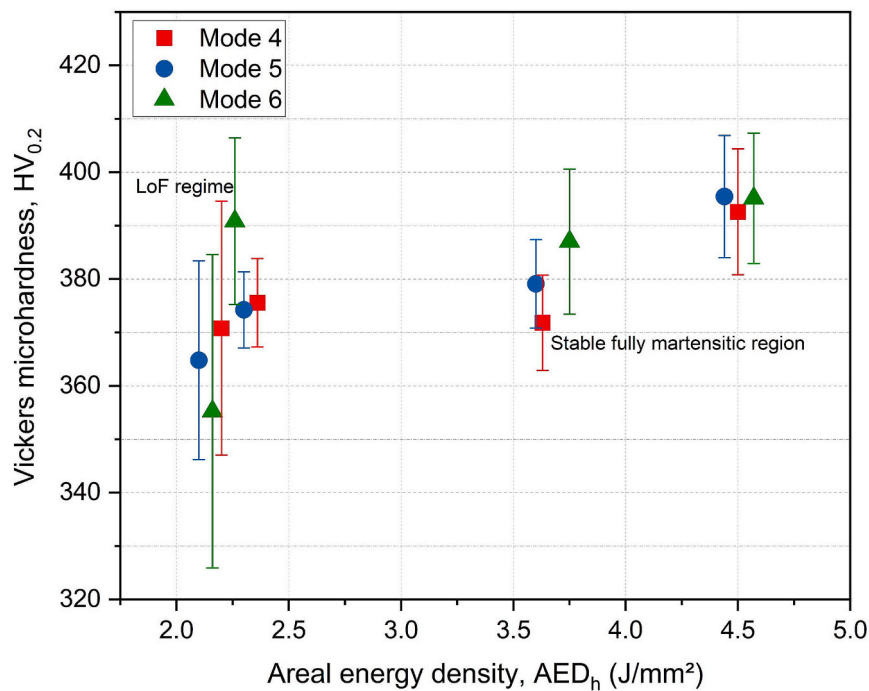


Fig. 22. Vickers microhardness ($HV_{0.2}$) versus AED_h for Modes 4–6. Error bars indicate standard deviation. Hardness increases with AED_h and stabilizes beyond ~ 3.0 J/mm^2 as LoF is suppressed and near-full density is achieved within α' -dominated microstructures.

3.5. Microhardness

Fig. 22 shows the Vickers microhardness ($HV_{0.2}$) as a function of areal energy density (AED_h) for the three beam Modes. Across all conditions, hardness falls within the typical range reported for martensitic PBF-LB/M Ti-6Al-4V (~ 360 – 400 $HV_{0.2}$), consistent with α' -dominated microstructures. A slight increase in hardness with AED_h is observed. At the lowest energy inputs (≈ 2.1 – 2.4 J/mm^2), all Modes show hardness in the range of ≈ 355 – 375 $HV_{0.2}$, whereas at the highest energy level (≈ 4.5 J/mm^2), hardness converges near ≈ 390 – 395 $HV_{0.2}$. This gradual increase is consistent with the densification behaviour discussed earlier.

Lower AED_h conditions are associated with localized LoF defects and incomplete remelting between tracks, which can introduce local heterogeneity near indentation sites and lead to slightly lower and more scattered hardness values. As AED_h increases and relative density approaches $\approx 99.9\%$, hardness stabilizes, and the scatter decreases, indicating more homogeneous load transfer through a fully consolidated martensitic matrix.

Differences between beam Modes are comparatively modest and mostly confined to the low-energy regime. At the smallest AED_h , Mode 6 tends to exhibit the lowest hardness and largest scatter, consistent with its higher sensitivity to LoF and the presence of more pronounced

porosity bands identified in the cross-sectional micrographs. Modes 4 and 5, which generate deeper and more continuous melt pools, show slightly higher hardness at the same energy level, reflecting their more robust densification under these conditions. At intermediate and high AED_h , the curves for all three Modes converge within the experimental error bars. This convergence is in line with the microstructural observations where, once density is high and the microstructure is fully martensitic in all cases, beam-shape-induced differences in prior- β morphology and α' -lath refinement are likely too subtle to produce large hardness contrasts at the present scale. Taken together, these results indicate that, under the present processing conditions, microhardness in PBF-LB/M Ti-6Al-4V is largely insensitive once near-full density and α' martensite are achieved. Beam Mode exerts only a minor influence once LoF defects are suppressed and fully dense microstructures are achieved.

4. Conclusion

Within the investigated cube geometry and processing range, this study provides a unified assessment of how laser beam shape, hatch spacing, and energy input jointly determine densification, microstructure, and hardness in PBF-LB/M processing of Ti-6Al-4V. Rather than providing only an optimized parameter set, this work establishes a beam-shape-dependent process-design framework linking spatial irradiance distribution to overlap requirements, inter-track remelting, densification, and microstructural response. By evaluating ring-type beams ranging from relatively core-weighted to ring-dominated profiles under energy-normalized conditions, the work demonstrates that the spatial distribution of irradiance controls not only the melt pool geometry but also the inter-track bonding mechanism, thereby defining the onset and suppression of LoF defects. Using physically meaningful metrics such as AED_h , normalized hatch spacing h/d , and overlap ratio W/h , the study establishes a clear framework for interpreting beam-dependent process stability. The key conclusions are summarized as follows.

- **Beam shaping and densification:** Within the investigated conduction and LoF dominated parameter range, beam-profile effects on densification were most pronounced in the low-energy and low-overlap regime. Relatively core-weighted (Mode 4) achieves high density at lower AED_h , whereas ring-dominated (Mode 6) requires higher energy input to suppress LoF. Simulations indicate that this sensitivity arises from insufficient remelting depth at the inter-track boundary (cusp formation), even when lateral overlap is present.
- **Design rules:** Dimensionless overlap descriptors provide a unified basis for hatch-spacing selection across beam Modes. Stable densification was achieved when the normalized spacing remained near $h/d \lesssim 1$, and the overlap ratio satisfied $W/h \gtrsim 1.2$ (Mode 6 at low energy: $W/h \approx 1.25$ – 1.30), yielding practical guidelines for the investigated beam profiles, hatch-spacing range, energy-input range, and cube geometry.
- **Solidification and microstructure:** Experimentally, all beam Modes produced predominantly α' -martensitic microstructures with columnar prior- β features, indicating columnar-dominated solidification across the investigated processing window. Numerical extraction of thermal gradients (G) and solidification rates (R) supports this interpretation, placing all conditions well within the columnar growth regime. Within this regime, beam shaping primarily modulates local solidification conditions: core-weighted Mode 4 maintains higher G/R , consistent with more strongly directional and continuous columnar features, whereas ring-dominated Mode 6 exhibits reduced gradients, consistent with slightly refined α' laths and less continuous columnar features under low-energy conditions.

- **Microhardness:** Microhardness remained in the typical range for martensitic PBF-LB/M Ti-6Al-4V and increased modestly with AED_h , converging once near-full density was achieved. The dominant driver of hardness differences was the presence/absence of LoF defects at low energy (lower and more scattered hardness), while beam-Mode-induced differences in lath refinement and prior- β morphology played only a secondary role after densification.

Taken together, these findings show that beam shaping can expand the usable process window in Ti-6Al-4V by improving melt-pool stability. However, successfully implementing ring-dominated beams requires careful compensation for their reduced penetration depth. The proposed energy-geometry metrics, validated by multiphysics modeling, provide a robust basis for optimizing these advanced scanning strategies within the investigated processing window. Future work should extend this framework to more complex geometries, thermal accumulation conditions, and keyhole-transition regimes, where beam-shaping effects may become even more pronounced.

CRedit authorship contribution statement

Abid Ullah: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Reshad Bakhtari:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Jan Johannsen:** Writing – review & editing, Software, Resources, Methodology. **Philipp Kohlwes:** Writing – review & editing, Visualization, Resources. **Kai Zhang:** Writing – review & editing, Resources. **Tingting Liu:** Writing – review & editing, Supervision, Resources. **Amjad Iqbal:** Writing – review & editing, Methodology. **Dirk Herzog:** Writing – review & editing, Supervision, Project administration. **Alexander Medvedev:** Writing – review & editing, Validation. **Andrey Molotnikov:** Writing – review & editing, Supervision. **Ingomar Kelbassa:** Writing – review & editing, Supervision, Resources. **Milan Brandt:** Writing – review & editing, Validation, Supervision, 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.matdes.2026.116617>.

Data availability

The processed data supporting the findings of this study have been deposited in Zenodo and will be made publicly accessible after publication: <https://doi.org/10.5281/zenodo.20549954>.

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