



Advancing laser powder bed fusion of metals via tailored laser beam shaping: A critical review[☆]

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ABSTRACT

Laser beam shaping is increasingly explored to enhance Laser Powder Bed Fusion of Metals (PBF-LB/M) by controlling the spatial energy distribution within the laser spot. While conventional Gaussian beams remain widely used in commercial systems, their concentrated energy input can promote steep thermal gradients and localized overheating, which may restrict process stability, productivity, and part quality. This review critically synthesizes recent progress in laser beam shaping for PBF-LB/M, with emphasis on work from 2020 to early 2026. Compared with earlier reviews that mainly focused on optical implementation or broader laser–material processing concepts, this review integrates beam-shape generation with melt-pool dynamics, defect formation, surface quality, microstructural evolution, mechanical response, productivity, and emerging shape-aware process descriptors. The discussion shows how profiles such as core–ring, ring–dominant, top–hat, and elliptical beams can broaden stable process windows, suppress spatter and keyhole porosity, and promote more uniform thermal histories, with implications for surface quality, mechanical isotropy, and build efficiency. Modeling and simulation studies are also summarized to clarify the coupled heat–fluid–solid interactions controlling melt-pool behavior, thermal gradients, and solidification kinetics. Furthermore, major implementation challenges such as optical integration, energy–delivery stability, process reproducibility, and the lack of standardized beam descriptors are summarized. The review concludes by outlining emerging research directions aimed at enabling practical, reliable, and industrial-scale adoption of beam-shaping technologies in additive manufacturing.

1. Introduction

Efficient use of processing time and material resources remains a critical challenge in modern manufacturing. Conventional processes such as hot isostatic pressing, extrusion, and injection molding require long processing times and costly tooling [1–3]. Additive Manufacturing (AM), based on layer-wise material deposition, offers a more resource-efficient alternative by enabling near-net-shape fabrication with

reduced material waste and shorter production cycles [2,4–6]. Among AM techniques, laser beam powder bed fusion of metals (PBF-LB/M; ISO/ASTM 52900), commonly referred to as laser powder bed fusion (LPBF), is a leading technology for producing complex, high-performance metal components for aerospace and automotive applications. Although PBF-LB/M can achieve near-full density through localized laser melting [7–9], it still faces challenges in process stability, quality consistency, and productivity. These challenges arise from coupled laser–powder–melt pool interactions that control melt-pool

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Nomenclature			
<i>Abbreviations</i>		EBV	Energy per Built Volume
Acronym	Meaning	HAZ	Heat-affected zone
AM	Additive manufacturing	IPF	Inverse pole figure
PBF-LB/M	Laser beam powder bed fusion of metals	LCoS	Liquid crystal on silicon
LPBF	Laser powder bed fusion	UTS	Ultimate tensile strength
AR	Aspect ratio	LED	Linear energy density
BS	Beam shaping	LE	Longitudinal elliptical
CA	Cellular automata	LoF	Lack of fusion
CFD	Computational fluid dynamics	AED	Areal energy density
CW	Continuous wave	M^2	Beam quality factor
$D4\sigma$	Second-moment beam diameter	$I_{\max}$	Maximum irradiance
DED	Directed energy deposition	PF	Pole figure
DEM	Discrete element method	HS	Hatch spacing
DOE	Diffraction optical element	Ra	Arithmetic mean surface roughness
EBSD	Electron backscatter diffraction	Sa	Areal surface roughness
FEM	Finite element method	SEM	Scanning electron microscopy
FWHM	Full width at half maximum	SpLM	Spatial light modulator
G	Temperature gradient	TE	Transverse elliptical
$G \times R$	Cooling rate	VED	Volumetric energy density
		Pe	Peclet number
		$\Delta H/hs$	Normalized enthalpy per hatch spacing

dynamics and subsequent solidification [10,11], often leading to porosity, spatter/ejecta, and lack-of-fusion (LoF) defects that reduce mechanical reliability and fatigue performance [12–14]. While most studies optimize process parameters [15–20], laser beam shape has received comparatively less attention because early PBF-LB/M systems offered limited beam-profile control and assumed fixed Gaussian optics.

Laser beam shaping, defined as the controlled spatial redistribution of laser energy, critically influences melt-pool geometry, thermal gradients, and solidification behavior [21,22]. Most commercial PBF-LB/M systems employ Gaussian beams because of their high spatial coherence and low divergence. However, the centrally peaked Gaussian profile can produce steep thermal gradients and high peak temperatures, narrowing the stable processing window and promoting keyholing and melt-pool instabilities at elevated energy input [23–25]. As a result, laser beam shape directly affects key outcomes, including melt-pool dimensions, process stability, surface quality, microstructure, mechanical performance, and build productivity [26,27]. Beam shaping has also emerged as a promising approach to improve the inherently low productivity of PBF-LB/M. Conventional processing with small spot sizes and thin layers limits build rates; increasing spot size improves areal coverage but lowers peak irradiance at a given power and can limit full melting at thicker layers. In contrast, non-Gaussian profiles such as annular and top-hat beams enable wider melt tracks and larger hatch spacing while maintaining high density, resulting in reported productivity gains of up to 100% or more [28]. However, these gains come with trade-offs in resolution. Therefore, adaptive beam-shaping systems capable of switching between Gaussian and shaped profiles have been proposed to balance precision and throughput within a single build [29,30].

Recent research has increasingly focused on non-Gaussian beam profiles to overcome the limitations of conventional Gaussian beams and improve both part quality and productivity in PBF-LB/M. Several beam shapes originally developed for laser welding, including ring, core-ring, top-hat, and elliptical profiles [31–34], have demonstrated potential for AM applications [29,35]. Adjustable core–ring modes, in particular, redistribute energy away from the beam center and enlarge the stable process window across different materials [36]. In parallel, experimental and numerical advances have substantially improved the understanding of how beam shaping influences thermal behavior and process stability [37]. Physics-based simulations that explicitly account for beam shape further show that the spatial intensity distribution controls peak temperature, melt-pool dimensions, and cooling rates

[21]. However, despite these advances, many individual studies remain focused on single-track or material-specific conditions, with limited integration across surface morphology, porosity evolution, microstructural development, mechanical performance, and productivity [25,38]. Existing reviews have each addressed complementary aspects of beam shaping but necessarily emphasize different dimensions such as optical implementation, process stability, or broader laser–material interactions, without a unified treatment of the full process–structure–property–productivity chain [29,35,39]. In this context, conventional descriptors such as volumetric energy density (VED) remain useful global indicators but are insufficient for comparing different beam profiles, because they do not fully capture beam geometry, peak irradiance, or spatial energy redistribution. This limitation further motivates the use of shape-aware metrics and dimensionless process frameworks [35,40].

Beam shaping, therefore, should be viewed not only as a process-stability enhancement strategy but also as a potential enabler for energy-efficient, high-throughput, and sustainable metal AM. Although previous reviews have provided valuable foundations, their emphasis differs from the present work. Bakhtari et al. [35] reviewed laser beam-shaping applications in PBF-LB/M, including shaping techniques and their effects on melt-pool geometry, process stability, and microstructure. Bi et al. [39] provided a broader overview of beam-shaping technologies in metal laser AM, covering both PBF-LB/M and directed energy deposition. More recently, Abdelmoula and Musinski [41] reviewed LPBF beam shaping, with primary focus on melt-pool morphology, microstructure, mechanical response, and simulation formulations. Building on these foundations, the present review provides a recent PBF-LB/M–focused process–structure–property–productivity synthesis that integrates beam-profile generation with melt-pool stability, surface quality, porosity evolution, microstructure, mechanical performance, productivity, modeling, shape-aware descriptors, standardization needs, and alloy-dependent transferability. The remainder of this review is organized as follows: Section 2 describes the methodology used for bibliometric mapping of beam-shaping literature. Section 3 introduces beam-shaping fundamentals and implementation routes in PBF-LB/M. Section 4 reviews thermo-physical effects and their manifestations, including melt-pool geometry, surface quality, densification, productivity, microstructural evolution, and mechanical properties. Section 5 summarizes modeling and simulation approaches. Section 6 discusses key challenges and limitations. Section 7 concludes with final

remarks and future outlook.

2. Methodology: Bibliometric mapping of PBF-LB/M beam-shaping literature (2020–early 2026)

From Google Scholar and Scopus searches, two complementary datasets were created: a broad bibliometric dataset used to map themes and keyword networks and a topic-relevant dataset used for technical synthesis and interpretation. Scopus served as the primary source due to consistent indexing and export in RIS format suitable for bibliometric analysis. A KEYWORD query combined PBF-LB/M terms with beam-profile and beam-modulation terms. A representative Scopus query structure was:

(TITLE-ABS-KEY ((“LPBF” OR “PBF-LB/M” OR “laser powder bed fusion”) AND (“ring beam” OR “annular beam” OR “top-hat” OR “flat-top” OR “core-ring” OR “elliptical beam” OR “Bessel beam” OR “beam shaping”))).

The literature search strategy and inclusion–exclusion criteria are summarized in Table 1. The search returned 1037 records before screening, which were used for the keyword co-occurrence mapping and clustering in VOSviewer, as shown in Fig. 1. It provides a bibliometric overview of the main keyword relationships in the PBF-LB/M beam-shaping literature. In the VOSviewer map, larger nodes indicate keywords that appear more frequently, thicker connecting lines indicate stronger co-occurrence between keywords, and colors represent clusters of closely related research themes. The map shows that beam-shaping studies are mainly clustered around laser-material interaction and melt-pool behavior, microstructure and mechanical properties, alloy-specific processing, and energy/heat-transfer concepts. Hence, the motivation for the current review study is derived from the map and aims to connect these themes into an integrated process-

Table 1
Summary of literature articles selected for the review as per the inclusion–exclusion criteria.

Literature Searching Criteria Summary	
Objective	Build a broad dataset for bibliometric mapping and a screened dataset for technical synthesis
Time window	2020–early 2026
Language	English
Search date	February 2026
Primary database	Scopus (consistent indexing + RIS export for bibliometrics)
Supplementary source	Google Scholar (early-online coverage, highly cited papers, and reference/citation tracing)
Core query blocks	Boolean combination of PBF-LB/M terms, beam profiles (ring/annular, top-hat/flat-top, elliptical/line, core-ring, Bessel, multimode), shaping methods
Selection limitations	English-only literature; Scopus-centered indexing; non-LPBF shaping methods excluded; possible omission of non-indexed studies
Records identified	1037 Scopus records identified before screening; Google Scholar used for supplementary retrieval and citation tracing
Export & processing	RIS export including author, title, abstract, and keywords; keyword normalization performed for LPBF/PBF-LB/M and beam-profile terminology
Bibliometric analysis	VOSviewer keyword co-occurrence, min occurrence = 10; cleaned set > 150 keywords
Inclusion criteria (synthesis set)	Must be PBF-LB/M, include defined beam profile or Gaussian vs shaped comparison, and report extractable outcomes (melt pool, defects/density, roughness, microstructure/texture, mechanical properties, productivity)
Exclusion criteria	Not PBF-LB/M; beam shaping not explicit; insufficient profile description; no extractable outcomes; duplicates/redundant versions; non-LPBF-applicable shaping method
Final included studies for synthesis	180 studies

structure–property and productivity-oriented discussion.

The subsequent identification, screening, eligibility assessment, and inclusion process is summarized in Fig. 2. Google Scholar was used as a supplementary source to capture new online articles not yet indexed in Scopus, identify highly cited or widely discussed studies, and support reference lists and “cited by.” Quotation marks were used in Scholar queries to enforce phrase matching and reduce irrelevant hits. Targeted searches combining alloy names with beam-profile keywords were also performed to capture material-specific studies (e.g., “SS316 L” AND (“ring” OR “core-ring” OR “top-hat” OR “elliptical”) AND (“PBF-LB/M” OR “LPBF”)). Only English-language publications were included. Conference papers, review articles, and journal papers were screened based on technical relevance and extractable experimental or simulation outcomes. Studies unrelated to PBF-LB/M beam shaping or lacking sufficient beam-profile information were excluded to maintain methodological consistency.

3. Fundamentals and implementation of laser beam shaping in PBF-LB/M

In PBF-LB/M, laser–material interaction is primarily driven by high-power continuous-wave fiber lasers, typically operating at near-infrared wavelengths (~1070 nm) and delivered through galvanometer-based scan optics. Key beam characteristics, such as focal spot size, beam quality (M^2), and spatial irradiance distribution, collectively define the local energy input to the powder bed and strongly influence melt-pool geometry, stability, and thermal gradients [42,43]. From a process-physics perspective, the spatial irradiance distribution determines not only the peak energy density but also its spatial uniformity across the interaction zone, thereby controlling melt-pool homogeneity, local heat accumulation, and the process sensitivity to thermal instabilities [37,44]. Near-Gaussian beams inherently concentrate energy at the beam center, resulting in steep radial energy gradients [45]. This can increase peak temperatures and sensitivity to thermal instabilities, particularly at higher power or lower scan speeds [25]. Although most commercial PBF-LB/M systems employ near-Gaussian beam profiles, the laser delivery architecture enables controlled modification of the spatial energy distribution through optical or source-based beam-shaping strategies. Representative irradiance distributions frequently discussed in the PBF-LB/M literature [46–48] include Gaussian, flat-top (top-hat), and ring-shaped beam profiles. These examples illustrate fundamental beam-profile concepts rather than an exhaustive classification of all beam shapes reported to date. Fig. 3 provides schematic illustrations of these representative beam profiles for clarity. To reduce ambiguity in beam-shape terminology across different studies and platforms, Table 2 provides a naming crosswalk that maps commonly used literature labels and study-specific codes (e.g., BS#, Mode #, core/ring ratios) to the harmonized beam-profile terms adopted throughout this review.

A further source of ambiguity in comparing beam profiles is the definition of beam diameter and the associated energy–density metric. Standardized beam characterization is therefore essential: ISO 11146–1 specifies methods for measuring laser beam widths/diameters, divergence angles, and beam propagation ratios, including second moment-based beam-width concepts such as $D4\sigma$, while ISO 13694 specifies methods and parameters for measuring laser beam power or energy–density distributions at a defined plane [49,50]. For near-Gaussian beams, the $1/e^2$ diameter and full width at half maximum (FWHM) are commonly reported descriptors. However, these definitions are not directly interchangeable with $D4\sigma$ and become less transferable for multimodal, annular, core–ring, top-hat, or elliptical profiles. For such shaped beams, additional descriptors such as inner/outer diameter, ring width, core-to-ring power ratio, effective irradiated area, threshold-based diameter, peak irradiance, and orientation relative to the scan direction are often required. This distinction is important because the selected diameter and profile definition directly affect calculated linear energy density ($LED = P/v$), areal energy density ($AED = P/vh$),

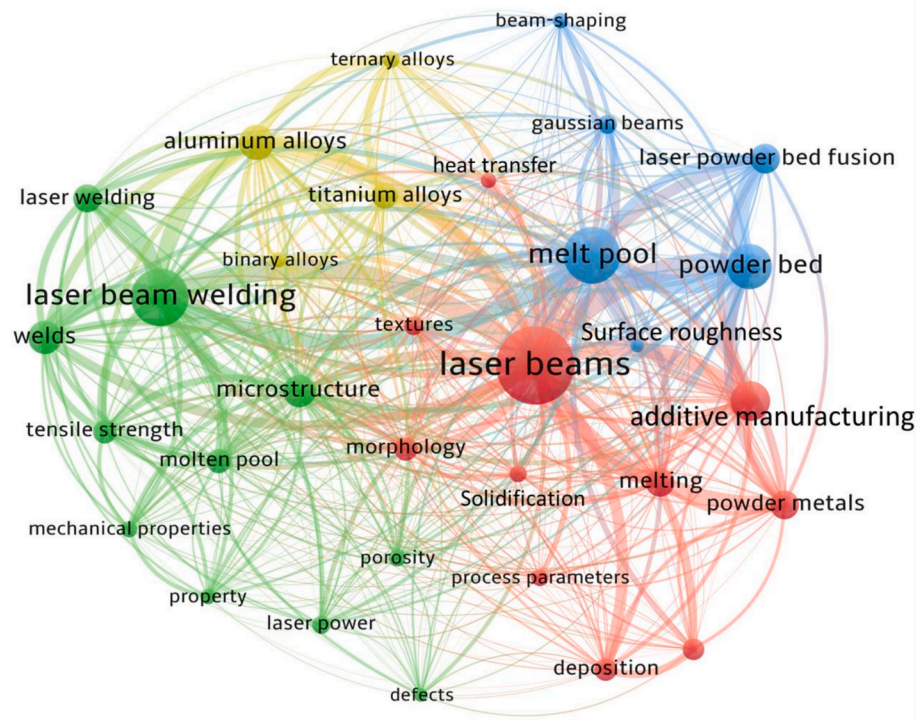


Fig. 1. Keyword co-occurrence map of PBF-LB/M beam-shaping literature from 2020 to early 2026 generated using VOSviewer. Node size indicates keyword occurrence frequency, link thickness represents co-occurrence strength, and colors indicate clusters of related research themes.

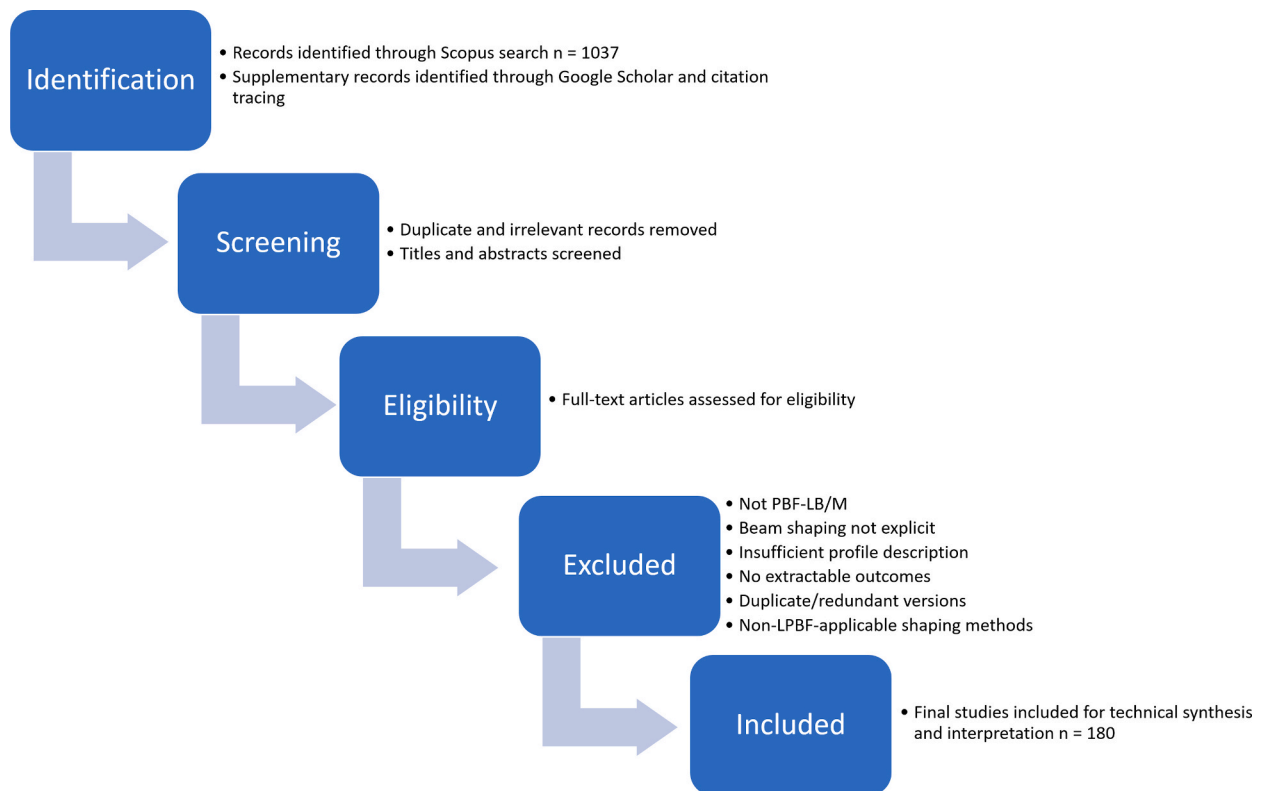


Fig. 2. PRISMA-style workflow summarizing the literature identification, screening, eligibility assessment, and final inclusion process used for this review study.

volumetric energy density ($VED = P/vht$), and productivity estimates. For example, Sow et al. [51] compared an $80\ \mu\text{m}$ Gaussian beam with a $500\ \mu\text{m}$ top-hat beam, both defined using the $1/e^2$ diameter, and showed that similar remelted depths could be achieved at substantially different

VED values; they also distinguished local VED from Energy per Built Volume (EBV) when evaluating part-scale energy input. More generally, LED, AED, and VED remain useful for initial screening, but they do not fully capture spatial irradiance redistribution, peak intensity, effective

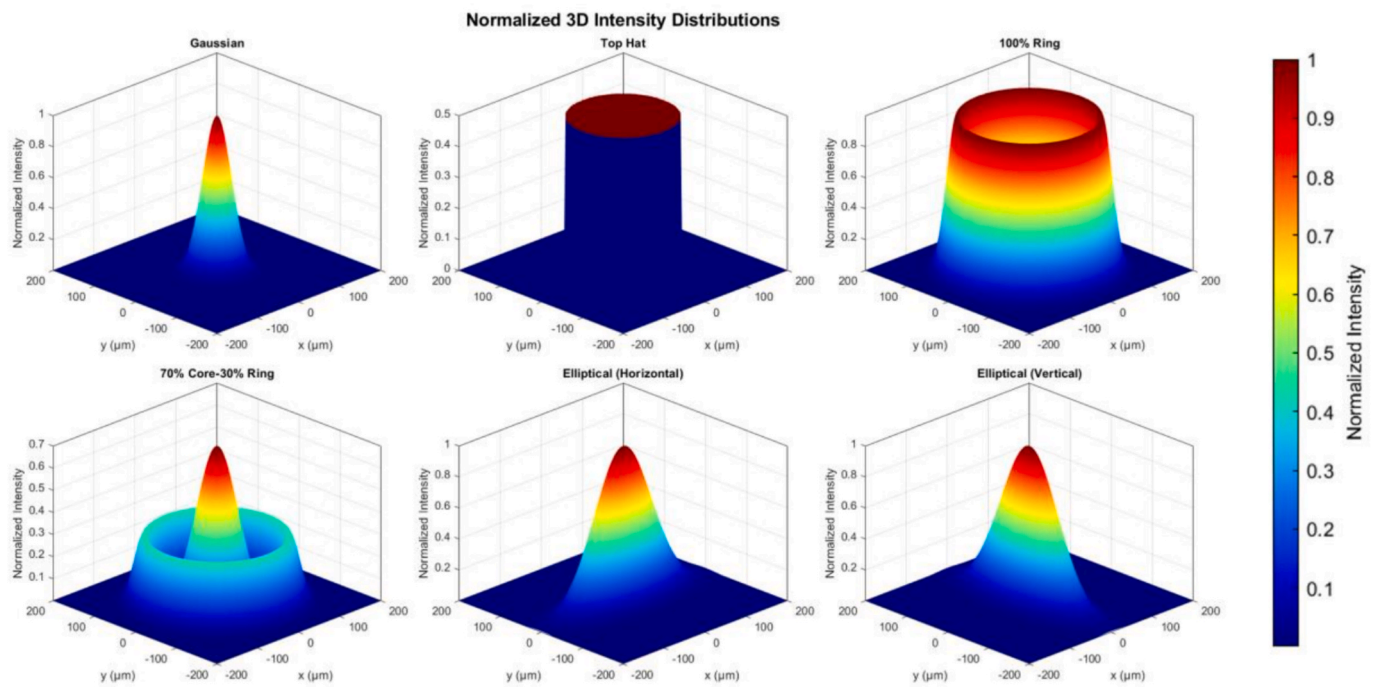


Fig. 3. Normalized 3D intensity distributions of common beam shapes (Gaussian, top-hat, ring, core-ring, and elliptical).

interaction width, or hatch-overlap conditions. Therefore, normalized or shape-aware descriptors, including normalized enthalpy, Péclet-type scaling, peak-irradiance-based metrics, beam-size-normalized energy input, and hatch-spacing-to-effective-melt-track-width ratios, can provide more meaningful comparisons across different beam sizes and profiles than nominal energy density alone [21,40,52–54]. Consequently, reported improvements in density, surface quality, or productivity should be interpreted together with the beam-diameter definition, irradiance distribution, and energy-normalization framework used in each study. To support more reproducible comparison across future studies, [Supplementary Table S1](#) proposes a minimum reporting set for PBF-LB/M beam-shaping studies, including beam-profile class, spot-size definition, irradiance descriptors, shape-aware energy metrics, process conditions, and part quality and productivity outputs.

In PBF-LB/M, beam shaping is primarily implemented by spatially tailoring the beam's irradiance distribution upstream of, or within, the beam delivery optics to obtain predefined profiles on the powder bed. Unlike conceptual discussions of beam characteristics, this section further focuses exclusively on beam-shaping strategies compatible with PBF-LB/M platforms, including high-power continuous-wave lasers, enclosed build environments, and industrial scan optics. Only methods that have been experimentally demonstrated or practically implemented in PBF-LB/M systems are considered [26,39,55]. These approaches can be broadly categorized into static optical beam shaping and source-based or dynamically adjustable beam shaping. Temporal-only shaping strategies are less common in PBF-LB/M and are therefore discussed only when coupled with spatial beam control [35,39].

3.1. Static optical beam shaping

Static beam shaping employs fixed optical components to tailor the spatial irradiance distribution before the powder bed and must remain optically stable under high power and long build durations [56–58]. Typical static solutions include diffractive optical elements (DOEs), refractive beam shapers, microlens arrays, and aspheric optical assemblies. For instance, DOEs [59,60] and axicon-based refractive shapers [61] have been used to generate flat-top, annular, and hybrid beam profiles. Previous reviews confirm that such passive optics are

compatible with industrial PBF-LB/M optical chains and enable reliable non-Gaussian intensity distributions [35,39]. A prominent static approach is aspheric (field-mapping) beam shaping, which uses tailored aspheric optical surfaces to remap a Gaussian input beam into a target irradiance distribution (e.g., flat-top or rectangular) based on energy conservation and optical path-length invariance [62]. Owing to their high energy efficiency and thermal robustness, field-mapping beam shapers are widely used in high-power laser applications [39]. In PBF-LB/M, refractive field-mapping architectures such as π Shaper and Focal- π Shaper systems have been incorporated as passive beam-modulating units within the beam delivery chain to realize non-Gaussian intensity distributions and influence melt-track formation under continuous-wave irradiation [42]. However, despite their technological maturity, these systems remain sensitive to variations in input beam quality and alignment, which can limit robustness and broader adoption in industrial PBF-LB/M environments.

A simpler yet practically relevant static shaping strategy is beam aperturing, in which the expanded laser beam is selectively truncated to extract a near-uniform irradiance region [57,58]. Apertures can be circular, rectangular, or application-specific and may function as binary, diffractive, holographic, or refractive shaping elements [63–65]. The main limitation of beam aperturing is the inherent loss of usable laser power due to partial beam blocking or truncation [66,67]. Nevertheless, such flattened intensity distributions have been applied in PBF-LB/M-related studies to evaluate their effect on melt-track geometry and process stability [51,68]. More advanced static approaches, including field-mapping beam shaping [69,70] and microlens-array beam homogenizers [71,72], can improve spatial uniformity but increase optical complexity. Although robust and simple, static beam shaping lacks adaptability during processing because the beam profile remains fixed once installed [39]. The working principles and trade-offs of representative static beam shaping methods relevant to PBF-LB/M are schematically illustrated in Fig. 4(a–c).

3.2. Source-Based and adjustable beam shaping

An increasingly important class of beam shaping methods in PBF-LB/M involves direct modification of the beam profile at the laser source.

Table 2

Crosswalk of beam-profile labels reported in the literature and the harmonized naming used in this review.

Beam profile (literature label(s))	Common name used in this review	Brief definition
Gaussian, near-Gaussian, Mode 0, BS0 (100/0)	Gaussian	Single central peak (reference baseline).
Ring, ring-shaped, donut/doughnut, annular	Ring (annular)	Energy concentrated in an outer ring (reduced center).
10/90, 20/80, 35/65 (core/ring)	Core-ring (ring-dominant)	Two-component beam; the ring carries most of the power.
40/60, 50/50 (core/ring), Gaussian-Ring	Core-ring (hybrid)	Mixed core + ring contribution (intermediate shape).
ring-core (80/20), core-ring (80/20)	Core-ring (core-dominant)	Two-component beam; core carries most of the power.
Point-Ring, dot-ring (sometimes written as dot-ring/point-ring)	Core-ring / multi-core ring	Central spot(s) + surrounding ring (implementation varies).
BS0–BS6, BS1–BS6, Beam Modes (M0–M6)	Beam-shaping index (study-specific)	Study-specific numbered beam set (e.g., BS0–BS6, or M0–M6); typically, five intermediate profiles between Gaussian-like (BS0) and ring-dominant (BS6); the exact mapping depends on the study.
BS3 (50/50), BS5 (20/80), BS6 (10/90) (when stated)	Core-ring family (with stated split)	Core-ring beam defined by the reported core/ring power split (e.g., 50/50, 20/80, 10/90); the BS code is the study's internal label.
Top-hat, flat-top, uniform beam profile	Flat-top (top-hat)	Approximately uniform intensity over the spot footprint.
Elliptical, transverse elliptical (TE), longitudinal elliptical (LE)	Elliptical (TE/LE)	Elliptical footprint: TE/LE indicates orientation relative to scan direction.
Bessel	Bessel	Non-Gaussian beam with a central lobe and surrounding rings (as used in cited studies).
Inverse Gaussian, inversely calculated profile, M-shaped	Inverse / redistributed	Reduced central intensity by design (profile defined by the cited study).
Tailored beam, LCoS-SLM, custom multi-spot	Programmable (tailored)	SLM-generated custom pattern (often multi-spot vs Gaussian).
AMB (Adjustable-Mode Beam), core-ring fiber (switchable)	Adjustable (source-based)	Laser source can tune/switch between Gaussian-like and ring-like modes.
Chair-shaped, Line//SD	Tailored (named patterns)	Chair-shaped, Line//SD, Tailored beam (named pattern). Study-specific named footprint; keep the original name.
Multi-core profiles	Multi-core / multi-spot	Multiple intensity peaks (often used to tailor melt-pool shape and properties).

Fiber-based laser systems, which dominate industrial PBF-LB/M platforms, enable adjustable beam shaping through controlled excitation of transverse modes or redistribution of optical power between the fiber core and cladding [73–75]. Core-ring and adjustable multimode fiber lasers allow continuous tuning between Gaussian-like, flat-top-like, and annular beam profiles without the need for external beam-shaping optics. By adjusting the relative power contribution of the core and cladding modes, these systems enable controlled modification of the spatial energy distribution delivered to the powder bed [76,77]. Several PBF-LB/M studies have demonstrated that such source-based shaping can be used to tailor melt-track width and overlap behavior while maintaining optical robustness and alignment insensitivity [26,55,78]. This source-based approach offers important practical advantages for PBF-LB/M, including reduced optical complexity, improved contamination tolerance, and compatibility with existing scan-head architectures. A representative example of a source-based adjustable beam shaping concept compatible with PBF-LB/M, based on core-ring fiber-laser

architectures, is schematically illustrated in Fig. 4(d). Moreover, the ability to rapidly switch between beam profiles enables flexibility in balancing resolution, stability, and productivity within a single build [28,79]. However, current implementations are largely limited to axisymmetric beam profiles, restricting the generation of asymmetric irradiance distributions. Nevertheless, due to their compatibility with high-power continuous-wave operation and industrial scanning systems, adjustable fiber-laser-based beam shaping solutions represent one of the most widely adopted and industrially relevant beam shaping approaches in PBF-LB/M research and emerging commercial platforms [46,80].

3.3. Programmable beam shaping in PBF-LB/M platforms

Programmable beam shaping approaches, most notably those based on spatial light modulators (SpLM) or acousto-optic modulation integrated into laser delivery systems, have also been explored in the PBF-LB/M context, as used in the study by Esmailzadeh et al [81]. These methods enable dynamic control of the spatial energy distribution, allowing transitions between beam profiles during a scan vector or across different build regions. In AM studies, SpLM-based shaping has been used to generate programmable flat-top, annular, or hybrid beam profiles, providing a high degree of flexibility in spatial energy control [22,82]. An example of programmable beam shaping implemented in PBF-LB/M research platforms, based on SpLM technology, is schematically illustrated in Fig. 4(e). Beyond SpLM-based systems, other programmable or arbitrary beam-generation concepts have also been explored, including optical phased-array/coherent-beam-combining approaches for rapidly reconfigurable beam shapes and high-frequency oscillation patterns, as well as optically addressable light-valve/intensity-filter systems for spatially patterned, layer-wise energy delivery [83,84]. However, their practical deployment remains constrained by power handling limitations, optical efficiency losses, speckle formation, and integration challenges with high-speed scan optics [85,86].

As a result, programmable beam shaping approaches in PBF-LB/M are currently limited to laboratory-scale or proof-of-concept demonstrations rather than widespread industrial implementation. However, these methods provide important insight into the potential of adaptive and multi-modal beam control, which is expected to play an increasing role in future laser-based AM system development. It is important to emphasize that not all beam shaping techniques reported in the broader photonics literature are suitable for PBF-LB/M. Methods requiring low-power operation, microscope objectives, nonlinear optical media, or highly specialized optical environments are generally incompatible with PBF-LB/M platforms and are therefore excluded from this review.

4. Thermo-Physical effects of laser beam profiles in PBF-LB/M

Once beam shaping strategies are implemented in PBF-LB/M systems, their influence primarily manifests through modifications to melt-pool geometry, thermal gradients, and defect formation. By redistributing spatial energy input, different beam profiles alter energy absorption and process stability. This section summarizes recent experimental and modeling insights that establish the mechanistic link between beam shape, process-window expansion, and resulting microstructure-property relationships.

4.1. Melt-Pool Geometry, Stability, and thermal implications

The geometry of the melt pool in PBF-LB/M is a critical determinant of process stability, porosity formation, surface quality, and subsequent microstructural evolution. Melt-pool geometry emerges from complex laser-matter interactions involving powder melting, solidification, heat conduction into previously solidified layers, and heat exchange with the surrounding environment [87,88]. The resulting temperature field defines the local temperature gradient (G) and solidification rate (R),

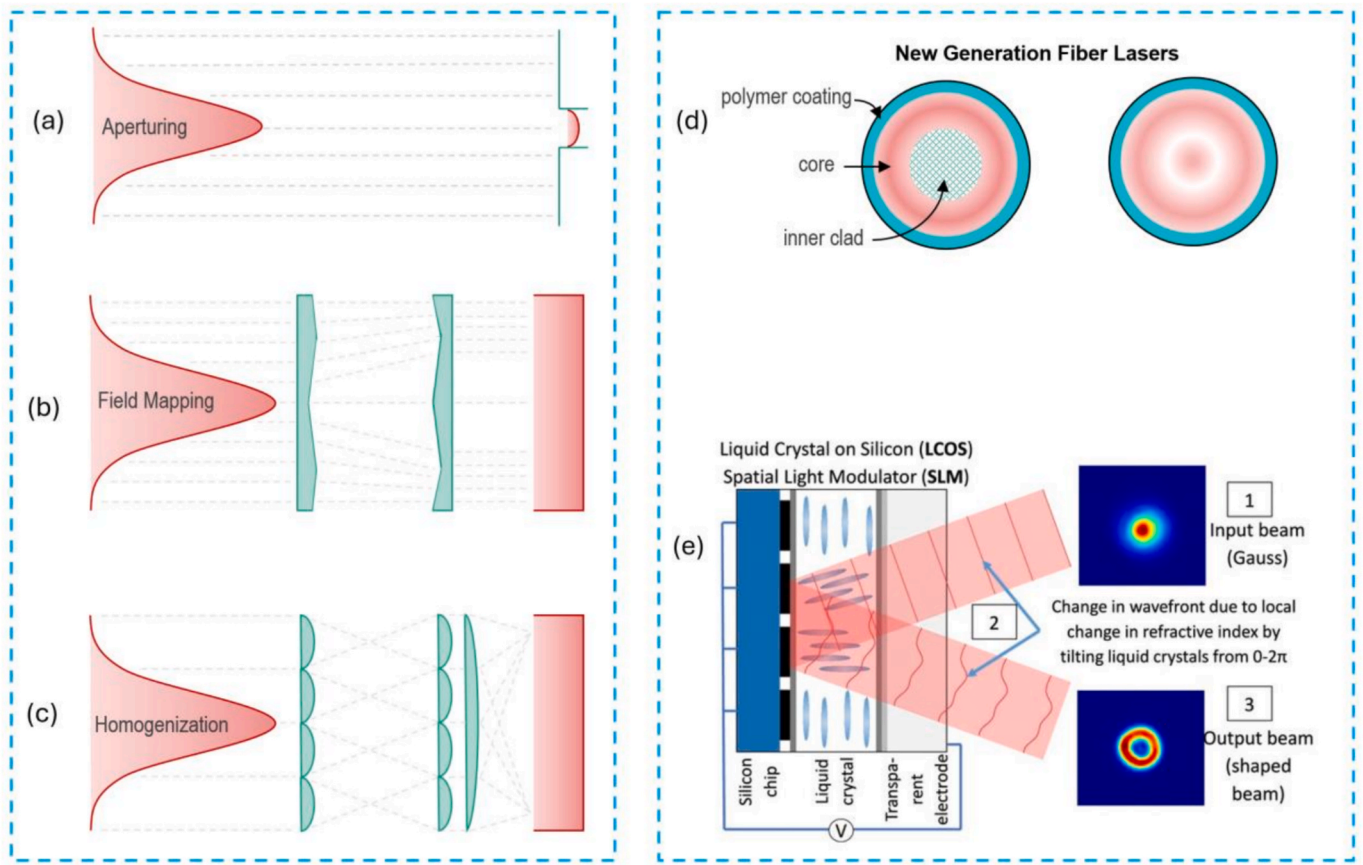


Fig. 4. Schematic illustrations of representative static and dynamic laser beam-shaping approaches used in PBF-LB/M: (a) beam aperturing, (b) field-mapping optics, (c) beam homogenization, and (d) fiber-based beam shaping, adapted from Refs. [35,72]; and (e) spatial-light-modulator (SpLM)-based beam shaping using a liquid-crystal-on-silicon (LCOS) device, adapted from Ref. [99] under the CC BY 4.0 license. Schematics are illustrative and not to scale.

which together influence solidification conditions and microstructural length scales [89,90]. Fig. 5 provides a simplified conceptual schematic

of melt-pool heat-transfer and melt-flow phenomena, including laser absorption/reflection, vapor depression and recoil pressure, radiation/

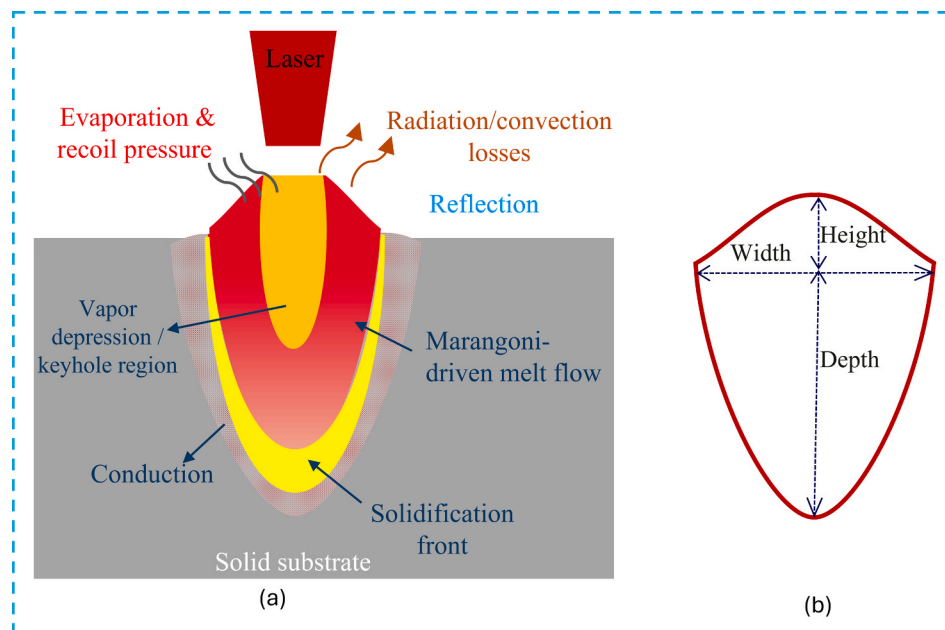


Fig. 5. Conceptual schematic of PBF-LB/M melt-pool phenomena: (a) vapor depression/keyhole region, evaporation, recoil pressure, multiple reflections, radiation/convection losses, Marangoni-driven melt flow, conduction into the substrate, and solidification front. (b) Definition of melt-pool width, penetration depth, and track height; the schematic is illustrative and not a quantitative melt-pool model.

convection losses, conduction into the substrate, Marangoni-driven melt flow, and representative 2D cross-sectional metrics. Laser beam profiles redistribute irradiance within the interaction zone, thereby controlling melt-pool size, penetration depth, and stability, and experimental studies confirm that beam shaping can mitigate instability-driven defects when combined with suitable power-speed settings [25,91].

Beam-profile effects on melt-pool stability can be rationalized through the coupled roles of peak irradiance, effective interaction area, and heat-flow direction. A narrow Gaussian beam concentrates energy near the melt-pool center, increasing local temperature, vaporization tendency, recoil pressure, and the likelihood of vapor-depression/keyhole formation [45,92]. In contrast, ring, core-ring, and top-hat

profiles redistribute part of the energy laterally, reducing local peak overheating and modifying Marangoni-driven melt flow, which generally promotes wider and shallower conduction-mode pools [25,80,93]. These changes also alter cooling-rate-related conditions, commonly linked to $G \times R$, and can shift the process between lack-of-fusion, conduction, and keyhole regimes [21,94]. Therefore, mechanistic comparisons should consider not only nominal LED/VED but also peak irradiance, beam diameter, effective overlap, and normalized descriptors such as normalized enthalpy or Péclet-type scaling [23,40].

Wischeropp et al. [95] compared Gaussian and donut (ring shape) profiles during PBF-LB/M of AlSi10Mg and showed that donut beams generated significantly wider and shallower melt tracks, with widths

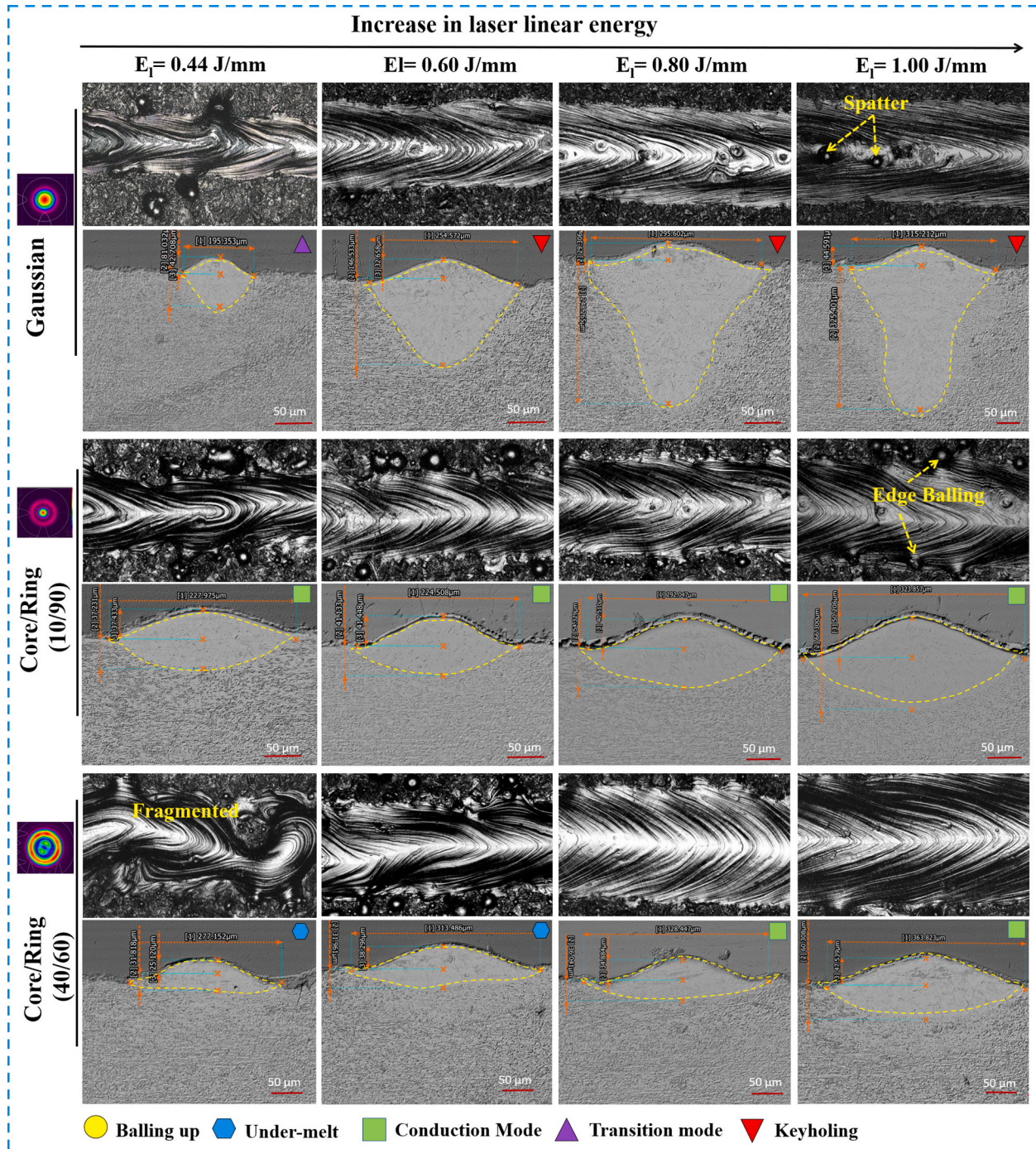


Fig. 6. Evolution of melt-pool morphology with increasing linear energy input for Gaussian and core-ring beams (40/60; 10/90 core/ring power split as per the source Ref. [98] under the CC BY 4.0 license.).

approximately 33% higher and depths about 36% lower than Gaussian profiles. The resulting width-to-depth ratios (3.5–6.2) indicated stable conduction-mode melting across a wide range of linear energy densities, whereas Gaussian beams transitioned to keyhole melting at higher inputs, leading to increased porosity. Similar behavior was reported by Galbusera et al. [48] for aluminum alloys, where ring-shape profiles

maintained conduction-mode melting across all investigated conditions despite increasing peak irradiance. Although higher peak irradiance deepened the melt pool for both beam shapes, ring profiles exhibited stable aspect ratios and sufficient interlayer bonding. Linear relationships between melt-pool geometry and peak irradiance highlighted that melt-pool stability is controlled more strongly by spatial energy

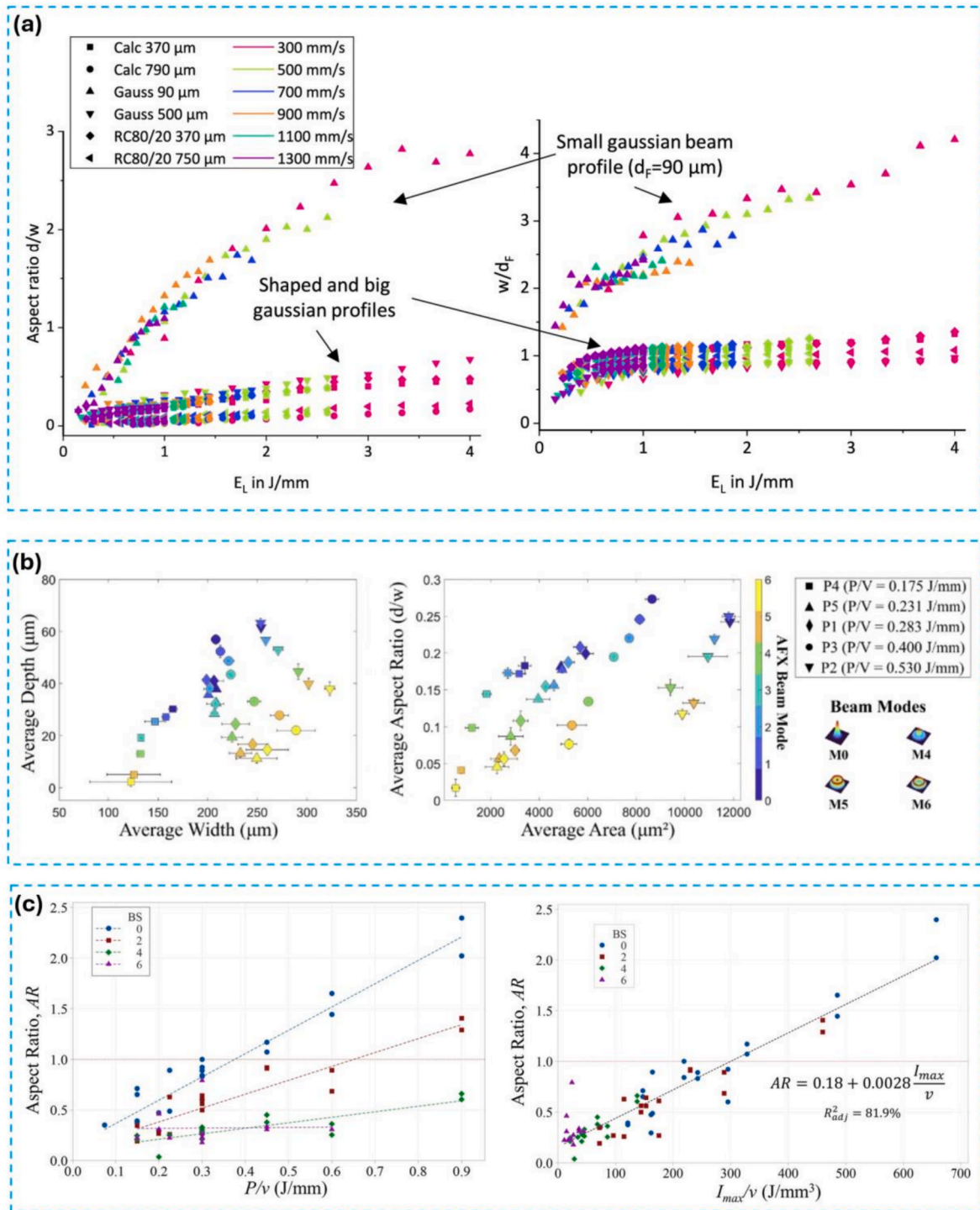


Fig. 7. (a) Aspect ratio (d/w , left) and normalized width (w/d_x , right) versus linear energy input (E_L) for Gaussian and shaped beams. Shaped or large-spot beams form wider, shallower pools, while small Gaussian beams yield deeper, narrower ones, adapted from Ref. [99], under the CC BY 4.0 license (b) Average melt-pool depth, width, and area for different beam modes (M_0 – M_6) under varying line energy densities (P/V). Increasing ring intensity broadens the pool and reduces the aspect ratio, adapted from Ref. [80] under the CC BY 4.0 license. (c) Correlation between aspect ratio and normalized power density (P/v) and peak irradiance per scan speed (I_{max}/v), showing that local peak intensity governs melt-pool geometry, with keyhole transition near $AR > 1$, adapted from Ref. [92] with permission from Springer Nature.

distribution than by nominal energy input alone. Pérez-Ruiz et al. [96] extended these findings to IN718, demonstrating that Gaussian produced deep, narrow melt pools with steep thermal gradients and pronounced keyhole tendencies, particularly at low scan speeds. In contrast, core-ring beams (20/80 core-to-ring ratio) generated wider and more stable melt pools by suppressing excessive penetration and maintaining conduction-mode melting. Complementary microstructural observations confirmed that smoother thermal fields under ring shapes promoted more uniform solidification behavior, consistent with enhanced melt-pool stability. Comparable beam-shape-dependent trends were reported by Bauch et al. [97] on pure copper, revealing that the stabilizing effect of ring-dominant shape extends to highly reflective materials. Increasing laser power enlarged melt-pool width, depth, and aspect ratio, with the 35/65 (core-ring) profile producing the deeper and widest pools due to higher peak intensity and stronger Marangoni convection. Ring-dominant (20/80 and 10/90) beams produced shallower melt pools by reducing vaporization and heat dissipation. Keyhole formation occurred at 1300 W for the 35/65 profile at low scan speeds ($<500 \text{ mm s}^{-1}$), while higher scan speeds or more annular profiles effectively suppressed keyholing. Consistent behavior was also observed by Ullah et al. [98] for Ti-6Al-4 V, where all beam modes operated in conduction mode at low to moderate linear energy densities ($0.44\text{--}0.66 \text{ J mm}^{-1}$). At higher linear energy density (LED) ($\geq 0.66 \text{ J mm}^{-1}$), Gaussian beams rapidly transitioned to keyhole melting accompanied by spatter and porosity, whereas shaped beams (40/60, 10/90 core to ring ratios) exhibited a more gradual transition and maintained wider, shallower, and more uniform melt pools (Fig. 6). Collectively, these studies demonstrate that beam shaping delays the onset of keyholing by redistributing energy away from the melt-pool center, thereby enhancing thermal stability and expanding the usable process window.

The stabilizing effect of beam shaping was further confirmed by Stoll et al. [99]. Their study investigated Gaussian, core-ring (20/80), and an inversely calculated beam profile with different spot sizes in PBF-LB/M of IN718. They showed that melt-pool protrusion/depression and the transition to keyhole melting depend strongly on beam shape in combination with laser power and scan speed (Fig. 7(a)). Compared with the small Gaussian beam, which exhibits a steep rise in aspect ratio and normalized width with increasing LED, the shaped and large-spot beams maintain a stable conduction regime ($w/d_x \approx 1$), thereby reducing penetration depth and mitigating keyholing-related porosity while enabling melt-pool widths up to $\sim 800 \mu\text{m}$ at shallow depths ($\sim 40 \mu\text{m}$). The inversely calculated beam profile produced particularly smooth and stable melt pools, enabling larger hatch distances and improved process efficiency. Another related study shows that increasing LED deepens the melt pool, while transitioning from Gaussian to ring-shaped modes produces wider but shallower melt pools at constant energy input, reducing AR and melt-pool area with increasing ring contribution (Fig. 7(b)) [80]. In a similar study, Baldi et al. [92] examined the combined effects of laser power, scan speed, and beam shape on melt-track geometry during PBF-LB/M of zinc. Their findings show that Gaussian shape produced deeper melt pools and higher AR, particularly at low scan speeds and high power, leading to keyhole formation. In contrast, ring-dominant redistributed power more evenly, transitioning the melting mode from keyhole to conduction and reducing melt pool depth. In addition, the melt track dimensions varied between $100\text{--}300 \mu\text{m}$ in width and $50\text{--}650 \mu\text{m}$ in depth, depending on energy input. This study also highlighted that zinc's low vaporization temperature ($T_v = 1180 \text{ K}$) promotes keyhole formation, which ring-dominant profiles can effectively suppress, thereby improving process stability. A predictive model based on LED (P/v) and maximum irradiance to speed ratio (I_{max}/v) was developed, which enables the optimized parameter selection for stable melt pool formation with a high degree of accuracy ($R^2_{\text{adj}} = 81.9\%$). The main relationships obtained are presented in Fig. 7(c).

Overall, Fig. 7(a–c) show that the laser's spatial energy distribution directs melt-pool geometry more effectively than the nominal energy

input alone. Gaussian shape exhibits strong sensitivity of AR to LED, promoting keyhole formation, while shaped beams sustain stable conduction-mode pools with widths close to the beam diameter. The scaling in Fig. 7(c) further confirms that local peak intensity primarily dictates melt-pool shape and stability. Similar to ring shapes, studies on top-hat shapes demonstrate melt-pool behavior that differs fundamentally from pure Gaussian [35,100], underscoring the need to optimize process parameters for specific beam shapes [47,101].

Numerical and simulation-based studies further corroborate the role of beam shaping in controlling melt-pool geometry and stability [25,102–104], while providing access to transient temperature fields, melt flow, and cooling rates that are difficult to measure experimentally. Their predictive capability, however, remains constrained by assumptions related to material properties, boundary conditions, powder representation, and vaporization models, necessitating experimental validation. Zöller et al. [93] numerically compared Gaussian and point-ring beam profiles at two beam diameters using a WCSPH model with ray-tracing and multiple reflections. Their results showed that beam-size-dependent energy density strongly controls the apparent beam-shape effect. At high energy density, beam-profile effects on single-track melt-pool depth, length, topology, temperature distribution, and local flow field were minor because deep vapor cavities and multiple reflections weakened the direct influence of the initial beam profile. In contrast, at lower energy density, the point-ring profile more clearly modified surface-temperature gradients, local melt flow, vapor-cavity topology, and evaporation behavior. Therefore, both beam size and spatial energy distribution must be considered when interpreting point-ring beam effects. Complementary simulations by Sinha et al. [21] on AlSi10Mg demonstrated that Gaussian, elliptical, top-hat, flat-top, ring-dominant, and adjustable-mode beams produce markedly different peak temperatures, melt-pool geometries, and cooling rates under identical processing conditions. Collectively, these studies show that spatial energy redistribution alters melt-pool behavior beyond what is captured by nominal energy input alone. Gaussian beams generally show greater sensitivity to LED and peak irradiance, which can promote high-aspect-ratio melt pools and earlier keyhole transition. By contrast, shaped and large-spot profiles often reduce local peak overheating and redistribute heat laterally, supporting wider, shallower, and more stable conduction-mode pools when beam size, power, scan speed, and overlap are appropriately optimized. The key findings of the reported studies are summarized in Table 3. These differences in melt-pool morphology provide the physical basis for the beam-shape-dependent porosity, microstructural evolution, and property responses discussed in the following sections.

4.2. Manifestation of Melt-Pool Dynamics: Surface Quality, part Density, and porosity formation

Beam shaping in PBF-LB/M has been shown to improve surface quality, part density, and defect mitigation, but the dominant benefit depends on the specific beam family and processing window. These improvements are consistently observed across studies employing non-Gaussian beam profiles, including top-hat, ring, and core-ring configurations [98,105,106]. This section summarizes studies demonstrating how modified melt-pool dynamics translate into measurable outcomes, including surface morphology, porosity evolution, and part density.

4.2.1. Influence on surface roughness

Surface roughness in PBF-LB/M is primarily influenced by melt-pool stability, wetting behavior, and track overlaps, and can be reduced through beam shaping that promotes uniform energy absorption and smoother melt-track formation. Accordingly, core-ring and ring-dominant profiles generate flatter, more continuous surfaces, whereas Gaussian beams tend to promote balling, spatter, and uneven tracks at high energy input [107–109]. The physical mechanisms underlying these improvements are closely tied to the spatial energy distribution of

Table 3

Summary of key findings on beam-shape effects on melt-pool characteristics in PBF-LB/M.

Reference	Beam Shape	Material	Dominant Melt-Pool Trend / Mechanistic Effect
Baldi et al. (2023) [92]	Gaussian, Core-Ring (BS2, BS4, BS6)	Zinc (Zn)	Gaussian beams promote deep, high-AR melt pools and keyholing, whereas ring beams transition melting to stable conduction mode and improve process stability.
Pérez-Ruiz et al. (2023) [96]	Gaussian, Core-Ring (20/80)	IN718 superalloy	Gaussian beams form deeper pools at low speeds, while ring beams produce wider, more stable melt pools with beam-shape-dependent remelting behavior.
Stoll et al. (2024) [99]	Gaussian, Core-Ring (80/20), Inverse Calculated	IN718	Beam shaping reduces penetration depth and keyholing, producing wider, flatter melt pools that enable larger hatch spacing and improved process robustness.
Galbusera et al. (2023) [48]	Gaussian, Core-Ring (BS1-BS6)	AlSi7Mg0.6	Melt-pool geometry is directed by peak irradiance, with beam shape modulating penetration depth while melt-pool width remains largely unchanged.
Sinha et al. (2025) [21]	Gaussian, Elliptical Gaussian, Top-hat, Flat-top, Ring, Adjustable Mode Beam (AMB)	AlSi10Mg	Beam shaping strongly controls melt-pool geometry and thermal behavior, with Gaussian beams producing deep, high-temperature pools and shaped beams yielding wider, more stable pools.
Grünewald et al. (2025) [178]	Ring shapes with varying Core-Ring (5/95, 10/90)	AISI 316 L Stainless Steel	Analytical modeling links melt-pool geometry and melting mode to dimensionless enthalpy, enabling accurate prediction of conduction-keyhole transition with reduced experimental effort.
Bauch et al. (2024) [97]	Core-Ring (35/65, 20/80, 10/90)	Pure Copper	Ring-shaped beams redistribute energy radially, producing wider, more stable melt pools and delaying keyhole formation in highly reflective copper.
Dai et al. (2025) [37]	Gaussian, Ring-dominant	316 L Stainless Steel	Gaussian beams induce concentrated heating and deep pools, while ring beams reduce thermal gradients and generate significantly larger, flatter melt pools.
Zöller et al. (2024) [93]	Gaussian, Point-Ring	Stainless steel 316	Beam-size/energy-density effects dominate: high-energy vapor cavities and multiple reflections weaken Gaussian-point-ring differences, whereas low-energy point-ring beams more clearly modify flow, temperature gradients, cavity topology, and evaporation.

Table 3 (continued)

Reference	Beam Shape	Material	Dominant Melt-Pool Trend / Mechanistic Effect
Chechik et al. (2024) [104]	Gaussian, Core-Ring (50/50, 40/60, 10/90)	Stainless Steel 316 L, Aluminum AW5083	Ring profiles enhance build rate at high energy input, while Gaussian beams perform better at low energy; alloy-dependent responses highlight material sensitivity to beam shape.
Ullah et al. (2025) [98]	Gaussian, Core-Ring (40/60, 10/90)	Ti-6Al-4 V	Gaussian beams form deep, narrow pools prone to keyholing, whereas ring and core-ring modes produce wider, stable conduction pools and significantly improve surface quality.
Pontrandolfi et al. (2025) [80]	Gaussian, Ring (BS0-BS6)	Ti-6Al-4 V	- Ring beams reduce peak temperature and stabilize melt-pool geometry compared to Gaussian beams. - CFD and pyrometry confirm reliable prediction of beam-shape effects.
Yuan et al. (2025) [120]	Gaussian, Ring-dominant	Ti-6Al-4 V	Ring-shaped beams stabilize keyhole morphology and reduce melt-pool fluctuations, whereas Gaussian beams exhibit unstable pools prone to defect formation.

the beam. The Gaussian profile creates steep temperature gradients and strong recoil pressure oscillations, driving intense outward Marangoni flow that destabilizes the melt-pool rim and leads to surface undulation and humping [110,111]. In contrast, ring and top-hat beams spread the energy laterally, maintaining conduction-mode melting with smoother flow and solidification fronts [48]. High-speed imaging and numerical simulations confirm that ring-shaped beams produce up to six times fewer spatters owing to lower vapor recoil and reduced temperature gradients [38].

While laser beam shaping plays an important role in reducing surface roughness, its effect cannot be fully isolated from other key process parameters such as laser power, scan speed, hatch spacing, and layer thickness. Most reported studies, therefore, assess beam-shape effects under controlled or systematically varied parameter sets, focusing on relative trends between beam profiles at comparable energy input and scan conditions, rather than absolute roughness values. Within this framework, Grünewald et al. [78] examined the influence of ring-shaped beam profiles on surface roughness and process stability in AISI 316 L. The study showed that surface roughness (S_a) reached its highest values in the area-energy range of approximately 2–4 J/mm², particularly for parameter sets combining high hatch distance and high laser power. Compared with Gaussian beams, ring-shaped profiles generally produced slightly lower roughness, which was attributed to their wider melt tracks and reduced surface protrusions. Similar trends were also reported in Ref. [112], as shown in Fig. 8(a). In a recent study, Wudy et al. [113] investigated large ring-shaped beams in PBF-LB/M of Inconel 718 and identified a surface instability termed surface bulging, which arises from high lateral velocity caused by large hatch distances and scan parameters. As shown in Fig. 8(b), surface roughness increased sharply with lateral velocity, particularly at high line energies, leading to severe roughness ($S_a > 200 \mu\text{m}$) and local lack-of-fusion defects, highlighting lateral velocity as a critical constraint when using large or ring-shaped beam profiles. Ullah et al. [98] showed that Gaussian beam profile

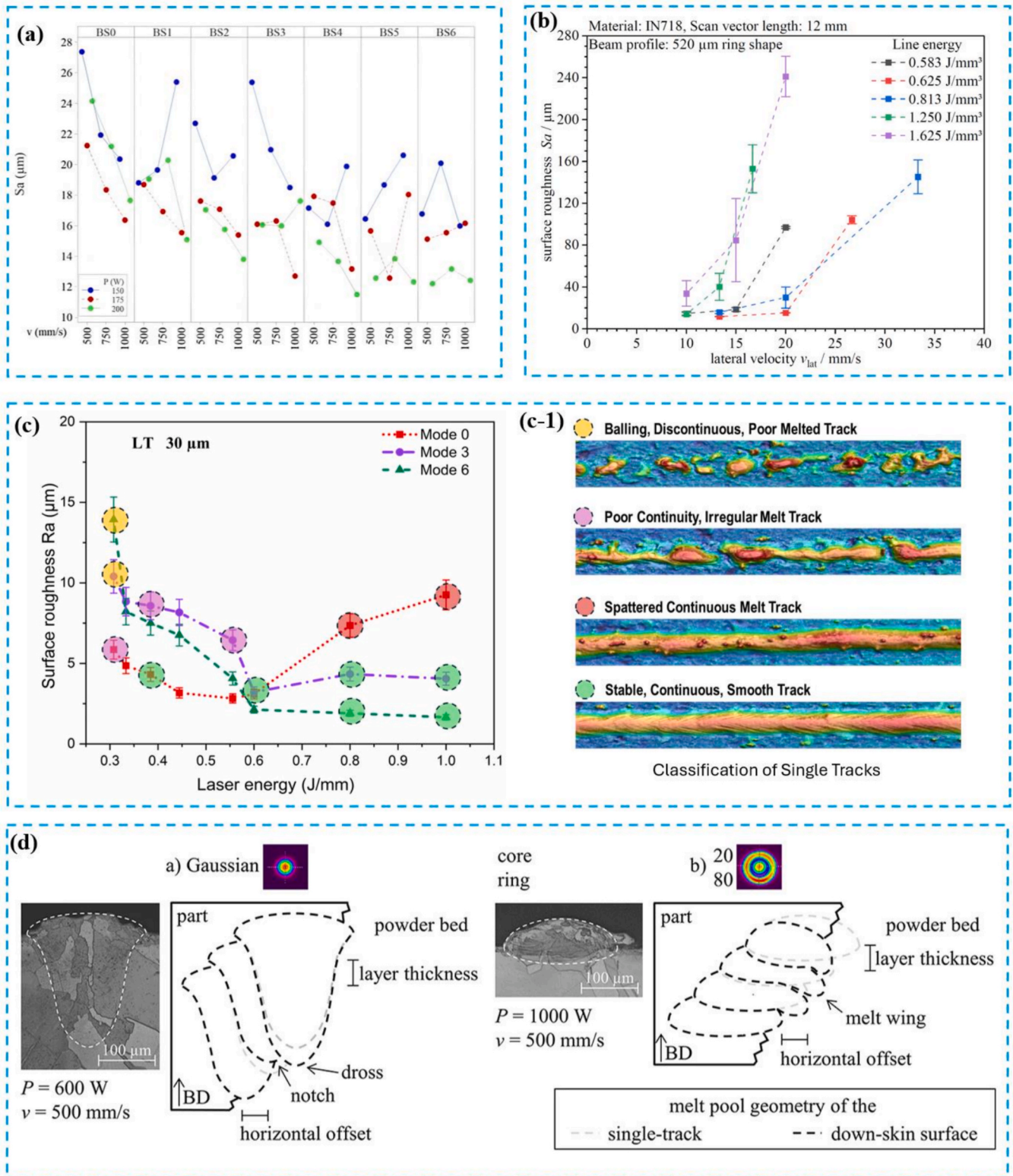


Fig. 8. Representative results showing the influence of laser beam shaping on surface roughness in PBF-LB/M. (a) Variation of S_a with linear energy density for different beam shapes, from Gaussian to ring-dominant profiles (BS0–BS6), adapted from Ref. [112] with permission from Elsevier; (b) Dependence of S_a on lateral velocity and line energy, where higher velocities lead to surface bulging and instability, adapted from Ref. [113] with permission from Elsevier; (c) Surface roughness versus laser energy for different beam shapes, with ring beams producing smoother tracks at optimal energy input; (c-1) Classification of single-track morphologies from unstable (balling) to stable (smooth) regimes, which are associated with surface roughness formation, adapted from Ref. [98] under the CC BY 4.0 license; (d) Surface roughness formation in PBF-LB/M of copper using Gaussian and ring-shaped (20/80) laser beam profiles under representative processing conditions, adapted from Ref. [106], under the CC BY 4.0 license.

increased roughness (in the top surface of single tracks) at high energy due to vaporization and spatter, whereas core-ring and ring-dominant beams reduced roughness by $> 30\%$ through stable melt-pool dynamics (Fig. 8(c)). However, the study also shows that the Gaussian beam produced significantly lower surface roughness at lower energy inputs. At low energy inputs, incomplete melting in ring modes marginally increased roughness, emphasizing the need for optimized energy-beam combinations. Bauch et al. [106] reported in detail that surface roughness in copper depends on beam shape and surface orientation: ring beams reduce down-skin roughness by up to 30% by forming shallower, wider melt pools with smoother melt wings, whereas Gaussian beams form deep keyhole pools and perform relatively better on up-skin surfaces, as illustrated in Fig. 8(d). Despite these advances, most studies remain limited to specific parameter sets, highlighting the

need for a unified roughness comparison framework. Grünwald et al. [40] in another study developed a dimensionless process map combining enthalpy, hatch distance, and build rate to predict surface roughness independent of beam shape. Their results showed that surface roughness increased sharply beyond a critical $\Delta H/h_s$ threshold (>6), particularly for beam profiles with high core intensity, whereas ring-dominant profiles maintained lower and more uniform roughness. This mapping provides a universal framework for optimizing surface quality across different beam configurations. Beyond ring-shaped profiles, alternative intensity distributions have also been explored to further enhance surface quality.

4.2.2. Control of porosity and density

Porosity in PBF-LB/M is a major source of cracks and defects,

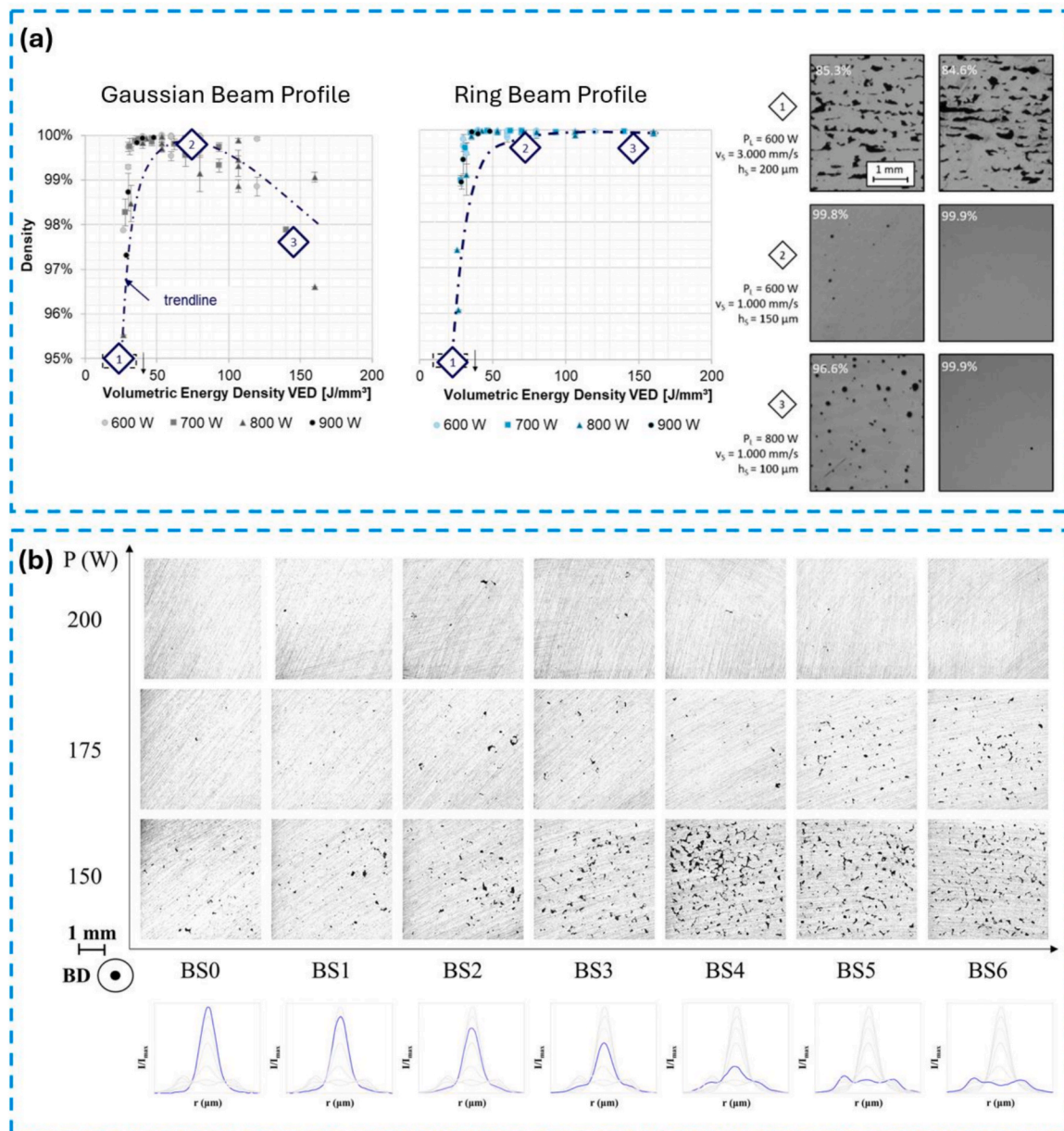


Fig. 9. Influence of beam profile on porosity and density in PBF-LB/M of aluminum alloys. (a) Gaussian versus ring beam processing of AlSi10Mg, showing that ring-dominant beams achieve $> 99.5\%$ density over a wider VED range; (a-1) corresponding metallographs indicate reduced porosity and more homogeneous melting, adapted from Ref. [95] with permission from AIP Publishing (b) Effect of different beam shapes from Gaussian to ring (BS0–BS6) and laser power on AlSi7Mg0.6, demonstrating that ring-dominant profiles (BS5–BS6) suppress pore formation and improve consolidation uniformity relative to Gaussian-like beams, adapted from Ref. [48] with permission from Elsevier.

strongly influenced by melt-pool geometry, stability, and evaporation behavior. Keyhole porosity, lack-of-fusion, and gas entrapment arise from melt-pool dynamics and the spatial distribution of laser energy, and act as stress concentrators that degrade tensile and fatigue performance [114–116]. While conventional parameter optimization can reduce porosity [117–119], laser beam shaping offers a more direct approach to stabilizing melt-pool behavior and enhancing densification, thereby reducing porosity.

The studies by Wischeropp et al. [95] showed that a ring-dominant (donut-shaped) beam in AlSi10Mg achieved > 99.5% density over a wider process window and suppressed keyhole porosity even at high laser power (Fig. 9(a)). Likewise, Galbusera et al. [48] reported that aluminum porosity strongly depends on beam intensity distribution: Gaussian beams caused lack-of-fusion at low energy input, while reduced-central-intensity profiles required higher power for full densification (Fig. 9(b) and Fig. 10(a)). Another similar study [96] reported that Gaussian beams in IN718 promoted keyhole porosity at low scan speeds, whereas higher scan speeds improved density above 99.5%. Ring-shaped beams produced shallower melt pools and were more prone to lack-of-fusion, but optimized ring-beam parameters still achieved > 99% density with higher process stability. In addition to reducing porosity, beam shaping contributes to high part density and overall

build integrity by suppressing pore formation, stabilizing melt-pool behavior, and improving layer consolidation [28,40,46,113]. However, the investigations indicate that relying only on changing the beam shape is not sufficient, as the energy-related parameters and layer thicknesses are crucial to control. For example, Vanmunster et al. [28] showed that ring-dominant beams widen the stable, high-density window for thin layers ($\sim 30 \mu\text{m}$), but lose this advantage at larger layer thickness. When densities around 99% are acceptable, ring beams allow significantly higher build rates. Similarly, a recent study by Ullah et al. [105] confirms that higher energy input is required to achieve fully pore-free parts using core-ring or ring-dominant profiles, as shown in Fig. 10(b, b-1). Furthermore, excessive hatch distance and lateral velocity can decrease density by causing surface bulging and local lack-of-fusion [113].

Grünwald et al. [40] proposed a dimensionless mapping framework showing that relative density increases with normalized enthalpy per hatch distance, with lack-of-fusion appearing below a threshold of ~ 1.5 (Fig. 10(c)). Gaussian-dominant beams showed stronger keyhole tendencies, while ring-dominant beams maintained > 99.8% density over broader conditions. As discussed in Section 3, VED-based comparisons of Gaussian and non-Gaussian beams are sensitive to beam-diameter definition, effective interaction width, peak irradiance, and hatch-overlap

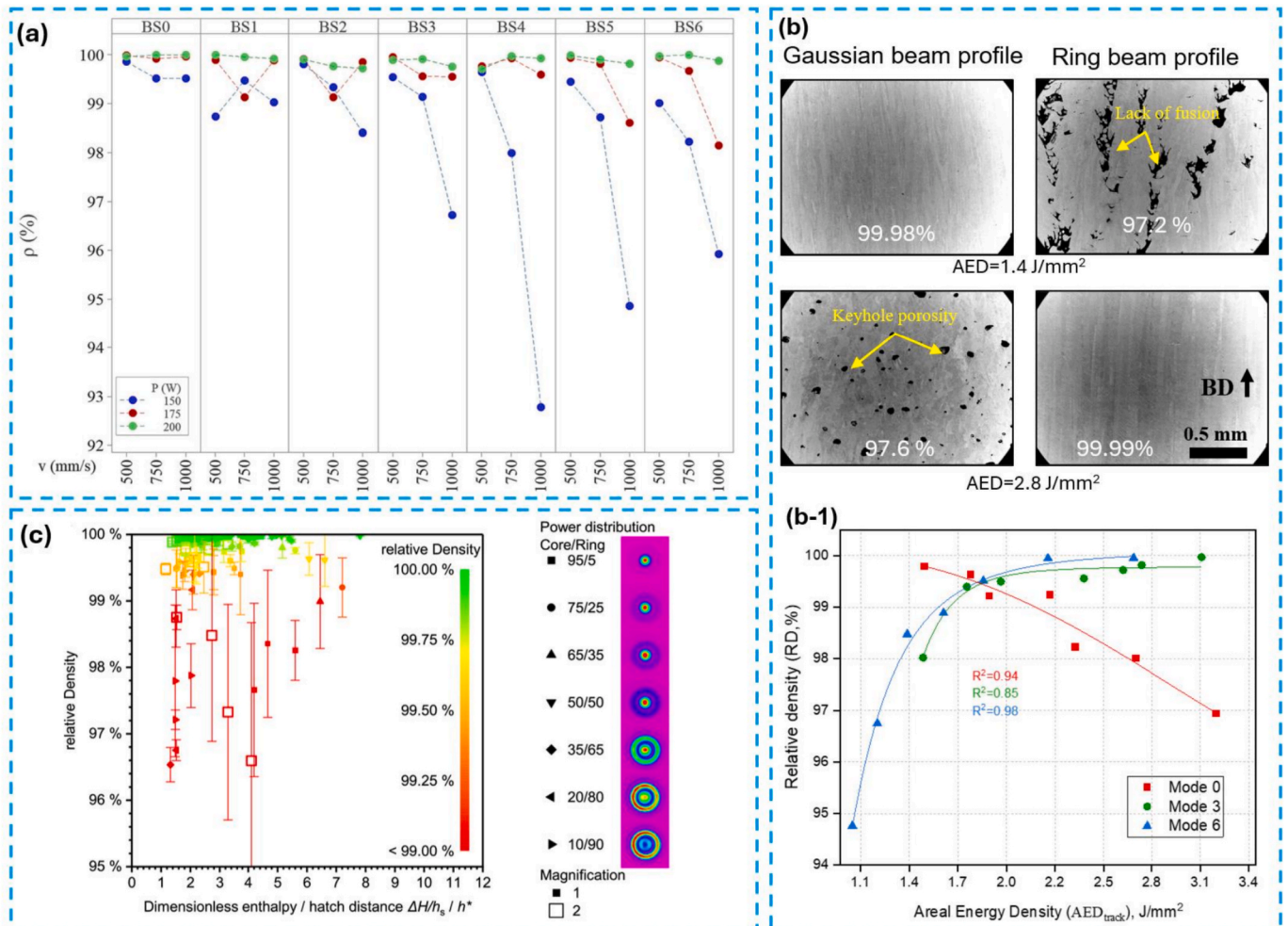


Fig. 10. Relative density of PBF-LB/M parts processed with different laser beam shapes and parameters. (a) Density as a function of scan speed and power for various beam profiles in Al-alloys, adapted from Ref. [48] with permission from Elsevier; (b) Melt-pool cross-sections of Ti-6Al-4 V showing Gaussian beams prone to keyhole porosity, whereas ring-dominant beams show lack-of-fusion at low energy but become nearly pore-free at higher input; (b-1) density versus areal energy density (AED) indicating optimal ranges for each beam mode, adapted from Ref. [105] under the CC BY 4.0 license; (c) Dimensionless density map based on normalized enthalpy per hatch distance, demonstrating overlapping process boundaries and consistent densification trends across beam shapes adapted from Ref. [40] under the CC BY license.

Table 4

Studies linking beam profile to melt-pool behavior, surface quality, and density in PBF-LB/M.

Reference	Beam Shape	Material	Key outcomes (surface quality + density/porosity)
Bauch et al. (2024) [97]	Core-Ring (35/65, 20/80, 10/90)	Cu	Among core-ring ratios, 35/65 achieved the highest density (99.77%), while more annular ratios (20/80, 10/90) showed reduced density due to shallower melt pools and increased lack-of-fusion porosity.
Bauch et al. (2025) [106]	Gaussian and Core-Ring (10/90, 20/80, 35/65)	Cu	- Ring beams reduced down-skin Sa by up to ~30% via smoother melt wings, whereas Gaussian beams performed better on up-skin and side surfaces. - Melt-pool aspect ratio directed the transition between conduction and keyhole modes, influencing defect formation.
Ullah et al. (2025) [98]	Gaussian, Core-Ring (40/60, 10/90)	Ti-6Al-4 V	- Ring modes widened melt tracks and reduced surface roughness by > 30% relative to Gaussian; excessive energy in Gaussian beams increased instability and roughening. - Core-ring and ring-dominant profiles improved melt-pool stability and supported near-full densification compared to Gaussian beams.
Ullah et al. (2026) [105]	Gaussian and Core-Ring (40/60, 10/90)	Ti-6Al-4 V	Gaussian beams showed a narrow processing window with keyholing at high energy, whereas ring and core-ring profiles enabled near-full densification (~99.9%) over a wider, more stable process window.
Wang et al. (2023) [140]	Gaussian, Flat-Top	Ti-6Al-4 V	Gaussian beams promoted high-aspect-ratio keyholing with elevated porosity risk, whereas flat-top profiles improved thermal uniformity and porosity control.
Yuan et al. (2025) [120]	Gaussian, Ring-dominant	Ti-6Al-4 V	Ring-shaped beams reduced pore formation and spatter by stabilizing melt-pool fluctuations, enabling quality retention at increased layer thickness.
Grünwald et al. (2025) [40]	Gaussian and Core-Ring (10/95 to 5/90)	AISI 316 L	- Roughness increased sharply beyond $\Delta H/hs > 6$, with the strongest increase for Gaussian-dominant beams; ring-dominant profiles maintained smoother surfaces. - Relative density increased with enthalpy per hatch distance, with ring profiles providing a broader high-density window and reduced keyholing.
Wischeropp et al. (2021) [25,95]	Gaussian, Ring-dominant	AlSi10Mg	Donut beams achieved > 99.5% density over a wider process window with reduced keyhole porosity, while Gaussian beams showed reduced density at high power due to gas porosity.
Galbusera et al. (2023) [48]	Gaussian, Top-Hat, Ring-dominant	AlSi7Mg0.6	Porosity was controlled by peak irradiance and reflectivity; ring profiles reduced keyhole porosity and enabled > 99% density when sufficient power prevented lack-of-fusion.
Pérez-Ruiz et al. (2024) [96]	Gaussian, Ring shapes (50/50, 20/80, 10/90 core/ring)	IN718	Gaussian beams promoted keyhole porosity at low scan speeds (<1000 mm/s), while ring profiles reduced keyhole porosity but could introduce lack-of-fusion at highly annular ratios; optimized parameters achieved > 99% density.
Grünwald et al. (2022) [179]	Gaussian, Ring-dominant	316 L stainless steel	- AOD-based quasi-static beam shaping was demonstrated in PBF-LB/M; all selected beam profiles achieved > 99.5% relative density. - Larger ring profiles showed irregular voids/lack-of-fusion-type defects when processed with unchanged parameters, indicating that laser power must be adapted to the larger exposed area.

conditions. Therefore, density and porosity trends should be interpreted using shape-aware or normalized descriptors rather than nominal VED alone. This becomes particularly problematic for core-ring and ring-dominant profiles, where the effective interaction width depends on the ring radius/thickness and cannot be represented by a single “spot diameter.” As a result, a nominally similar VED may correspond to markedly different overlap conditions (hatch spacing relative to effective melt-track width), and apparent lack-of-fusion in shaped beams can partly reflect a mismatch between hatch spacing and the effective beam/track width, rather than energy input alone. Tenbrock et al. [68] showed that top-hat beams in 316 L can achieve densities above 99.95% when the applied energy exceeds $\sim 57 \text{ J/mm}^3$ and the peak intensity remains above a critical threshold, emphasizing that melt-pool stability and keyhole suppression depend strongly on beam-profile design. Yuan et al. [120], linked porosity directly to keyhole stability and showed that Gaussian beams induce unstable keyholes, causing pores, spatter, and melt-pool oscillations. Ring-dominant beams redistributed the energy more uniformly, stabilizing the keyhole and reducing both porosity and surface defects while maintaining sufficient melting efficiency. The above-mentioned studies are further summarized in Table 4, providing a concise comparison of their key findings and the influence of different beam profiles on density and porosity-related defect formation.

Overall, existing studies consistently demonstrate that beam shaping contributes to controlling porosity and achieving high part density in PBF-LB/M by tailoring spatial energy distribution, peak irradiance, and melt-pool dynamics. Gaussian beams tend to promote keyhole porosity due to excessive central intensity, whereas ring-dominant and top-hat profiles distribute energy more uniformly and suppress keyholing. However, insufficient peak irradiance or inadequate overlap due to hatch spacing relative to the effective track width can induce lack-of-fusion defects, highlighting the need to maintain a critical irradiance threshold for adequate penetration and bonding. Material reflectivity further governs densification behavior, with highly reflective alloys such

as aluminum requiring higher irradiance than more absorptive materials like IN718. Beyond beam shape, optimization of laser power, scan speed, and hatch spacing remains essential to balance melting efficiency, process stability, and final density.

4.3. Build Rate, process Stability, and productivity

To address low build rates and high production costs in PBF-LB/M, laser beam shaping offers an effective strategy to balance productivity with process stability. Conventional approaches to increasing build rate, primarily through higher laser power, often exacerbate powder vaporization, spatter, and localized overheating, particularly for Gaussian beams, leading to porosity and lack-of-fusion defects [35,121–123]. Hardware-based solutions such as multi-laser systems can reduce build time but introduce additional quality risks in overlap regions [124,125]. By redistributing energy spatially, beam shaping mitigates thermal fluctuations and stabilizes melt-pool behavior, enabling higher energy input and more reliable, cost-effective production. However, productivity gains reported for beam shaping are difficult to compare directly across studies. Reported values may refer to exposure-only build rate, volumetric build rate, reduction in total build time, or energy/cost saving, and these metrics are not equivalent. The comparison is further affected by the selected Gaussian baseline, beam diameter and defocus condition, hatch spacing, layer thickness, density threshold, material absorptivity, and whether contour/core or hatch-only strategies are considered. Therefore, productivity claims should be interpreted together with part-quality criteria, such as density, surface quality, pore size distribution, and mechanical performance, rather than as isolated numerical gains.

Within this context, peer-reviewed studies generally report productivity improvements ranging from modest gains to several-fold increases, depending on the material, layer thickness, beam diameter, and accepted quality threshold. Grünwald et al. [78] showed that ring-

shaped beams in AISI 316 L expanded the process window by enabling higher laser powers, scan speeds, wider melt tracks, and larger hatch spacings. However, the productivity benefit was linked to the selected process-window definition and the requirement to maintain stable conduction-mode melting. Cozzolino et al. [122] reported a more moderate but experimentally quantified improvement for nickel alloy 718, with the ring beam reducing build time by 19%, reducing energy consumption by 10%, and increasing productivity by 23% while maintaining comparable density and mechanical response. Pallier et al. [126] reported up to $3.3 \times$ build-rate/printing-speed increase for Ni625 using adapted annular/ring-shaped intensity distributions. However, this work should be interpreted as an industrial/conference demonstration rather than a directly comparable peer-reviewed benchmark.

Kohlwes et al. [38] reported that homogeneous energy redistribution through beam shaping can increase build-up rate and process stability, with corresponding reductions in part cost under the investigated AlSi10Mg conditions. As summarized in Fig. 11, increasing the Gaussian beam diameter from 85 to 140 μm reduced the calculated part cost, while switching from a 140 μm Gaussian to a 140 μm ring-dominant profile provided an additional cost reduction under the reported conditions. A study by Gusarov et al. [127] further showed that modulated profiles, including flat-top and inverse-Gaussian beams, can expand the process window by enabling higher power and scan speed while improving melt-pool stability and reducing material loss.

In addition, source-based adjustable core–ring fiber lasers, such as nLIGHT's AFX platform, are relevant because they enable rapid switching between Gaussian-like and ring-dominant profiles and have been reported to support higher-productivity PBF-LB/M processing [30]. However, because some of these productivity demonstrations are industry-reported rather than peer-reviewed and provide limited details on beam-diameter definition, defocus condition, and productivity metrics, they should be treated as indicative evidence of potential rather than directly comparable quantitative benchmarks.

An overview of beam-shape effects on build rate, process stability, and productivity is summarized in Table 5. These studies demonstrate the potential of beam shaping to improve PBF-LB/M efficiency and process reliability, but the reported productivity gains should not be treated as directly comparable because beam diameter, layer thickness, hatch spacing, density criteria, and productivity metrics differ across studies. The strong dependence of productivity on layer thickness and quality criteria was recently demonstrated by Vanmunster et al. [28]. For 30 μm layers, the ring beam provided a larger process window and higher build rate, whereas for thicker layers, an equally powered ring-shaped beam was not necessarily more productive than a Gaussian beam because its flatter melt pool required lower scan speeds to achieve sufficient penetration. The study also showed that accepting a small

amount of porosity can substantially change the apparent productivity advantage of ring beams, although larger pores may be more detrimental to fatigue performance. These findings highlight that beam-shape-induced productivity gains must be optimized together with layer thickness, hatch spacing, density threshold, and application-specific property requirements. A broader cross-profile comparison of productivity, porosity, and microstructural effects is provided in Supplementary Table S2.

4.4. Microstructural evolution

Microstructural evolution plays a vital role in the performance and reliability of PBF-LB/M components, influencing grain morphology, phase distribution, texture development, and defect sensitivity. Owing to highly non-equilibrium conditions induced by localized energy input, directional heat flow, and rapid solidification, even subtle variations in thermal history can produce pronounced changes in grain structure and phase constitution. The formation of microstructures during laser–material interaction is directed by heat flow direction, thermal gradients, and cooling rates, which control phase transformations and grain growth mechanisms [8,102,128,129]. By tailoring the spatial distribution of laser energy, beam shaping adds a new level of process control over melt-pool dynamics and solidification. While a Gaussian beam typically induces steep gradients that favor columnar or cellular growth, alternative beam profiles modify the thermal field and cooling conditions, enabling refined or more heterogeneous microstructures [130–133]. Recent studies confirm that optimized beam profiles allow targeted microstructure control in PBF-LB/M without altering alloy composition [55,58,112,134–136].

Galbusera et al. [137] investigated Gaussian and ring-containing beam profiles during PBF-LB/M of Fe-2.9wt.%Si and demonstrated that ring irradiance can modify both grain morphology and crystallographic texture. Under Gaussian conditions, the microstructure mainly consisted of elongated columnar grains aligned with the build direction. In contrast, ring-containing profiles at low scan speed shifted the grain morphology toward coarser, less columnar, and more equiaxed-like structures, although the grains remained elongated along the build direction rather than fully equiaxed. Quantitatively, the addition of ring irradiance reduced the grain aspect ratio to below ~ 5 under selected conditions, compared with values of ~ 9 – 15 for Gaussian profiles at comparable high energy density. However, this grain-shape change was accompanied by stronger crystallographic texture and lower grain-boundary density. As shown in Fig. 12(a), increasing ring irradiance (Ir) at a constant scan speed of 100 mm/s increased the texture index and produced coarser grains, indicating that ring-based beam shaping modifies texture and grain morphology but does not necessarily produce

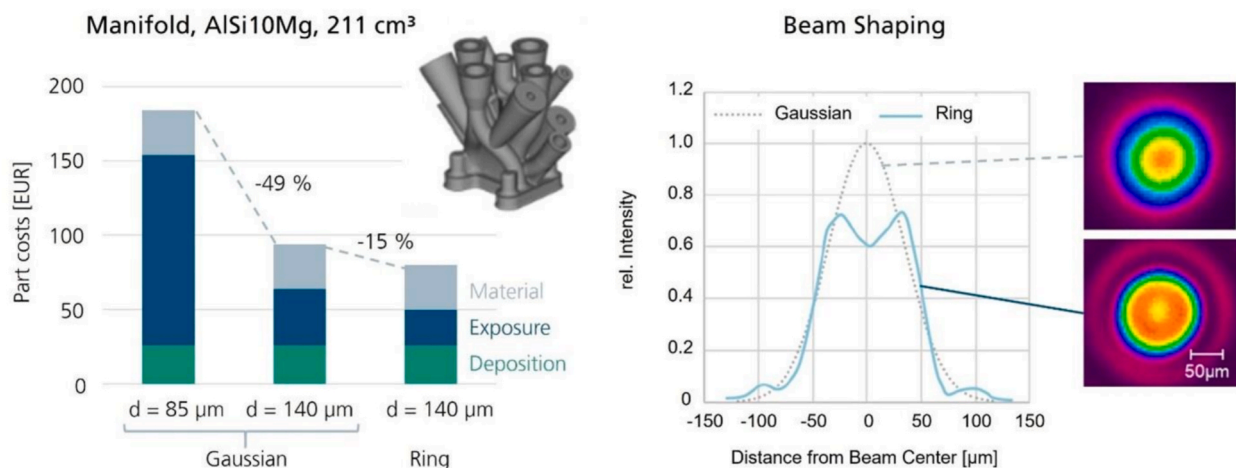


Fig. 11. Cost Reduction and Beam Shaping Effects in PBF-LB/M of AlSi10Mg [38].

Table 5

Reported effects of laser beam profiles on build rate, process stability, and productivity in PBF-LB/M. Values are not directly comparable because study conditions and productivity metrics differ.

Reference	Beam Shape	Material	Effects on Build Rate, Process Stability, and Productivity
Grünewald et al. (2021) [78]	Gaussian, Ring-dominant	AISI 316 L	• Ring-shaped beams expanded the process window, enabled wider melt pools and larger hatch spacing, resulting in higher productivity and reduced build time. • Improved stability relative to Gaussian beams due to conduction-mode melting.
Holla et al. (2023) [103]	Optimized Ring-dominant	AISI 316 L	• Optimized beam profiles reduced overheating and produced more uniform melt pools. • Indicates potential for improved stability and build rate, although direct productivity gains were not quantified.
Cozzolino et al. (2024) [122]	Gaussian, Ring-dominant	Nickel Alloy 718	• Ring-shaped beams increased productivity by ~23% and reduced build time by ~19%. • Energy consumption reduced by ~10%.
Pallier et al. (2024) [126]	Gaussian, Tailored Beam, Ring-dominant	Ni625, Inconel 939	• Reported $3.3 \times$ theoretical build-rate increase using adapted intensity distributions. • Industrial/conference demonstration; direct comparison with peer-reviewed studies is limited.
Wischeropp et al. (2021) [95]	Gaussian, Ring-dominant	AlSi10Mg	• Donut beams provided a broader process window and achieved > 99.5% density; direct productivity gain was not fully quantified, but wider stable melt tracks suggest possible productivity benefits.
Gusarov et al. (2018) [127]	Gaussian, Top-Hat, Inverse Gaussian	CoCrMo	• Flat-top and inverse-Gaussian profiles expanded the stable process window compared with Gaussian beams. • Enabled higher feasible power/scan-speed combinations with improved melt-pool stability and reduced material loss.
Vanmunster et al. (2025) [28]	Gaussian, Ring-dominant	316 L Stainless Steel	• Ring beams increased build rate by up to 66% and expanded the process window at thin layers (~30 μm). • At thicker layers, the productivity advantage diminished and depended strongly on the accepted density threshold.

a fully equiaxed microstructure. Similarly, Mirzabeigi et al. [136] investigated five different beam profiles in PBF-LB/M of IN718 and showed that tailored asymmetric profiles, particularly Line//SD and chair-shaped beams, reduced grain elongation and texture strength compared with ring-shaped beams. The reported texture index decreased from a strongly textured condition (J-index ≈ 4.6 for the ring-shaped profile) to near-random values for the best tailored profiles (≈ 1.37), indicating reduced anisotropy rather than fully equiaxed grain

formation. This was attributed to changes in melt-pool morphology and heat-flow direction, where higher melt-pool curvature and modified G/R conditions promoted grain refinement and more equiaxed-like morphologies.

The EBSD findings in the study by Cozzolino et al. [46] showed that Gaussian beams produced fine equiaxed to weakly elongated grains with weak/random texture, whereas increasing ring contribution promoted vertically elongated columnar grains and stronger build-direction texture. Despite these microstructural differences, all conditions achieved > 99% relative density and similar average microhardness. Complementary modeling by Moore et al. [94] demonstrated that Gaussian beams promote columnar grains due to localized high temperatures and deep melt pools, whereas ring-dominant shapes induce mixed morphologies with columnar grains at the melt-pool periphery and more equiaxed-like grains along the centerline. Bessel beams, which produced smaller melt pools and lower peak temperatures in the simulations, were predicted to promote grain refinement and a more equiaxed-like morphology compared with Gaussian beams (Fig. 12(b)). However, these results should be interpreted mainly as modeling-based trends. The available experimental work on Bessel/nondiffractive beam shaping suggests that the resulting grain refinement is modest and should not be interpreted as full equiaxed grain formation throughout the build direction [61].

Pontrandolfi et al. [80] combined experiments and CFD simulations to study programmable ring beam profiles in PBF-LB/M of Ti-6Al-4 V. Ring shapes reduced melt-pool temperature by up to 35%, producing wider and shallower pools that suppressed humping and improved process stability. Although all beam profiles produced ultrafine α laths with retained β , the growth orientation shifted from a radial pattern under Gaussian beams to predominantly vertical growth under ring beams. A strong negative correlation ($r = -0.91$) between beam mode and melt-pool temperature confirmed that peripheral energy redistribution enhances thermal stability and promotes uniform solidification. Esmailzadeh et al. [81] employed tailored beam profiles generated via an LCoS-SpLM to control microstructural evolution in PBF-LB/M of Ti-6Al-4 V. By combining FEM, in-situ thermal imaging, and EBSD, the study showed that tailored beams reduced cooling rates to $\approx 620 \text{ K s}^{-1}$ (compared to $\approx 2400 \text{ K s}^{-1}$ for Gaussian beams), promoting diffusive β into $\alpha + \beta$ transformation instead of α' martensite. FEM further confirmed that reduced temperature gradients (G) and solidification rates (R) lowered the $G \times R$ product, consistent with lamellar $\alpha + \beta$ formation, while EBSD revealed coarser prior- β grains in the tailored-beam regions (Fig. 13a).

Consistent trends were reported by Ullah et al. [105], where EBSD and SEM analyses showed that beam shape affects grain morphology and texture beyond nominal energy density. Core-ring 40/60 and 10/90 profiles produced broader, more stable melt pools, continuous prior- β grains, and uniformly oriented α' laths, whereas the Gaussian beam generated fragmented β grains and finer α' martensite due to steeper thermal gradients and faster cooling (Fig. 13b). No retained β phase was detected within EBSD resolution, indicating near-complete martensitic transformation under the investigated conditions. Similar trends have also been reported for other core-ring beam configurations [78,138,139].

Wang et al. [140] showed that the flat-top beam strongly influences phase transformation and microstructural evolution in PBF-LB/M of Ti-6Al-4 V. Compared to the Gaussian, flat-top beam promoted higher β -phase retention, particularly at smaller hatch spacing, due to prolonged sub-critical thermal exposure and reduced temperature gradients. Conversely, Gaussian produced primarily α/α' microstructures with minimal β phase. Similar effects were reported by Yuan et al. [141] for IN718, where the flat-top beam with larger spot sizes generated wider and flatter melt pools that suppressed stray grain nucleation and promoted stable directional grain growth (Fig. 14a). Iveković et al. [142] similarly reported that Gaussian produced finer grains, whereas the top-hat beam yielded elongated grains with aspect ratios exceeding 1 mm

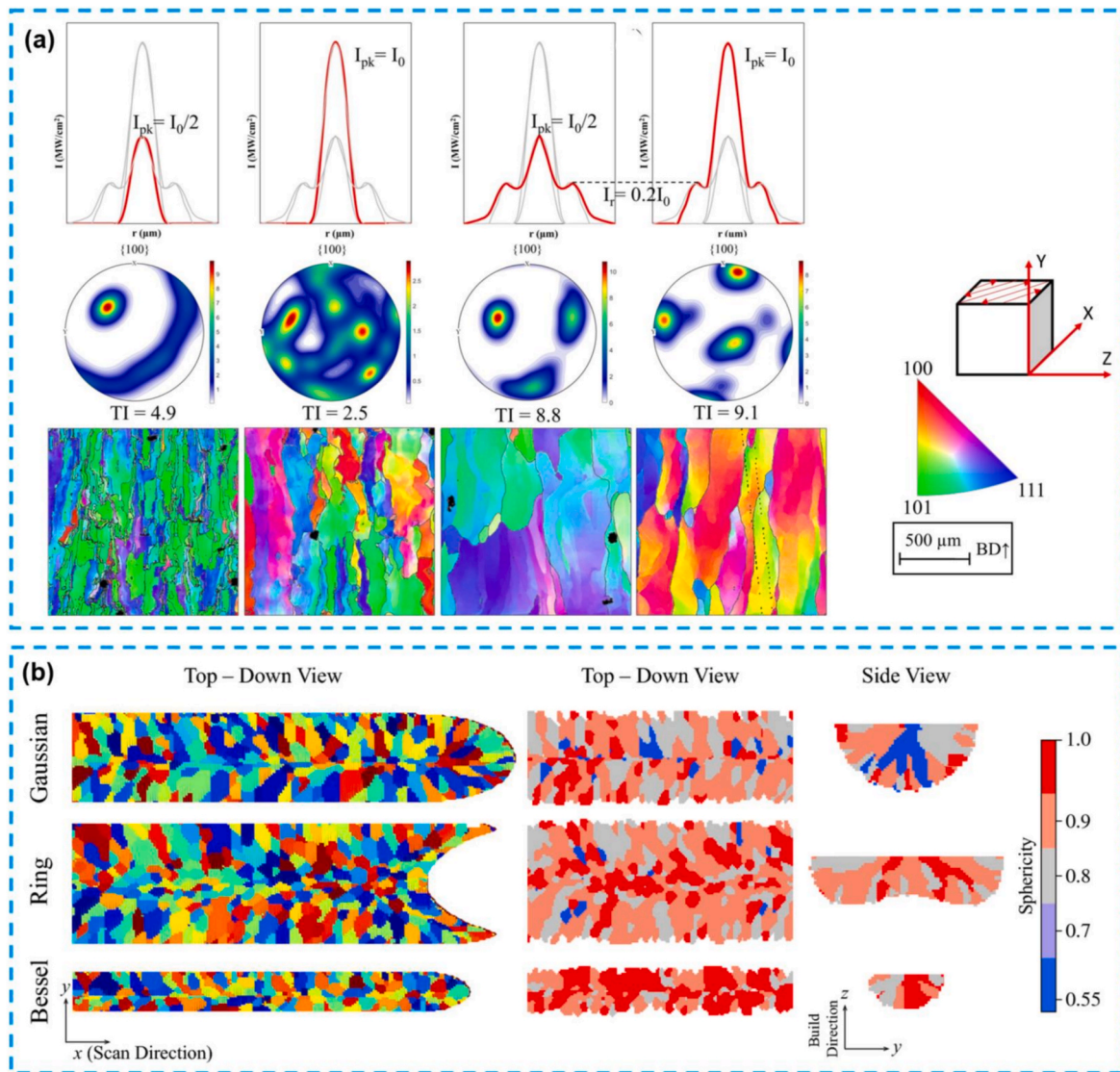


Fig. 12. Microstructural evolution under different beam-shaping configurations. (a) PF and IPF maps along the build direction for samples fabricated at $v = 100$ mm/s under different peak and ring irradiance conditions, with texture indices shown below each PF, adapted from Ref. [137] with permission from Elsevier (b) Simulated grain structures (top and side views) colored by orientation and sphericity for Gaussian, ring-dominant, and Bessel beams, illustrating predicted grain-refinement trends rather than fully equiaxed grain formation, adapted from Ref. [94] with permission from Springer Nature.

along the build direction. This transition was attributed to altered melt-pool geometry and reduced thermal gradients associated with uniform intensity distributions, promoting directional solidification and texture development [143–145]. These results indicate that top-hat/flat-top beams do not necessarily promote grain refinement; depending on spot size, thermal history, and alloy response, they may instead promote elongated or directionally grown grains.

Beyond general microstructural effects, a few studies have quantified changes in the columnar-to-equiaxed-like grain balance. For instance, Matthews et al. [134] showed that elliptical beam shaping, particularly transverse elliptical profiles, refined the microstructure and increased the equiaxed-like grain fraction in 316 L stainless steel compared with Gaussian beams under comparable processing conditions. This effect was associated with shallower melt pools, lower depth-to-width ratios, reduced thermal gradients and conduction-mode solidification conditions. Roehling et al. [58] further showed that transverse elliptical beam shaping refined the microstructure in PBF-LB/M of 316 L, increasing the reported equiaxed-grain fraction from $\sim 30\%$ to $\sim 47\%$ and reducing the average grain area by nearly 50% compared with Gaussian beams (Fig. 14b). Rather than indicating a fully equiaxed build, these results

reflect a higher fraction of small equiaxed-like grains, weaker texture, and a reduced columnar fraction under the investigated conditions. This refinement was associated with lower thermal gradients, enhanced nucleation frequency, and shallower melt depths that helped preserve equiaxed-like grains during subsequent layer deposition. High-fidelity ALE3D multiphysics simulations and G–R solidification maps further supported that transverse elliptical beams provide thermal conditions more favorable for increased equiaxed-like grain formation and mixed columnar–equiaxed growth.

Complementary numerical simulations by Shi et al. [102] confirmed these trends, showing that transverse elliptical beams produced the highest nucleation propensity during laser scanning, while longitudinal elliptical beams generated the deepest melt pools and strongest columnar texture. The reported simulations also showed a higher number of nuclei for transverse elliptical beams than for circular Gaussian and longitudinal elliptical beams under comparable conditions, supporting increased mixed columnar–equiaxed-like grain formation rather than fully equiaxed microstructures. Key results are summarized in Table 6.

Overall, the available literature suggests that static or quasi-static

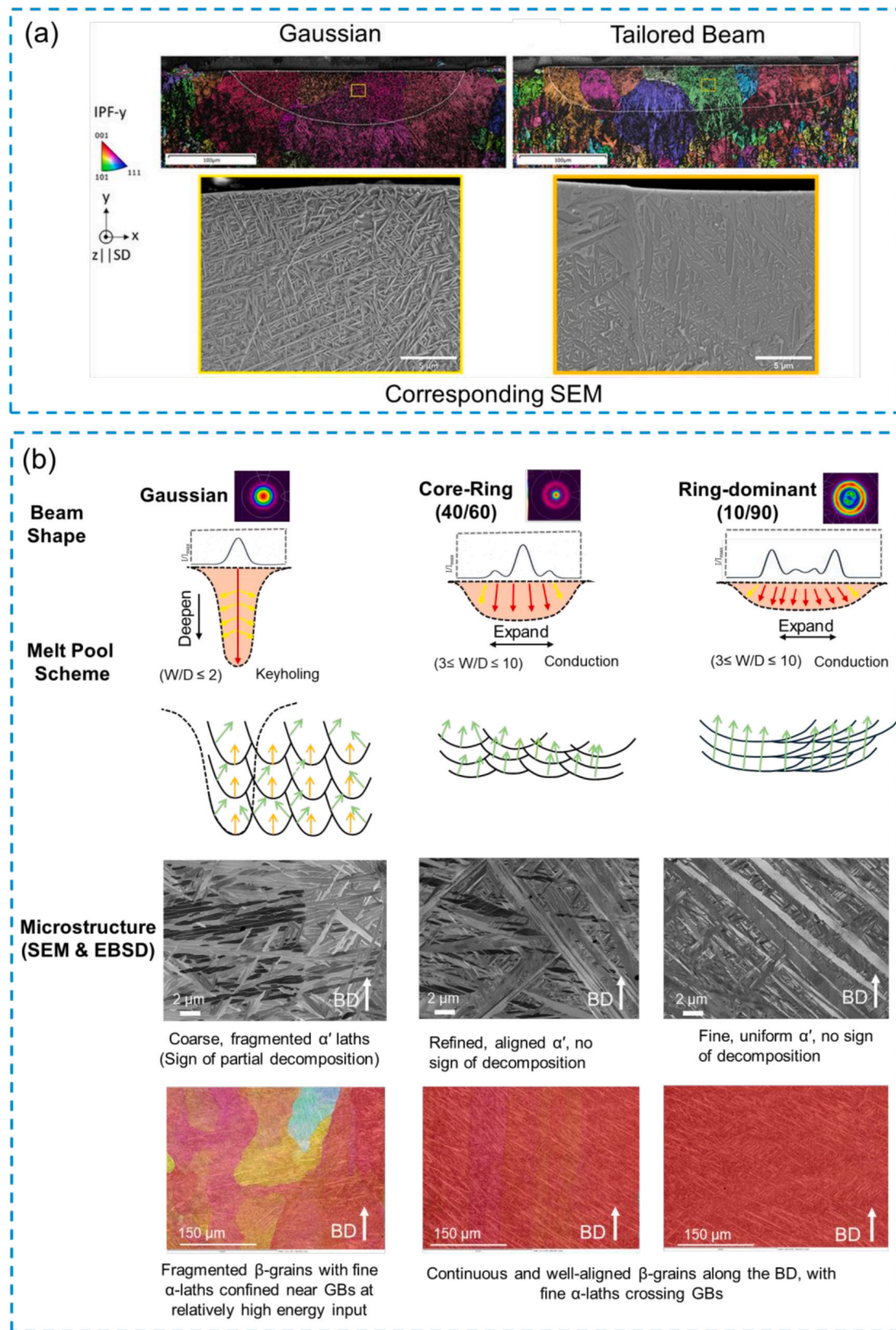


Fig. 13. Microstructure of Ti-6Al-4 V processed with different beam shapes. (a) EBSD IPF/SEM comparison of Gaussian and tailored beams, showing fine α' under Gaussian and coarser lamellar α + β under tailored beams, adapted from Ref. [81] under the CC BY license; (b) Schematic showing how Gaussian, Core-Ring and Ring beams influence melt-pool geometry and grain orientation, ring-shaped beams yielding wider, shallower pools and more uniform, vertically aligned grains, adapted from Ref. [105], under the CC BY 4.0 license.

single-beam shaping can modify grain morphology and texture by changing melt-pool geometry, thermal gradients, and cooling rates, but it rarely produces a fully equiaxed microstructure throughout the build direction. The reported effects are better described as moderate grain refinement, increased equiaxed-like fraction, reduced texture strength, or altered columnar growth direction. Quantitatively, reported changes include near-random texture in selected tailored profiles, up to $\sim 35\%$ reduction in melt-pool temperature for ring profiles, cooling-rate reduction from ~ 2400 to $\sim 620 \text{ K s}^{-1}$ for tailored Ti-6Al-4 V tracks, and nearly 50% average grain-area reduction for elliptical beams in 316 L. Therefore, stronger control of fully equiaxed grain structures may require dynamic beam modulation, multi-beam strategies, scan-strategy optimization, inoculation, or alloy-design approaches rather than static single-beam shaping alone.

4.5. Mechanical properties

Based on the understandings from the previous sections, laser beam shaping influences microstructure, porosity, melt pool dynamics, and surface quality, which ultimately have a significant impact on the mechanical properties of PBF-LB/M-fabricated parts. While studies in this area are limited, the few available findings highlight the influence of tailored beam profiles on mechanical properties and their potential to enhance fatigue strength, crack resistance, ultimate tensile strength

(UTS), and ductility [48,96,136,137,140,146]. Similar studies in weld-ing processes have also shown that laser beam shaping influences weld geometry, microstructure, and eventually the mechanical properties, improving weld quality and performance [34,147–149].

A thorough investigation by Pérez-Ruiz et al. [96] showed that beam shaping significantly influences the mechanical properties of PBF-LB/M-fabricated IN718 by altering melt-pool geometry and microstructure. The ring-dominant beam (20/80) expanded the operational window and achieved high densification across a broader scan-speed range. Tensile tests revealed a larger variation in Young's modulus for the ring beam ($\Delta E = 129 \text{ GPa}$) than for the Gaussian beam ($\Delta E = 50 \text{ GPa}$), indicating increased elastic anisotropy due to beam-induced texture; however, the absolute modulus values must also be considered to evaluate the practical stiffness of the material. The ring configuration also provided a favorable balance between strength and ductility, attributed to refined microstructure and reduced porosity. Similarly, Godec et al. [150] reported that ring-shaped beams enabled higher build rates but produced a more columnar microstructure, resulting in slightly lower tensile strength and hardness (by $\sim 3\text{--}7\%$) compared to Gaussian beams, which yielded finer grains and more isotropic behavior. For both beam profiles, optimal mechanical performance was achieved after heat treatment at 984°C , whereas higher temperatures ($>1034^\circ\text{C}$) led to recrystallization and carbide coarsening, which degraded properties. Representative results are shown in Fig. 15(a). Despite its lower

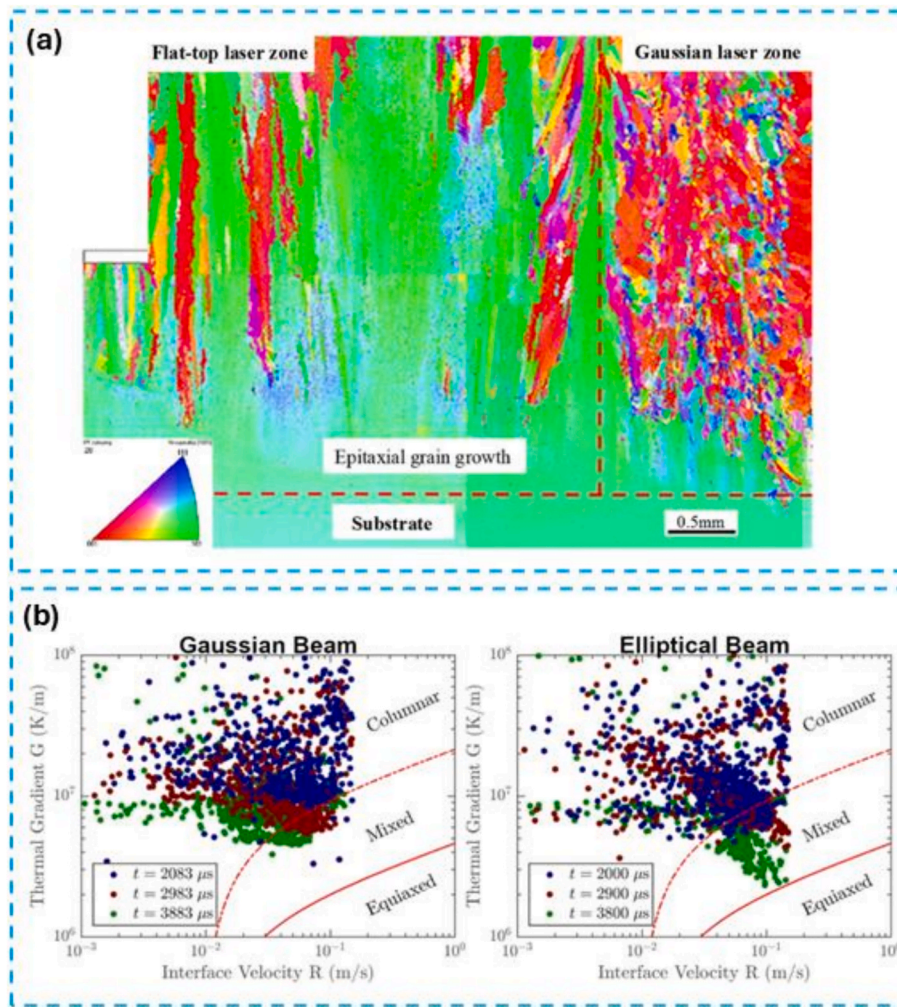


Fig. 14. (a) EBSD map showing epitaxial grain growth across Gaussian and flat-top laser zones in Inconel 718 fabricated using double-laser scanning (900 W flat-top, 300 W Gaussian), adapted from Ref. [141] under the CC BY 4.0 license; (b) Thermal gradient (G) vs. interface velocity (R) plots for Gaussian and elliptical beams based on Hunt's solidification map, illustrating transitions between columnar, mixed, and equiaxed growth modes, adapted from Ref. [58] with permission from Elsevier.

Table 6

The influence of laser beam profiles on microstructures in PBF-LB/M process.

Reference	Beam Shape	Material	Influence of Beam Shaping on Microstructure
Cozzolino et al. (2025) [46]	Gaussian, defocused Gaussian, half Gaussian–half ring, full ring	Nickel alloy 718	- Ring contribution produced wider, shallower melt pools and promoted vertically elongated columnar grains with stronger build-direction texture. - Gaussian beams produced finer grains with weak/random texture. Density remained > 99% and average microhardness was similar across profiles.
Mirzabeigi et al. (2024) [136]	Ring-shaped, Core-ring, Line//SD (parallel to SD), Line⊥SD (perpendicular to SD), Chair-shaped	Inconel 718	- Chair-shaped and Line//SD beams produced more equiaxed-like grain morphologies, lower texture index values, and reduced anisotropy compared with ring-shaped beams. - Ring-shaped beams promote columnar grains with dominant (100) orientation.
Pérez-Ruiz et al. (2024) [96]	Gaussian, Ring-dominant (BS5, BS6)	IN718	- Gaussian: Hierarchical lamellar microstructures with multiple crystalline orientations ($\langle 011 \rangle$, $\langle 101 \rangle$); high misorientation between melt pool zones. - Doughnut: Uniform $\langle 111 \rangle$ texture with reduced misorientation; grain refinement due to elongated non-remelted zones and thermal gradient misalignment.
Bayat et al. (2024) [22]	Gaussian, Ring, Radially Symmetric Beam Profiles	Ti-6Al-4 V	- Gaussian: Deep narrow, melting pools with long columnar grains converging at the centerline, forming localized equiaxed-like grains near the melt-pool root. - Ring-shaped: Produce wide, shallow melt pools with columnar grains parallel to the z-direction, reducing equiaxed-like grains at the centerline. - Radially symmetric profiles offer high width-to-depth ratios (5–6), increasing productivity by reducing hatching but limiting melt pool depth for thicker layers.
Esmailzadeh et al. (2025) [81]	Tailored beam using LCoS-SLM (custom multi-spot vs. Gaussian)	Ti-6Al-4 V	- Tailored beam reduced cooling rate by $\sim 3.8\times$ (620 K/s vs. 2400 K/s), promoting $\alpha + \beta$ lamellar microstructure instead of α'-martensite. - FEM and thermal imaging confirmed correlated lower thermal gradients. - Grain coarsening and Burgers orientation relationship verified by EBSD. - Demonstrated potential for site-specific microstructure control and architected dual-phase regions without post-heat treatment.
Ullah et al. (2025) [105]	Gaussian, Core-Ring (40/60, 10/90)	Ti-6Al-4 V	- Ring-dominated beams produced wider, shallower, and more stable melt pools, leading to continuous β grains and uniformly oriented α' laths. - Gaussian beams caused fragmented β grains and fine α' martensite due to steep thermal gradients and rapid cooling. - No retained β phase was detected within EBSD resolution - Flat-top beam promoted β-phase formation at smaller HS, while martensitic α' phase dominated at larger HS; the balance of β-phase improved mechanical properties.
Wang et al. (2024) [140]	Gaussian, Flat-Top	Ti-6Al-4 V	- Gaussian produced deep melt pools with columnar grains spanning the pool width. - Ring beams showed mixed morphologies, with more equiaxed-like grains near the centerline and columnar grains at the periphery. - Bessel beams generated smaller melt pools and finer grains in simulations, with a higher fraction of equiaxed-like grains compared with Gaussian beam. - Laser beam shaping altered temperature gradients, introducing a new design space for tailoring grain structures.
Moore et al. (2024) [94]	Gaussian, Ring-dominant, Bessel	316 L Stainless Steel (validated against 304 L)	- Gaussian: Dominated by columnar grain growth, limited equiaxed grain formation, strong crystallographic texture, larger grains, and less grain refinement. - Elliptical beams increased the reported equiaxed-like grain fraction, reduced texture strength, decreased average grain area, and promoted grain refinement compared with Gaussian beam.
Roehling et al. (2020) [58]	Gaussian, Elliptical	316 L Stainless Steel	- Transverse Elliptical (TE): Promotes mixed columnar–equiaxed-like grain morphologies due to wider supercooled zones and smaller G/R ratios. High nucleation frequency during laser operation, but reduced nucleation post-laser shut-off. - Circular Gaussian (CG): Dominated by columnar grains with moderate texture strength and fewer equiaxed-like grains compared to TE. Limited nucleation due to higher thermal gradients. - Longitudinal Elliptical (LE): Produces the strongest columnar grain texture among the beam profiles. Similar nucleation behavior to CG, but stronger grain alignment.
Shi et al. (2020) [102]	Transverse Elliptical, Gaussian, Longitudinal Elliptical	316 L-stainless steel	- Gaussian beams produced columnar grains - Core–ring/ring-containing profiles shifted the morphology toward less columnar, more equiaxed-like grains under selected conditions. - Ring beams enabled coarser grains, reduced grain boundaries, and stronger crystallographic texture.
Galbusera et al. (2024) [137]	Gaussian, Core-Ring, Ring-dominant	Fe-2.9wt.%Si alloy	

strength, the ring beam reduced carbide formation and improved elongation in horizontal samples, attributed to slower cooling and reduced thermal gradients.

Wu et al. [14] investigated the influence of Gaussian and dot-ring (flat-top) beams on the microstructure and mechanical properties of DD6 nickel-based superalloy fabricated by PBF-LB/M. The dot-ring beam produced a wider, shallower melt pool that promoted stable epitaxial columnar growth with a strong $\langle 001 \rangle$ texture and significantly

reduced solidification cracking. Compared with the Gaussian beam, it increased ultimate tensile strength by $\sim 20\%$ (1205 MPa) and elongation by $\sim 46\%$ (15.2%), attributed to a higher fraction of low-angle grain boundaries, enhanced strain hardening, and reduced defect density. In contrast, Gaussian beams generated deeper, unstable melt pools with macrocracks, higher residual stress, and lower ductility (Fig. 15(b)). Overall, the study demonstrates that homogenizing laser energy distribution through beam shaping enhances both strength and ductility in

PBF-LB/M–processed superalloys. Building on their earlier analysis of melt-pool geometry and porosity evolution, Galbusera et al. [48] demonstrated that beam-shape-induced variations in melt-pool aspect ratio (AR) and depth-to-layer-thickness ratio (h/z) directly govern the mechanical response of PBF-LB/M AlSi7Mg0.6. By varying beam profiles and irradiance levels, they showed that both UTS and elongation at fracture (ϵ_f) strongly depend on melt-pool geometry. A peak irradiance of 27.1 MW/cm² using a Gaussian beam (BS0, 266 W) produced the highest UTS (413 MPa) and ϵ_f (9.4%), attributed to deeper melt pools and refined microstructures. In contrast, flatter beam profiles with higher beam indices yielded shallower melt pools, resulting in reduced UTS (down to 199 MPa) and ϵ_f (0.8%) due to non-uniform microstructures.

These results highlight that optimizing both peak irradiance and ring intensity is essential to balance mechanical performance and maintain high densification (>99.5%), underscoring the role of beam shaping in tailoring grain structure, defect population, and the strength–ductility trade-off. However, the literature on this topic remains limited. Only a few studies have demonstrated that laser beam shape can markedly influence the mechanical performance of PBF-LB/M–fabricated parts, affecting properties such as stiffness, hardness, compressive strength, ductility, and structural homogeneity, as summarized in Table 7. Therefore, mechanical-property changes should be interpreted as the combined effects of defect population, melt-pool geometry, grain morphology, and texture, rather than as a direct consequence of beam shape alone. More systematic investigations are still needed across different materials and beam configurations to isolate the intrinsic effect of beam shape from variations in spot size, energy distribution, and processing conditions.

Taken together, the relative effectiveness of beam shaping depends strongly on both the beam family and the target outcome. Core–ring and ring-dominant profiles are most consistently linked to improved melt-pool stability, reduced spatter/keyhole tendency, and potential productivity gains, but highly ring-dominant profiles may increase lack-of-fusion risk when penetration or hatch overlap is insufficient. Top-hat/flat-top beams provide more uniform energy delivery and can support large-spot processing, whereas Bessel and elliptical/tailored beams are more often associated with melt-pool aspect-ratio control, grain refinement, and texture modification. Direct comparison across studies remains difficult because beam diameter, energy normalization, material system, density threshold, and productivity metrics are not reported consistently. A cross-profile comparison is provided in Supplementary Table S2.

5. Modeling and simulation for laser beam shaping in PBF-LB/M

Numerical modeling and simulation are essential for understanding beam-shape-dependent laser–material interactions in PBF-LB/M. Because melt-pool evolution occurs over micro- to millisecond time-scales and involves coupled heat transfer, free-surface deformation, Marangoni flow, recoil pressure, vaporization, and rapid solidification, many mechanisms are difficult to isolate experimentally. Validated simulations therefore provide an important route for linking spatial irradiance distribution to melt-pool geometry, thermal gradients, defect formation, and microstructural evolution, supporting the design and optimization of advanced beam-shaping strategies [151].

High-fidelity melt-pool models are particularly valuable because they resolve the coupled heat-transfer and fluid-flow mechanisms that influence process stability. Three-dimensional transient thermo-fluid simulations have shown that recoil pressure, surface tension, Marangoni shear, and convective heat transport strongly influence melt-pool morphology and keyhole behavior [152,153]. Parametric studies further show that increasing laser power can deepen the vapor depression and melt pool, whereas higher scan speed reduces effective line energy and shortens the interaction time. Similarly, insufficient overlap at large hatch spacings can promote lack-of-fusion defects between

adjacent tracks [93,154]. These studies demonstrate that modeling can help identify how beam shape modifies the balance between conduction-mode melting, keyhole instability, and lack-of-fusion. To clarify the current numerical landscape, this section summarizes modeling progress across the simulation chain, from optical-field definition and powder-bed representation to thermo-fluid modeling, microstructure prediction, and emerging data-driven surrogate approaches.

5.1. The simulation route: From optics to grain evolution

5.1.1. Optical field and beam propagation modeling

The simulation route begins with defining the spatial irradiance distribution delivered to the powder bed. For static beam-shaping systems, such as diffractive optical elements, scalar diffraction or Fourier-optical methods are commonly used to describe phase modulation and far-field intensity formation [155]. Refractive field-mapping systems, including aspheric beam shapers, are often modeled using geometric ray tracing to describe the transformation of a Gaussian input beam into flat-top, annular, or other target intensity distributions at the focal plane [156]. In many PBF-LB/M simulations, however, the measured or prescribed beam profile is directly implemented as a surface or volumetric heat source.

5.1.2. Meso-Scale powder bed generation

Once the beam footprint is defined, its interaction with the powder layer depends strongly on powder-bed morphology. High-fidelity models increasingly use the discrete element method (DEM) to generate realistic particle-scale powder layers with stochastic packing and size distributions [157]. This is important because local porosity, particle contacts, and shadowing influence absorptivity, heat conduction, and melting behavior, especially under non-Gaussian beam profiles. Nevertheless, most beam-shaping simulations still use simplified continuum powder or bare-plate assumptions to reduce computational cost.

5.1.3. Meso-Scale Thermo-Fluid dynamics (CFD)

At the melt-pool scale, thermo-fluid CFD models are used to capture heat transfer, fluid flow, free-surface evolution, and vaporization-related effects. These models are particularly useful for comparing Gaussian and shaped beams because they can resolve how spatial irradiance redistribution changes peak temperature, recoil pressure, Marangoni flow, melt-pool depth, and surface stability. Gaussian beams concentrate energy near the track center, promoting localized overheating, steep thermal gradients, and deeper melt pools. By contrast, ring-dominant, annular, and top-hat profiles distribute energy more laterally, often reducing peak temperature and promoting wider, shallower, and more stable conduction-mode melt pools [22,158].

5.1.4. Microstructural and solidification modeling

To connect melt-pool behavior with final material properties, thermo-fluid simulations are increasingly coupled with cellular automata, phase-field, or CET-based solidification models. Thermal histories extracted from melt-pool simulations provide local temperature gradients G , solidification rates R , cooling rates, and G/R ratios, which control grain nucleation, competitive growth, texture evolution, and columnar-to-equiaxed transition behavior [102,159,160]. High G/R conditions generally favor directional columnar growth, whereas reduced thermal gradients and enhanced constitutional undercooling can increase equiaxed-like grain formation. These models therefore help explain how beam shaping modifies grain morphology and texture by changing melt-pool geometry and heat-flow direction.

5.1.5. Data-Driven Surrogates and Machine learning

Because high-fidelity thermo-fluid simulations are computationally expensive, data-driven surrogate models are increasingly being explored

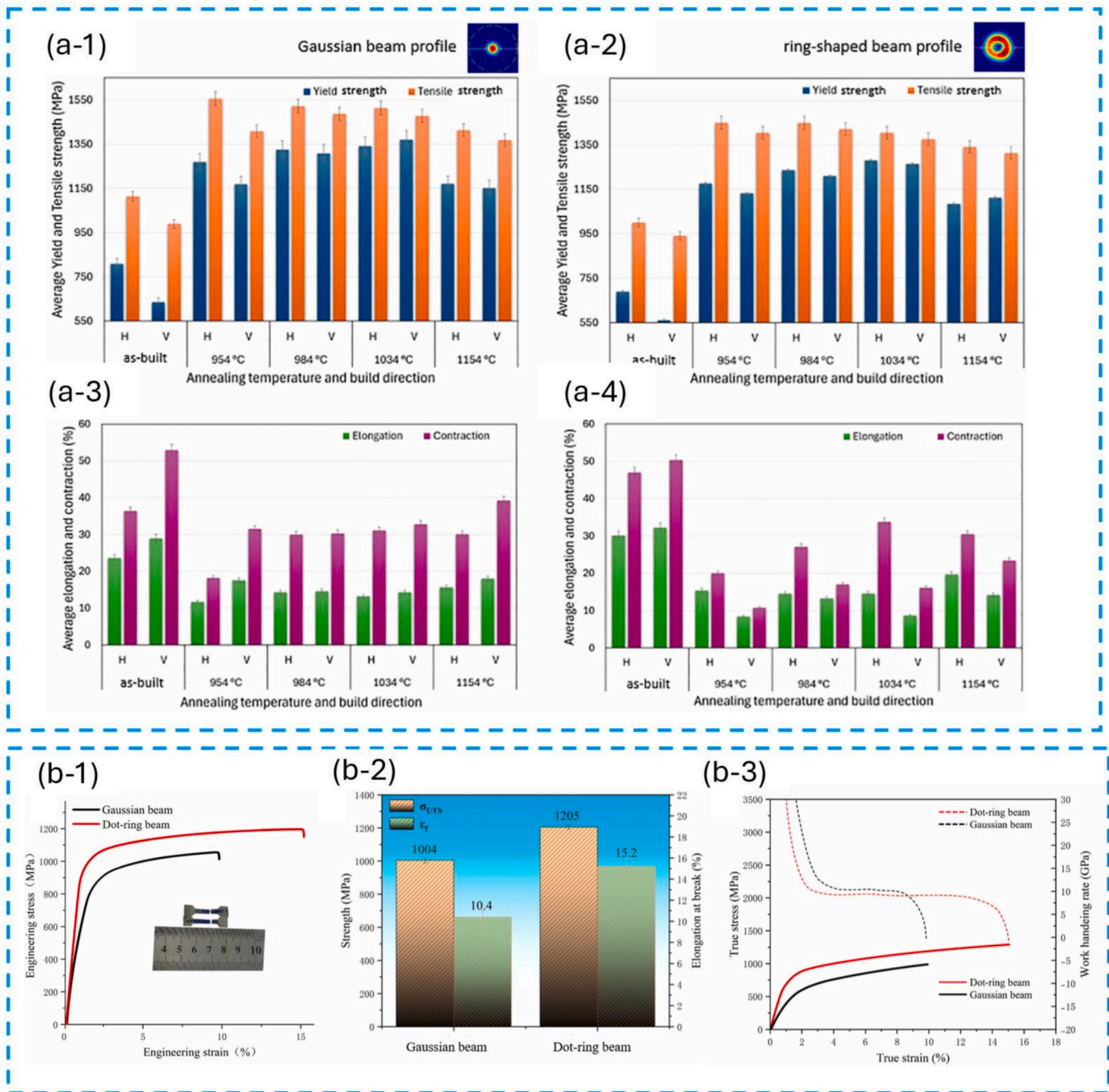


Fig. 15. (a) Mechanical performance of PBF-LB/M-processed Inconel 718 fabricated with Gaussian and ring-shaped beam profiles under as-built and post-heat-treated conditions. (a-1, a-2) Average yield and tensile strength for Gaussian and ring-shaped beams of as-built specimens, respectively. (a-3, a-4) average elongation and contraction of heat-treated samples, adapted from Ref. [150] with permission from Elsevier; (b) Tensile behavior of DD6 superalloy produced with Gaussian and dot-ring beams at room temperature: (b-1) engineering stress-strain curves with failed sample images; (b-2) comparison of ultimate tensile strength (σ_{UTS}) and elongation (ϵ_f), and (b-3) true stress-strain and work-hardening rate curves, adapted from Ref. [14] with permission from Elsevier.

to accelerate prediction and optimization. Gaussian process regression, neural networks, and physics-informed learning frameworks can be trained using simulation and experimental datasets to predict melt-pool dimensions, thermal gradients, and defect susceptibility across large parameter spaces [60,161,162]. These approaches do not replace physics-based models but can complement them by enabling rapid screening of beam shapes, process parameters, and material responses.

5.2. Mathematical integration of beam Shape: Reduced-Order vs. Free-Surface CFD

Reduced-order thermal models incorporate the laser beam profile as an analytical surface or volumetric heat source within continuum heat-transfer formulations. These models are computationally efficient and useful for predicting thermal histories and approximate melt-pool dimensions over larger domains [163,164]. However, they often simplify or neglect melt-pool hydrodynamics, recoil pressure, free-surface deformation, and spatially varying absorptivity, which limits their ability to predict keyhole instability, spatter formation, or melt-pool

Table 7
Influence of Laser Beam Profiles on Mechanical Properties in PBF-LB/M Process.

Reference	Material	Beam Shape	Effects on Mechanical Properties
Pérez-Ruiz et al. (2024) [96]	IN718	Gaussian	• Produces limited mechanical property range with lower anisotropy. • Exhibits lower Young's modulus difference ($\Delta E = 50$ GPa) compared to beam shaping modes.
		Core-Ring (20/80)	• Shows a wider mechanical property range, with high Young's modulus difference ($\Delta E = 129$ GPa) indicating higher anisotropy.
		Core-Ring (50/50)	• Offers the broadest range of mechanical properties as a function of laser speed, with sensitivity to melt pool shape and texture index variations.
		Core-Ring (10/90)	• Shows a linear correlation between the melt pool's radius of curvature and the texture index, facilitating tailored mechanical properties.
Galbusera et al. (2023) [48]	AlSi7Mg0.6	Gaussian	• Higher UTS and ductility but limited flexibility in tailoring the melt pool shape and microstructural properties.
		Ring	• Beam shaping enables tailored melt pool geometries; melt pool depth and h/z index strongly influenced by ring intensity, improving UTS.
		Multi-core profiles	• At constant energy density, beam shaping directly impacts UTS and elongation at break, correlating mechanical properties with h/z ratio.
Hadibeik et al. (2024) [180]	Bulk metallic glasses	Gaussian	• Produces higher stiffness and less structural inhomogeneity but limits ductility and free volume content.
		Tailored Beam	• Enhances amorphicity and rejuvenation, resulting in higher compressive strength, greater ductility, and a wider hardness distribution.
Wang et al. (2024) [140]	Ti-6Al-4 V	Gaussian	• Higher tendency for keyhole pore formation and wall collapses due to greater fluctuation at the keyhole front wall, limiting fatigue performance compared to flat-top beam.
		Flat-Top	• Reduces porosity and keyhole instability, enlarges process window, and enhances fatigue crack growth (FCG) resistance (as built: $3.7 \text{ MPa}\sqrt{\text{m}}$; heat-treated: up to $6.3 \text{ MPa}\sqrt{\text{m}}$). • Improves fatigue limit above 600 MPa with reduced LOF defects.
Godec et al. (2025) [150]	Inconel 718	Gaussian	• Produced a fine-grained, mostly isotropic microstructure with slightly higher yield and ultimate tensile strength (3–7%) and hardness. Showed greater strength anisotropy between horizontal and vertical builds, which decreased after heat treatment at 984°C.
		Ring	• Generated larger columnar/dendritic grains with lower

Table 7 (continued)

Reference	Material	Beam Shape	Effects on Mechanical Properties
Wu et al. (2025) [14]	DD6 Ni-based superalloy	Gaussian	• strength but improved isotropy; slower cooling reduced carbide formation/segregation, improved horizontal elongation, and limited strength loss after high-temperature heat treatment.
		Dot-ring (Flat-top)	• Produced deeper, unstable melt pools with macrocracks, higher residual stresses, and reduced ductility (UTS ≈ 1005 MPa, elongation $\approx 10\%$). • Formed wider, shallower melt pools with stable epitaxial growth and strong (001) texture; improved UTS by $\sim 20\%$ (1205 MPa) and elongation by $\sim 46\%$ (15.2%) due to higher LAGB fraction and reduced defect.

oscillations. In contrast, high-fidelity free-surface CFD models treat the beam profile as a spatially resolved boundary condition interacting with a deformable gas–liquid interface. Advanced ray-tracing or Fresnel-based absorption formulations can account for local surface topology and temperature-dependent absorption, enabling more detailed prediction of vapor depression, recoil pressure, Marangoni convection, and keyhole dynamics [102,165]. Such models show that Gaussian beams promote localized vaporization and deeper vapor depressions, whereas ring-shaped profiles redistribute energy away from the center, reduce recoil-pressure localization, and can suppress keyhole-type instabilities under suitable processing conditions [22,120].

5.3. Summary of key modeling literature

When validated against single-track experiments, in situ imaging, or melt-pool measurements, simulations provide a useful framework for optimizing beam-shaping parameters and predicting defect sensitivity, melt-pool stability, and microstructure evolution [22]. Fig. 16 summarizes representative simulation approaches and investigated beam profiles. Adjoint-based and optimization-driven modeling approaches have also been introduced to identify laser intensity distributions that achieve target thermal fields [103]. These methods show that optimized ring-like or flattened profiles can reduce peak intensity, expand the conduction-mode window, mitigate keyholing, suppress spatter, and provide more direct control over solidification metrics such as G, R, and G/R [58]. A consolidated comparison of representative modeling studies, including beam profiles, physical domains, validation methods, and key process insights, is provided in Supplementary Table S3.

5.4. Current limitations and the emergence of new modeling techniques

High-fidelity physics-based models provide detailed mechanistic insight, but their routine use for engineering-scale optimization remains limited by computational cost. Resolving multiphase interfaces, discrete powder-bed morphology, localized vaporization, and ray tracing requires fine spatial and temporal discretization, often involving sub-micron grids and very small time steps. As a result, simulations are commonly restricted to short scan lengths, simplified geometries, or selected process conditions rather than full part-scale or layer-by-layer predictions.

Model accuracy is also affected by uncertainties in material behavior at extreme temperatures. Reliable data for liquid–metal absorptivity, temperature-dependent surface tension, vaporization behavior, and

plume/shielding effects are often limited or simplified in numerical implementations. These uncertainties are particularly important for volatile or highly reflective alloys such as Zn, Al, and Cu.

To address these limitations, recent work is increasingly exploring hybrid modeling strategies that combine targeted high-fidelity simulations, experimental validation, in-situ monitoring, and surrogate models. Machine-learning-based surrogate models can accelerate parameter screening and beam-shape optimization when trained on reliable simulation or experimental data. When integrated with real-time monitoring, such approaches may support faster process qualification and more robust transfer of beam-shaping strategies toward industrial PBF-LB/M applications.

6. Challenges and limitations of beam shaping in PBF-LB/M processes

Despite its demonstrated benefits in controlling melt-pool dynamics, porosity, and microstructure, beam shaping in PBF-LB/M still faces several challenges that hinder its broader industrial implementation.

1. Most commercial PBF-LB/M systems are fundamentally designed around Gaussian beam optics. Integrating advanced beam shaping technologies such as ring, top-hat, or dynamically reconfigurable profiles requires substantial modification of optical paths, beam delivery systems, and process control architectures, posing significant technical and logistical barriers to industrial adoption [25,60,166]. Current systems are largely restricted to static or partially dynamic beam configurations, limiting the ability to tailor microstructures or properties within a single build.
2. Maintaining stable and repeatable energy distributions remains an important challenge. From an industrial implementation perspective, this includes beam-diameter repeatability, focal-plane stability, pointing/alignment sensitivity, scan-field variation, optical efficiency, core–ring power-ratio stability, and temporal stability of the irradiance profile. Small deviations in ring diameter, core–ring balance, or focus position can change peak irradiance, penetration depth, and hatch overlap, thereby shifting the process between lack-of-fusion, conduction, and keyhole regimes. Fluctuations in shaped beam profiles can lead to variability in melt-pool behavior, defects, residual stresses, and inconsistent mechanical performance. Although dynamic beam shaping with real-time energy redistribution shows promise, it remains at an early research stage and is rarely deployed industrially [29,167]. Compared with static beam-shaping optics, which are generally simpler and more stable once aligned, dynamic or source-based shaping offers greater adaptability but requires additional calibration of switching repeatability, scanner synchronization, thermal drift, and in-process verification [40,168]. Reproducibility is further complicated by strong sensitivity to material properties, machine configurations, and process parameters.
3. The interaction of non-Gaussian beam shapes with material behavior introduces additional complexity. While shaped beams can improve thermal gradients and solidification dynamics, their effects on microstructure evolution, residual stress development, and long-term mechanical performance are not yet fully understood. This uncertainty limits confidence in deploying beam shaping for load-critical components, particularly where anisotropic behavior may arise.
4. Another remaining challenge is the absence of standardized formulas and terminology for beam shaping in PBF-LB/M. Variations in beam definitions, normalization metrics, and reporting methods hinder meaningful comparison across studies. In addition, accurate measurement of the actual beam profile at the build plane remains a practical metrology challenge, especially for high-power non-Gaussian beams, and can limit reliable transfer of parameters from research and simulation to production. Establishing unified beam descriptors and shape-aware energy metrics will be essential for

improving reproducibility and advancing beam shaping toward industrial implementation. A practical minimum reporting set is provided in [Supplementary Table S1](#) to support more consistent reporting of beam descriptors and process metrics.

5. The development and validation of advanced beam shaping strategies require significant experimental investment in customized optics and diagnostics. While numerical modeling approaches (CFD, FEM) and data-driven methods offer cost-effective alternatives, their systematic application remains limited [68]. Moreover, existing in-situ monitoring systems are largely optimized for Gaussian beams. Shaped beams alter temperature fields, plume dynamics, and emissivity patterns, complicating signal interpretation and limiting real-time control. Only a few studies have begun integrating shape-aware sensing, in-process qualification, and adaptive feedback strategies [37].
6. Material-dependent factors such as laser absorption, reflectivity, and thermal conductivity further constrain the transferability of beam shaping strategies across alloys. Highly reflective materials, in particular, exhibit different responses to non-Gaussian energy distributions, emphasizing the need for universal, material-aware predictive frameworks [104,169]. To address these barriers, future beam-shaping research is expected to move toward shape-aware, material-adapted control and closed-loop monitoring, as summarized in [Fig. 17](#).

Taken together, the remaining barriers to industrial beam shaping can be grouped into three categories. First, technical challenges include optical integration, beam stability, focal alignment, scan-field consistency, and control of shaped-beam interactions with melt-pool dynamics. Second, standardization challenges involve inconsistent beam-profile terminology, spot-size definitions, energy metrics, and qualification methods. Third, economic and organizational challenges relate to the cost and complexity of retrofitting existing Gaussian-based PBF-LB/M platforms versus developing new systems with integrated dynamic or source-based beam shaping. These issues become even more complex in multi-laser systems, where overlapping shaped beams and interacting thermal fields may alter local energy input and process stability beyond single-beam assumptions.

7. Conclusion, Remarks, and future outlook

Laser beam shaping is increasingly used to improve process control in PBF-LB/M by redistributing the spatial irradiance profile, thereby tailoring melt-pool behavior, defect formation, microstructural evolution, and productivity. Compared with conventional Gaussian beams, shaped profiles such as core-ring, ring-dominant, and flat-top beams generate wider and more thermally stable melt pools, suppress keyhole-induced porosity, and expand the conduction-mode processing window across a broad range of alloys. Beyond densification, beam shaping provides a practical route for microstructure engineering. By modifying thermal gradients and solidification rates, tailored beam profiles influence grain morphology, crystallographic texture, and phase transformations, thereby improving mechanical isotropy and reducing defect sensitivity in materials including Ti-6Al-4 V, IN718, stainless steels, and aluminum alloys. At the same time, their ability to maintain stable melting at higher power levels can enable higher build rates under optimized conditions, offering a viable pathway to address the long-standing productivity limitations of PBF-LB/M.

It should be noted that most beam-shaping studies to date, including those reviewed here, are based on single-beam configurations. In emerging multi-laser PBF-LB/M platforms, overlapping thermal fields and interacting melt pools mean that the process is governed by a combined energy distribution rather than an isolated beam profile. This introduces additional complexity that must be explicitly considered when extending beam-shaping concepts to hybrid, synchronized multi-beam, and multi-laser systems, where beam–beam thermal interaction,

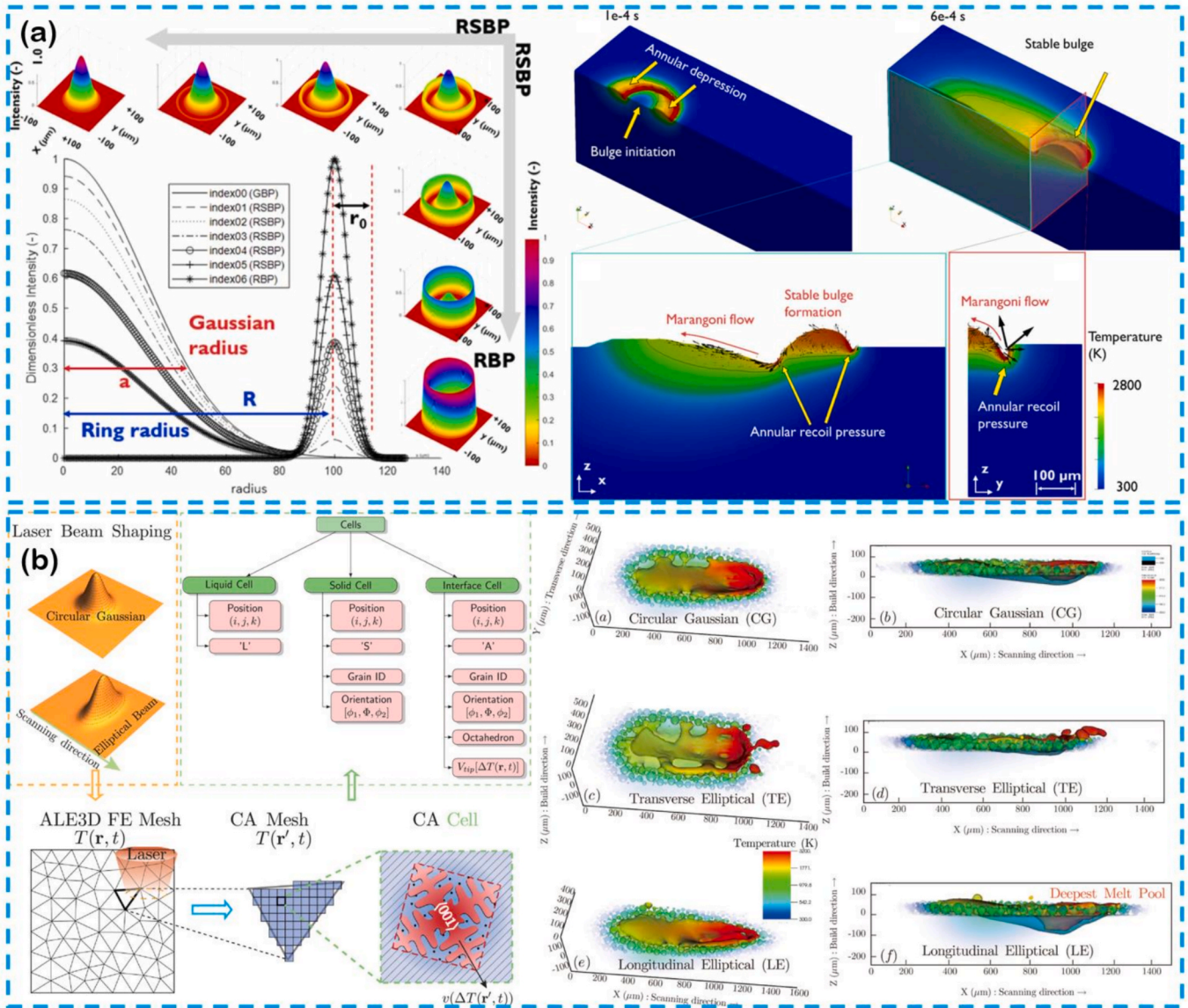


Fig. 16. Representative numerical approaches for laser beam shaping in PBF-LB/M: (a) beam intensity profiles and predicted melt-pool surface effects, including Marangoni flow and recoil pressure, adapted from Ref. [22] with permission from Elsevier; and (b) coupled ALE3D-CA simulation framework and predicted melt-pool/microstructure response for circular Gaussian, transverse elliptical, and longitudinal elliptical beams, adapted from Ref. [102] with permission from Elsevier.

overlap-region stability, and local energy accumulation become critical design variables [28,170,171].

For continued advancement, the following research directions are recommended:

Future work should extend beam-shaping research beyond single tracks and simple geometries toward complex parts and functionally graded microstructures. Hybrid strategies that combine Gaussian beams for fine features and shaped profiles for bulk regions offer a practical route to balance accuracy, productivity, and microstructural control within a single build. Such adaptive beam-switching approaches can enable localized tailoring of thermal gradients, densification, and mechanical performance. Systematic validation on multi-scale geometries, lattices, overhangs, contours, hatch regions, and heat-accumulation zones will be essential, since each region may require a different beam profile or switching logic. Develop coupled physics-based models that explicitly integrate beam characteristics with material thermophysical behavior to predict melt-pool geometry, porosity formation, and solidification responses

under non-Gaussian intensity fields. Recent modeling studies also highlight that beam size and beam shape should be treated together, since both the energy density and its spatial distribution influence melt-pool dynamics and evaporation behavior [41,93].

Implement adaptive beam-shaping systems capable of real-time beam modulation, dynamic mode switching, or programmable profile selection within a single build. Recent work on dynamic beam shaping shows that transient energy input can be coupled to process features, while deformable-mirror-based systems demonstrate the feasibility of changing melt-pool morphology during deposition [29,172,173].

Extend beam-shaping frameworks to highly reflective and high-conductivity alloys (e.g., Al, Cu, and refractory metals), where stable melting requires careful balancing of peak irradiance and penetration depth. This is particularly important because the optimum beam profile may differ between absorptivity-limited alloys, crack-sensitive alloys, and alloys requiring strict microstructural control. Combine in-situ thermal, optical, or multispectral monitoring with beam-profile-aware digital-twin simulations to establish feed-

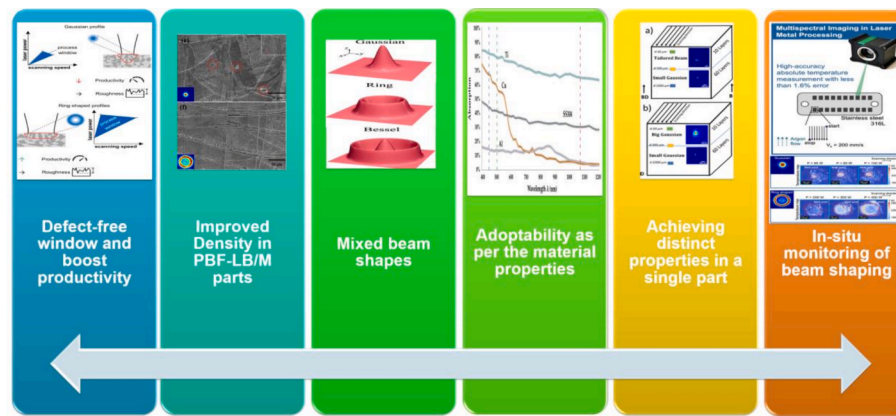


Fig. 17. Future research directions for beam shaping in PBF-LB/M, including shape-aware and dimensionless process control, alloy-specific profile selection, dynamic or site-specific beam tuning, and in-situ monitoring for validation and closed-loop control. Insets are adapted from Refs. [37,78,79,81,94,177] with permission where required.

forward and closed-loop qualification frameworks. Feed-forward approaches can use predicted local thermal history to adjust process parameters before defect formation, while monitoring criteria should be updated for shaped beams because melt-pool geometry, plume behavior, and thermal signatures differ from Gaussian-beam processing [87,174–176].

Establish scalable and standardized beam-shaping frameworks that combine data-driven optimization with physical understanding. Future studies should consistently report beam-diameter definition, irradiance distribution, peak intensity, core–ring ratio, energy-normalization method, hatch-overlap condition, and accepted defect threshold to enable reliable comparison of productivity, density, microstructure, and mechanical-property results across beam profiles, machines, and materials.

CRediT authorship contribution statement

Abid Ullah: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Kashif Azher:** Investigation, Data curation, Writing – review & editing. **Tingting Liu:** Investigation, Writing – review & editing, Funding acquisition. **Philipp Kohlwes:** Resources, Writing – review & editing. **Dirk Herzog:** Resources, Supervision, Writing – review & editing. **Reshad Bakhtari:** Writing – review & editing. **Alexander E. Medvedev:** Writing – review & editing. **Asif Ur Rehman:** Writing – review & editing. **Kai Zhang:** Supervision, Writing – review & editing. **Andrey Molotnikov:** Supervision, Writing – review & editing. **Ingomar Kelbassa:** Supervision, Project administration, Funding acquisition, Writing – review & editing. **Milan Brandt:** Supervision, Project administration, Funding acquisition, Writing – review & editing.

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.2026.116548>.

Data availability

Data will be made available on request.

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