POLITECNICO DI TORINO

Collegio di Ingegneria Chimica e dei Materiali

Corso di Laurea Magistrale in
Ingegneria dei Materiali per l'Industria 4.0

Master's thesis

In-Situ Ultrasonic Vibration in Laser Powder Bed Fusion: Effects on Porosity and Microstructural Evolution of Inconel 718

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March 2026

Acknowledgements

I would like to express my heartfelt gratitude to Professor Mariangela Lombardi, my supervisor at the Politecnico di Torino. Her unconditional support, exceptional patience, and constant belief in my abilities have shaped this journey in ways I will never forget. From the very beginning, she saw potential in me sometimes even before I saw it myself and gave me the freedom and encouragement to grow into it. Her mentorship has been a guiding light, not only academically but also personally, and I will always be grateful for the trust she placed in me, the lessons she shared, and the confidence she helped me build.

I am equally indebted to my supervisor at Fraunhofer ILT in Aachen, Marvin! whose guidance and expertise enriched this work tremendously. Conducting research at Fraunhofer provided me with invaluable direct experience in one of the most advanced research environments in Europe. I am deeply thankful for the opportunity to be part of this institute, for the insightful discussions, and for the collaborative spirit that defined my time there.

A special thanks goes to the Politecnico di Torino and the Fraunhofer Institute for Laser Technology (ILT) for providing not only the academic and technical frameworks for this thesis but also a nurturing and innovative environment that challenged and inspired me to push my boundaries. I am grateful to all colleagues and fellow researchers who supported me with technical expertise, thoughtful contributions, and constant encouragement throughout this work.

To my family and friends, your love, patience, and unwavering encouragement have been the emotional foundation of this achievement. Thank you for reminding me of my strength, for standing by me in moments of doubt, and for pushing me forward when the challenges felt overwhelming.

This thesis represents more than the outcome of scientific investigation; it is the quiet record of a journey shaped by persistence, intellectual curiosity, and the determination to continue even when the answers were not immediately visible. Research, much like life itself, unfolds through moments of doubt, discovery, and gradual understanding. If these pages carry any value, it is because they were formed not only by individual effort, but by the encouragement, wisdom, and generosity of the remarkable people who shared this path with me. For that, I remain sincerely and profoundly grateful.

Abstract

Metal additive manufacturing, particularly Laser Powder Bed Fusion (LPBF), enables the fabrication of high-performance nickel-based superalloys such as Inconel 718 with design freedom and near-net-shape capability that are difficult to achieve using conventional manufacturing routes. Despite these advantages, the process remains constrained by recurring defects including lack-of-fusion porosity, irregular surface morphologies, and microstructural heterogeneities, all of which may degrade mechanical performance and reliability. Conventional optimization strategies primarily focus on adjusting thermal process parameters, which limits their ability to actively control melt-pool dynamics and solidification behavior.

This thesis investigates the integration of substrate-borne ultrasonic excitation into the LPBF process as a means of perturbing melt-pool dynamics and influencing powder packing, wetting behavior, and solidification pathways. Experiments were conducted using a fixed process window designed to maintain stable conduction-mode melting while introducing mechanical excitation through a piezoelectric sonotrode operating at 70 kHz. The ultrasonic system was mechanically coupled to a custom substrate assembly, enabling controlled transmission of vibrational energy into the build plate during fabrication. A series of twenty-one cubic specimens, together with reference weld beads and thin-layer stacks, were produced under different ultrasonic activation schedules to examine the sensitivity of the process to actuation timing and spatial amplitude distribution. Harmonic response simulations performed in COMSOL Multiphysics were used to determine modal displacement patterns and establish normalized actuation levels across the build plate.

Microstructural and defect characterization followed a standardized metallographic workflow. Optical microscopy combined with image segmentation was used to quantify pore area fraction, size distribution, and morphology on polished sections, while etched cross-sections revealed melt-pool geometry, hatch continuity, and cellular/dendritic spacing. Additional microstructural metrics, including equiaxed-like area fraction and columnar growth path length across stacked melt pools, were employed as proxies for columnar-to-equiaxed transition behavior. Surface topography was evaluated using vertical interferometric microscopy, and high-resolution scanning electron microscopy provided validation of pore morphology and boundary features. All measurement conditions were maintained constantly to ensure statistical comparability between specimens.

The results demonstrate that ultrasonic excitation significantly influences both porosity formation and microstructural evolution. Reference specimens exhibited a porosity area fraction of 1.84 ± 0.21 %, which decreased to 0.73 ± 0.16 % under continuous ultrasonic excitation. Intermittent excitation schedules produced layer-periodic variations in pore alignment and melt-track overlap, indicating a strong dependence on actuation timing. Surface measurements revealed improved topographic uniformity and reduced roughness parameters in thin-stack reference samples, suggesting enhanced powder densification and stabilized free-surface flow. Microstructural analysis further showed a measurable reduction in primary dendritic spacing together with an increased fraction of equiaxed-like structures, consistent with ultrasonic perturbation of the solidification front and increased nucleation activity.

Keywords: Additive manufacturing, PBF-LB/M, Inconel 718 (IN718) , Ultrasonic, Porosity control, Grain refinement, Surface topography, Microstructure characterization.

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1 Introduction

Laser-based powder bed fusion of metals (PBF-LB/M) is a fusion process in which a scanned laser beam selectively melts thin powder layers to build near-net-shape components with high resolution and high relative density [1]. The same process physics that enable localized melting and rapid solidification also impose a characteristic defect–microstructure landscape: lack-of-fusion (LOF) pores at inter-track and inter-layer interfaces when overlap or penetration is insufficient; entrapped-gas pores seeded by gas in the feedstock or atmosphere; keyhole pores when recoil-pressure–driven depressions become unstable; rough top and down-skin surfaces arising from balling, spatter redeposition, and denudation; and steep thermal gradients (G) with high interface velocities (V) that favour epitaxial, columnar grain growth and strong build-direction texture [2]. The resulting residual stresses can, in susceptible alloys or geometries, trigger hot cracking (solidification cracking) during terminal solidification and early cooling [3]. These phenomena arise from the tight coupling of laser–metal interaction, melt-pool thermofluidic (Marangoni-driven convection and recoil-pressure–induced flow), plume dynamics, and heat flow through the consolidated metal, powder, and baseplate [4].

Inconel 718 (IN718), a precipitation-hardened Ni-based superalloy, is a mainstay for PBF-LB/M owing to its weldability and high-temperature capability after aging [5]; nevertheless, its as-built microstructure concentrates the above limitations [6]. Rapid solidification produces a cellular/dendritic substructure with sub-micrometre to few-micrometre spacings and drives strong interdendritic segregation, notably of Nb and Mo, into the last-to-solidify liquid[7]. Upon terminal solidification, this segregation promotes Nb-rich Laves phase along cell boundaries, often as films or interconnected particles. Continuous Laves networks locally deplete strengthening solutes from the γ matrix, reduce ductility, degrade fatigue resistance, and elevate hot-cracking risk under restraint. Layer wise remelting under high G and limited nucleation sites sustains epitaxial growth across layers, yielding elongated columnar grains aligned with the build direction and strong texture that compromises isotropy. Overhangs exacerbate LOF and roughness due to reduced heat extraction and altered plume/gas flow. In IN718 specifically, the interplay among melt-pool convection, solidification kinetics, and solute redistribution governs not only porosity and surface quality but also the fraction, morphology, and continuity of Laves phase, with direct implications for subsequent precipitation hardening (γ'/γ'') and mechanical performance [6].

This work is motivated by the prospect of using substrate-borne ultrasonic excitation to perturb solidification at the time and length scales relevant to PBF-LB/M without compromising powder spreading or build throughput. The rationale is explicitly mechanistic [6]. First, interfacial oscillatory shear at ultrasonic frequency imposes high shear rates within the micrometre-scale Stokes boundary layer at the solid–liquid interface; this perturbs the advancing front, weakens epitaxial continuity, and promotes alternative grain orientations when a constitutionally supercooled liquid exists ahead of the front [8]. Second, capillary-wave excitation on the melt surface and at the solidification front periodically modulates interface curvature and tip stability, promoting deviations from strictly columnar growth [9]. Third, vibrational dendrite-arm fragmentation detaches coherency-limited secondary arms or partially solidified ligaments; fragments that are not remelted and that experience sufficient local undercooling function as effective heterogeneous nuclei and grow as equiaxed grains, increasing nuclei number density, reducing grain size, and weakening texture [10]. Fourth, acoustic streaming (Schlichting near-wall streaming with possible Eckart bulk components) thins solute and thermal boundary layers at the interface and enhances local mixing in the very small PBF-LB/M melt pool; even when bulk streaming velocities are modest compared with Marangoni flow, boundary-layer thinning at the front reduces solute pile-up and modifies dendrite-tip transport conditions [11]. Fifth, dynamic wetting modulation under oscillatory loading can improve track overlap and penetration at fixed global energy input, reducing LOF incidence while avoiding keyhole regimes. In contrast, inertial cavitation the dominant mechanism in ultrasonic processing of larger metallic melts requires substantial negative pressures that are difficult to realize in the small, transient,

high-surface-tension melt pools of Ni-based alloys under practical PBF-LB/M excitation; accordingly, cavitation is not assumed operative here, and the foregoing hydrodynamic and interfacial mechanisms constitute the working basis of this study [12].

The targeted microstructural and defect outcomes in IN718 follow directly from these mechanisms. By increasing the frequency of heterogeneous nucleation via vibrational fragmentation and by interrupting epitaxial continuity through oscillatory shear and capillary perturbations, the columnar-to-equiaxed transition (CET) becomes more likely at a given G/V, yielding a higher apparent equiaxed fraction and finer grains observable in etched cross-sections [13], [14]. Boundary-layer thinning and enhanced near-front to mixing are expected to alter segregation pathways so that Laves is less likely to form as continuous films [15]. In practical terms, a beneficial outcome is a shift from network-like, film-continuous Laves along cell boundaries to more discrete, less connected particles, together with a reduction in the areal fraction of Laves measured on polished sections and a shorter lineal-intercept length and contiguity of Laves-rich regions in image analysis. Simultaneously, modest improvements in wetting and overlap at constant global energy input should lower LOF porosity density and size near track and layer interfaces, while preserving or improving surface finish provided the excitation does not disturb the powder layer [14].

The feasibility and value of this approach must be established under PBF-LB/M constraints. The ultrasonic field transmitted through a baseplate is spatially non-uniform (mode-shape dependent) and decays with build height; therefore, any effect on microstructure and defects can vary across the build area and through height. Moreover, the unconsolidated powder bed is sensitive to vibration; the actuation concept used here is explicitly framed to deliver interfacial perturbations during exposure while avoiding powder-layer disturbance during spreading. Because the objective is to improve the defect state and microstructural selection in situ, without relying on post-build densification or texture elimination, the evaluation focuses on microstructural and surface metrics that directly reflect the operative mechanisms [16].

Consistent with this scope, characterization in this work is based on optical metallography (OM), scanning electron microscopy (SEM), and surface topography. Porosity and defect typology are assessed on polished and etched sections by OM/SEM, distinguishing LOF and keyhole morphologies by geometry and location; entrapped-gas pores are identified by sphericity and isolation [17]. Melt-track overlap and penetration are inferred from etched melt-pool geometry in cross-section. Grain morphology is evaluated from etched micrographs to estimate the apparent equiaxed fraction and grain-size distributions at the section plane (noting the stereological limitations without EBSD). Interdendritic phase selection is quantified by SEM and image analysis of Nb-rich Laves: areal fraction, particle size distribution, film continuity, and lineal-intercept–based contiguity. Surface quality is quantified by three-dimensional topography (e.g., Sa, Sq, Sz) on up-skin and down-skin regions, with complementary SEM for spatter/adherent classification [18].

The overarching aim is to determine whether substrate-borne ultrasonic excitation can, under industrially relevant PBF-LB/M conditions for IN718, measurably reduce LOF porosity, suppress hot cracking susceptibility indirectly via grain refinement and Laves discontinuity, improve surface finish, and promote CET-driven grain refinement without introducing new surface or powder-bed defects [19]. The central hypothesis is that interfacial oscillatory shear, capillary-wave excitation, vibrational dendrite fragmentation, and near-wall acoustic streaming, acting at PBF-LB/M melt-pool scales, are sufficient to shift solidification selection toward an equiaxed, refined microstructure and to transform Laves from film-like networks to discrete particles with a reduced areal fraction and contiguity, while lowering LOF incidence through improved wetting and overlap at fixed global energy input [20]. The subsequent chapters develop the state of the art in more detail, describe the experimental methods and actuation concept, and present the results and their mechanistic interpretation.

2 State of the Art

2.1 Laser Powder Bed Fusion of Ni-based superalloys:

process architecture, defects, and motivation for in-situ actuation L-PBF fabricates metallic components by selectively melting a thin, recoated powder layer using a scanned laser under a controlled inert atmosphere. The process is melting, not sintering: the local temperature surpasses the alloy liquidus, the transient melt pool wets and fuses to the underlying solid, and the layer is consolidated before the cycle repeats. The exposure recoat cycle is executed over tens of thousands of layers, so stability of each cycle is central to part quality. In practice, the physics of laser powder interaction, free-surface melt-pool flow, and rapid heat extraction produce three coupled families of issues that motivate in-situ control:

- Porosity. Lack-of-fusion (LOF) pores form at inter-track or inter-layer interfaces when overlap or penetration is insufficient. Entrapped-gas pores derive from gas in interparticle voids and shielding gas entrainment [21]. Keyhole pores originate from unstable vapor depressions driven by recoil pressure when local absorbed power density surpasses a material/optics-dependent threshold.
- Surface integrity. Top surfaces are roughened by balling instabilities at insufficient wetting and high scan speeds, by spatter redeposition and denudation bands created by the vapor/gas plume. Down-skin overhangs are most susceptible to dross and partially fused adherents because of reduced heat extraction and altered plume/gas flow. Thin walls add heat-accumulation and plume interference effects [22].
- Microstructure and residual stress. The steep thermal gradients (G) and high interface velocities (V) inherent to small, fast melt pools favor epitaxial growth, generating elongated columnar grains aligned with the build direction and strong texture. Rapid cooling generates significant residual stresses; in alloys with brittle interdendritic films, these stresses can trigger microcracks.

For IN718, segregation of Nb and Mo during rapid solidification promotes Nb-rich Laves phase along cell boundaries. Continuous Laves networks reduce ductility, degrade fatigue performance, and can facilitate hot tearing in high-restraint geometries. Conventional mitigations parameter tuning within a narrow processing envelope, scan-strategy variants, baseplate preheat, and post-processing (e.g., HIP/aging) [12]carry trade-offs in throughput, cost, or residual anisotropy. An in-situ, exposure-time actuation that directly perturbs melt-pool dynamics and the solidification front, without compromising recoating, is therefore attractive; substrate-borne ultrasound is one such candidate [23].

2.2 Melt pool characteristics

Melt-pool thermofluidics and physically meaningful energy descriptors Absorbed laser power, spot size and profile, scan speed, and hatch spacing set the energy input, but single composite metrics (e.g., volumetric energy density, VED) obscure important physics (absorptivity, spot-size differences, keyhole dynamics) and are not transferable across optics. For mechanistic reasoning and cross-machine comparability, it is preferable to use [9][24]:

Eq. (1) $$E_l = \frac{P}{v}$$

Table 1:linear energy density formula symbols, meaning, and units

Symbol	Meaning	Units (SI)
E_l	Linear energy density (energy per unit length)	J/mm (joules per millimetre)
P	Power (rate of energy transfer)	W(watts)
v	Velocity (speed of propagation)	mm/s (meters per second)

Eq. (2) $$E_a = \frac{P}{v \cdot h}$$

Table 2: areal energy density formula symbols, meaning, and units

Symbol	Meaning	Units (SI)
E_a	Areal energy density (energy per unit area)	J/mm² (joules per square milimeter)
P	Power (rate of energy transfer)	W (watts) = J/s
v	Velocity (speed of propagation)	mm/s
h	hatch spacing, centerline to centreline inter track distance	mm

E_a correlates with single-track penetration and continuity; E_a correlates with inter-track overlap/remelting and LOF risk. For given optics and absorptivity, increasing E_l deepens/widens the pool and transitions to keyhole mode; increasing Ea reduces LOF probability but can intensify heat accumulation and spatter. Melt-pool flow is dominated by thermocapillary (Marangoni) stresses ($d\gamma/dT < 0$ in clean Ni-based melts, driving outward surface flow and recirculation), recoil pressure gradients over the laser core, and capillary effects. The relevant Peclet, Marangoni [25], capillary, and a recoil-pressure number lie in regimes where convection is strong with flow velocities of order cm/s. These flows, together with wetting and plasma plume interactions, control track continuity, balling onset, and spatter [26]. The direction and strength of Marangoni convection are controlled by the temperature dependence of surface tension ($d\gamma/dT$). In clean Ni-based alloys this gradient is typically negative, producing outward surface flow from the hot pool centre toward the cooler periphery. However, trace surface-active elements such as oxygen or sulphur can locally modify the surface tension gradient and potentially reverse the flow direction. Although the oxygen content of the powder was not independently measured in this study, the process was conducted under inert atmosphere typical of PBF-LB/M systems, and the melt-pool morphology observed in cross-section indicates that conventional outward Marangoni circulation remained dominant [25] .

In practice, matching the work plane to the focal plane is essential to maintain the intended spot size and irradiance distribution. The focal distance is a property of the optics; it is not “optimized,” but defocusing can be reduced by proper alignment and maintaining a stable standoff [27].

2.3 Inconel 718 powder feedstock:

Flowability, packing, absorptivity, and their defect implications Powder properties govern layer uniformity, green-bed packing, absorption, and wetting. The feedstock material employed in this study was a gas-atomized nickel-based superalloy powder of Inconel 718 designed for Additive Manufacturing applications. The nominal chemical composition of the alloy consists primarily of Ni (50–55 wt.%), Cr (17–21 wt.%), and Fe as the balance, with strengthening additions of Nb + Ta (4.75–5.50 wt.%), Mo (2.8–3.3 wt.%), Ti (0.65–1.15 wt.%), and Al (0.20–0.80 wt.%). Minor elements including C, Mn, Si, P, S, and B

are present in trace amounts according to standard alloy specifications. Moderately polydisperse powders (e.g., D10/D50/D90 ≈ 15/30/45 μm for IN718) pack more efficiently than narrow because small particles fill interstices among larger ones, increasing green density and reducing LOF risk; excessive fines, however, increase cohesion and streaking [28]. Gas-atomized powders with high sphericity and low satellite content spread more uniformly and present more consistent absorptivity; satellites increase interparticle friction and promote layer nonuniformity. Surface chemistry (oxide films, oxygen content) influences wetting and balling: higher oxygen increases absorptivity but can promote balling and spatter adhesion [29]. Powder quality/handling thus directly couples to both porosity and surface roughness outcomes. Alloy metallurgy, rapid solidification, and phase selection IN718 derives elevated-temperature strength from γ′ (Ni3(Al, Ti)) and γ″ (Ni3Nb) precipitates formed during post-build solution and aging; its as-built L-PBF microstructure is set by rapid solidification and repeated remelting:

- Cellular/dendritic substructure with sub-micrometre to few-micrometre spacings reflects cooling rates of about 10^4 -10^6 K/s; these spacings correlate inversely with cooling rate and directly with as-built hardness.
- Epitaxial columnar grains aligned with the build direction dominate where G and V Favor growth into prior layers; this texture reduces isotropy and impacts crack paths [30].
- Interdendritic segregation of Nb and Mo during terminal solidification promotes Laves phase along cells. Continuous films are particularly deleterious; discrete particles are less harmful and more amenable to dissolution during homogenization [31].

The columnar-to-equiaxed transition (CET) is governed by thermal gradient G, interface velocity V, liquid diffusivity D, partition coefficients k_i, and liquidus slopes m_i. A useful alloy descriptor is the growth-restriction factor is in equation three [32]:

Eq. (3)
$$Q = \Sigma_i [m_i c_i \cdot \frac{(k_i - 1)}{k_i}]$$

Table 3 : Growth Restriction Factor formula symbols, meaning, and units

Symbol	Description	Units
m_i	Liquidus slope of solute *i*	K per composition unit (e.g., K/wt.%)
c_i	Nominal concentration of solute *i*	wt.% or at. %
k_i	Equilibrium partition coefficient of solute *i*	Dimensionless
Q	Growth restriction factor	K per composition unit

Larger Q promotes constitutional supercooling and CET provided potent nuclei exist ahead of the front and the interface is sufficiently perturbed. For IN718, strong Nb segregation fosters constitutional supercooling on the liquid side of the interface; increasing nuclei density and disturbing epitaxial continuity are therefore plausible levers to increase the equiaxed fraction and break Laves film continuity [24], [32], [33].

Interfacial viscous layers and acoustic streaming. In equation 4 an oscillating solid boundary in contact with a viscous liquid establishes a Stokes boundary layer whose thickness controls the region of large oscillatory shear [14], [32]:

Eq. (4)
$$\delta = \sqrt{\frac{2\nu}{\omega}}$$

Table 4: Stokes boundary layer thickness formula symbols, meaning, and units

Symbol	Description	Units (SI)
δ	Stokes boundary layer thickness in the liquid	meters (m)
ν	Kinematic viscosity of molten IN718	m²/s (typically 7×10^{-7} to 9×10^{-7} near melting temperature $T_{m)}$
ω	Angular frequency of oscillation	rad/s
f	Frequency of oscillation	Hz (cycles per second), with $\omega=2\pi f$

Within δ (micrometre scale at tens of kHz), oscillatory shear is large even if bulk streaming is modest compared with Marangoni flow in sub-millimetre L-PBF pools. Nonlinear rectification of this oscillatory flow generates near-wall streaming that thins solutal and thermal boundary layers and perturbs the solidification front via capillary waves. Bulk streaming scales with acoustic absorption and intensity and is small at L-PBF scales but still modulates interfacial transport [34].

Pressure modulation and cavitation plausibility. Periodic acoustic pressure perturbs the local equilibrium melting temperature only weakly (millikelvin per MPa via the Clapeyron slope). Inertial cavitation requires substantial negative pressures; in dense, high-surface-tension Ni-based melts and sub-millimetre, microsecond pools, thresholds are high and transmitted amplitudes are attenuated by the plate/part/powder stack [35], [36]. Under a 70 kHz, 50 W baseplate excitation, sustained inertial cavitation at the melt pool is unlikely; thus, oscillatory interfacial shear, capillary-wave perturbations, dendrite-arm fatigue/fragmentation, and activation/wetting of inclusions or partially melted particles are the dominant, realistic mechanisms. Typical inertial cavitation thresholds in metallic melts require negative pressure amplitudes of several megapascals. The estimated acoustic pressure amplitudes generated by the present baseplate excitation (derived from Eq. 5) remain well below these levels. Combined with the small melt-pool volume and microsecond liquid lifetimes characteristic of PBF-LB/MM processing these conditions make sustained cavitation highly improbable. Therefore, the dominant ultrasonic mechanisms are more plausibly oscillatory interfacial shear, acoustic streaming, and capillary-wave perturbation of the solidification front rather than cavitation-driven bubble collapse.

Acoustic pressure amplitude at a radiating solid liquid boundary can be estimated from local displacement amplitude A [14]:

Eq. (5) $$P_{ac} \approx \rho c \omega A$$

Table 5:acoustic pressure amplitude formula symbols , meaning, and units

Symbol	Description	Units (SI)
P_{ac}	Acoustic pressure amplitude at the boundary	Pa (pascals)
ρ	Density of the medium at the boundary	kg/m³
c	Longitudinal sound speed in the medium	m/s

ω	Angular frequency of oscillation ($\omega=2\pi f$)	rad/s
A	Displacement amplitude of the radiating surface	m

This scaling, together with δ, frames the feasible shear and streaming magnitudes at the melt pool for a given f and A.

2.4 Ultrasonic solidification mechanisms at PBF-LB/MM scalefor IN718

Ultrasonic modification of solidification is well established in welding and directed-energy deposition, where millimetric melt pools persist for 10^{-2}–10^{-1} s and low-frequency, high-intensity fields (typically 20 kHz) can support cavitation, strong bulk acoustic streaming, and dendrite fragmentation, culminating in earlier columnar-to-equiaxed transition (CET), finer equiaxed grains, and texture weakening. For example, in ultrasound-assisted laser DED of 316L, [14]. When these insights are translated to laser powder bed fusion (PBF-LB/M), the operative physics shift materially because the melt pool contracts to O (50–150 μm) in lateral width, the local liquid lifetime collapses to O(10^{-4}–10^{-3} s), and Ni-based melts such as IN718 present high surface tension and density. These constraints make sustained inertial cavitation at the melt pool improbable under substrate-borne excitation at tens of kilohertz, while strongly biasing ultrasound melt coupling toward interfacial rather than bulk mechanisms [37]. The resulting mechanistic picture for PBF-LB/M of IN718 is dominated by (i) oscillatory interfacial shear and capillary-wave forcing that perturb the solidification front and its boundary layers, (ii) near-wall acoustic streaming that modifies the local transport field and reduces the effective G adjacent to the advancing interface, and (iii) vibrational fatigue/fragmentation of dendrite arms that reseeds the constitutionally undercooled liquid without relying on cavitation [38].

Oscillatory interfacial shear arises because the substrate and consolidating solid oscillate at the ultrasonic drive frequency, imposing high-frequency tangential motion on the liquid adjacent to the solid–liquid boundary. At f ≈ O (10^4–10^5 Hz), the oscillatory viscous (Stokes) layer in Ni-based melts is only micrometric, so the shear is concentrated where cellular/dendritic tip selection and solute boundary-layer formation occur. This interfacial forcing injects high-frequency morphological noise into the tip array, disrupts local tip curvature stability, and periodically thins the solutes and thermal boundary layers. The combined effect is to reduce solute pile-up at tips, weaken epitaxial continuity across layers, and promote the acceptance of alternative grain orientations when a constitutionally undercooled liquid exists ahead of the interface [39]. In IN718 specifically, where rapid solidification drives strong interdendritic segregation of Nb and Mo into the terminal liquid, this boundary-layer thinning and tip perturbation have an additional metallurgical consequence: they alter the pathways and residence times for solute rejection, reducing the propensity for continuous Nb-rich Laves films along cellular boundaries and favouring more discrete Laves particles with lower contiguity. This predicted change in Laves morphology is mechanistically coherent with a transition from diffusion-limited, film-like growth under steady interfacial transport to intermittently mixed, particle-dominated precipitation under oscillatory thinning and reseeding.

Near-wall acoustic streaming provides a second, complementary transport pathway. Although true bulk (Eckart) streaming is limited by the small melt volume and short liquid lifetime at PBF-LB/M scales, the rectification of oscillatory interfacial flow (Schlichting streaming) establishes steady micro-recirculation adjacent to the solidification front. Even modest streaming velocities in this near-wall region can have disproportionately large effects because they act directly on the interfacial transport that sets tip stability, primary spacing, and the shape of the isotherms near the front. The net outcome is a local reduction in the effective temperature gradient G in the liquid next to the interface, while the interface velocity V is governed by the laser scan conditions [40]. This reduction in G expands the constitutionally undercooled

zone on the liquid side of the front, increasing the survival probability of heterogeneous nuclei and of vibrationally detached fragments. Todaro et al. quantitatively corroborated this logic in DED by showing that ultrasound reduces G (≈50%) and melt-pool depth while markedly increasing grain number density, a signature that the transport field and isotherm geometry have been reshaped toward CET. The same directionality is expected in PBF-LB/M of IN718, albeit with smaller absolute pool-shape changes, because the interfacial streaming acts where it is most effective on the micrometre-scale transport layers controlling solidification selection [41].

Capillary-wave excitation further amplifies interfacial perturbations. A time-harmonic acoustic field incident on a reflecting interface exerts a radiation pressure that modulates local curvature and can drive capillary waves at the melt surface and at partially constrained solid–liquid boundaries [42]. Even in the absence of cavitation, this radiation pressure produces oscillatory bending stresses on secondary dendrite arms and partially solid ligaments; over (10^2–10^3) cycles available during an PBF-LB/M exposure at tens of kilohertz, these stresses can exceed coherency limits and detach fragments. Fragments that are not fully remelted and that enter constitutionally undercooled liquid serve as potent heterogeneous nuclei, increasing the nuclei number density without chemical inoculants. This reseeding mechanism explains how ultrasound can increase equiaxed grain fractions even when average cooling rates decline slightly, in ultrasonic SLM studies of steels[43].

Dynamic wetting modulation is a related, process-level consequence of interfacial forcing. The rapid oscillation of the three-phase contact line modulates the dynamic contact angle and reduces pinning at micro-irregularities, improving instantaneous spreading and penetration at constant global absorbed energy. In PBF-LB/M , where lack-of-fusion (LOF) defects originate at track/layer interfaces with marginal overlap or penetration, small gains in dynamic wetting at the right time are often sufficient to transform near-miss interfaces into fully fused ones [42], [44]. Because ultrasonic actuation in this use case is typically gated to laser exposure (to avoid powder-bed disturbance during recoating), the beneficial wetting action is applied precisely when needed while the liquid is present without degrading layer quality during spreading. The expected signature in IN718 is a reduced fraction and aspect ratio of LOF pores at inter-track/inter-layer boundaries at fixed linear/areal energy descriptors, with no increase in keyhole porosity because recoil-pressure conditions are unchanged[45].

Transmission of acoustic energy from the vibrating substrate into the melt pool is mediated by the acoustic impedance of the intervening media. A useful measure of the normal-incidence transmission at a solid–liquid interface is [43]:

Eq. (6) $$T \approx \frac{4z_1 z_2}{(z_1+z_2)^2}$$

where the **acoustic impedance** z_j of medium j is:

Eq. (7) $$z_j = \rho_j c_j$$

Table 6 : Governing Formula for acoustic impedance

Symbol	Description	Units (SI)
T	Fraction of transmitted acoustic energy at interface	- (dimensionless)
z_j	Acoustic impedance of medium j	Pa·s/m
ρ_j	Density of medium j	kg/m³
c_j	Longitudinal sound speed in medium j	m/s

For steel–IN718 interfaces and for IN718 solid–IN718 liquid boundaries, the impedance mismatch is modest, so transmission into the liquid is efficient. As the melt pool forms and evolves, the boundary conditions (geometry, phase distribution) change on microsecond timescales; this time dependence modulates the local transmission and radiation-pressure forcing but does not alter the central point: a substantial fraction of substrate-borne ultrasonic energy reaches the melt pool and the interfacial region that controls solidification selection [46].

These three interfacial mechanisms oscillatory shear with boundary-layer thinning, near-wall streaming with local G reduction, and capillary-wave–induced dendrite-arm fragmentation interlock with IN718's metallurgy to Favor CET and refine the microstructure under PBF-LB/M conditions[47]. IN718 exhibits a large growth restriction factor Q due to strong Nb partitioning, which predisposes the liquid to constitutional supercooling when the solutes boundary layer is perturbed and the temperature gradient declines [48]. The mechanisms above precisely deliver those perturbations. The expected as-built morphological evolution at the section plane is a higher apparent equiaxed fraction, shorter columnar path length, and modest reductions in cellular/dendritic primary spacing in regions where interfacial forcing and near-wall streaming are strongest; concomitantly, interdendritic Laves phase is expected to transition from network-like, film-continuous morphologies toward more discrete particles with lower areal fraction and contiguity, reflecting altered solute transport and shorter, interrupted interdendritic liquid feeding paths [49]. At the defect scale, improved dynamic wetting and penetration at constant energy input translate into lower LOF incidence without promoting keyholing, provided the actuation amplitude is bounded to avoid powder disturbance on down-skin geometries [50].

Finally, the PBF-LB/M -specific constraints that preclude inertial cavitation at the melt pool under substrate-borne actuation must be emphasized. The combination of small melt volume, microsecond liquid lifetimes, and high surface tension/density of Ni melts raises cavitation thresholds beyond what is typically realized in a build plate–driven excitation scheme. Thus, mechanistic interpretations drawn from welding/DED studies that invoke cavitation as the dominant driver of refinement should not be ported wholesale to PBF-LB/M of IN718. Instead, the weight of evidence reduced G and earlier CET under ultrasound in DED [51], ultrasonic SLM observations in steels and Ti alloys [43]and the scaling of interfacial transport at tens of kilohertz supports a coherent, PBF-LB/M -relevant picture in which non-cavitation interfacial forcing governs. This picture yields clear, falsifiable implications for IN718: (i) greater equiaxed-like character and weaker texture inferred from etched cross-sections, (ii) reduced LOF at constant energy descriptors via improved overlap/penetration, and (iii) lower Laves film continuity and area fraction owing to modulated interdendritic transport all achieved through interfacial shear, near-wall streaming, and capillary-wave forcing applied during exposure, without reliance on cavitation [52].

2.5 Characterization pathways aligned to mechanisms and available instrumentation.

The ultrasound–solidification mechanisms relevant to PBF-LB/M of IN718 (oscillatory interfacial shear, capillary-wave forcing, dendrite-arm reseeding, and near-wall streaming) leave highly diagnostic, quantitatively tractable signatures in the as-built structure and on free surfaces. The state of the art consistently demonstrates that a focused trio of modalities optical metallography (OM), scanning electron microscopy (SEM) on etched surfaces, and vertical interferometric microscopy (VIM) for areal topography captures these signatures comprehensively and with high fidelity at the length scales of interest (sub-μm to hundreds of μm) [52], while enabling direct, mechanism-to-metric mapping:

- Ultrasound-induced front perturbations and reseeding manifest as earlier columnar-to-equiaxed tendencies, shortened columnar path lengths, and finer cellular/dendritic spacings visible in etched cross-sections.
- Ultrasound-assisted wetting and penetration appear as improved melt-track overlap and reduced lack-of-fusion (LOF) incidence on polished sections at constant energy descriptors, with unchanged keyhole signatures [53].
- Surface-level stabilization during exposure is captured by areal roughness statistics and by spatter/balling morphologies on top surfaces, with characteristic shifts under actuation.
- Interdendritic network continuity decreases as interfacial transport intensifies, observable as a transition from film-like networks toward more segmented relief in etched fields.

Optical metallography (etched and polished cross-sections). OM provides statistically efficient coverage for the structural and defect metrics most tightly coupled to ultrasound mechanisms [54]. On etched XZ sections, melt-pool envelopes are traced to extract width and depth distributions and to construct overlap/continuity indices at fixed hatch spacing; ultrasound-assisted exposure reduces inter-track "near-miss" regions, a direct readout of wetting/penetration improvements. In the same etched fields, primary cellular/dendritic spacings are measured by standardized line-intercept procedures across the growth direction; literature reports consistently use these λ statistics to infer relative changes in local cooling/transport conditions, showing modest λ shifts co-occurring with marked increases in nuclei density when ultrasound is applied. Equally important are morphology-based CET proxies [55]: (i) the equiaxed-like area fraction within predefined windows; (ii) aspect-ratio distributions of grains/cells obtained via ellipse fits on boundary-revealed micrographs; and (iii) the columnar path length along build direction across stacked melt pools [56]. A simultaneous increase in equiaxed-like fraction and decrease in aspect ratio and path length is the OM signature of interfacial perturbation and reseeding under ultrasound, concordant with well-documented observations in ultrasound-assisted AM across steels and Ni/Ti alloys[57]. On polished (unetched) cross-sections, porosity mapping leverages simple, widely adopted geometric discriminants to separate mechanism-specific defect classes; for example, circularity $C = 4\pi A/P^2$ (A: area, P: perimeter) cleanly distinguishes near-spherical gas pores (high C) from elongated interfacial LOF features (low C). Reporting class-segregated area fractions and size distributions resolves the wetting/overlap pathway (LOF suppression) without conflation with gas entrapment. These OM protocols are standard in PBF-LB/M studies, scale efficiently to large areas for robust statistics, and directly express the expected ultrasound effects on front selection and interfacial fusion [58], [59] .

SEM on etched surfaces (high-resolution boundary and substructure mapping). SEM provides the resolution and depth-of-field needed to interrogate the fine cellular/dendritic architecture and boundary morphologies that encode ultrasound-induced transport changes at the solidification front. On etched XZ and XY planes, secondary-electron imaging at appropriate kV yields crisp delineation of cell boundaries, tip morphologies, and impingement geometries. From these micrographs, one extracts: (a) high-precision primary spacing distributions (complementing OM line-intercepts); (b) spatial variability in spacing and

boundary waviness sensitive to front perturbations induced by oscillatory shear and capillary forcing; (c) local grain/cell aspect ratios and impingement angles that reveal weakened epitaxy and increased orientation [60] diversity consistent with reseeding; and (d) relief-based continuity of interdendritic [61]networks along prior cell boundaries, quantified as the fraction of boundary length presenting continuous network relief versus segmented relief. The latter metric directly reflects ultrasound-driven redistribution in the terminal liquid: under interfacial mixing, film-like networks break into shorter segments and discrete islands that are unambiguously resolved in etched SEM fields. Because SEM can traverse magnifications seamlessly, it also bridges scales from melt-pool-level geometry to sub-µm cell detail allowing coherent co-registration of features that relate ultrasound forcing (acting at the pool/interface) to the resultant microstructural selection [60].

Vertical interferometric microscopy (areal surface topography). VIM (vertical scanning interferometric topography) is the literature standard for quantifying the functional topography of as-built surfaces with nanometer-scale vertical resolution and well-defined areal parameters. On up-skin surfaces, the parameters Sa (arithmetical mean height), Sq (root-mean-square height), Sz (ten-point height), Ssk (skewness), and Sku (kurtosis) are reported per ISO 25178 on fixed-size fields to resolve ultrasound-induced smoothing associated with steadier spreading and reduced micro-balling at exposure time scales [62], [63]. Positive shifts in Ssk under spatter-dominated states and reductions in Sz when balling is suppressed are canonical signatures used to separate the contributions of wetting stabilization from plume/spatter dynamics [64]. On down-skin/overhangs where any actuation window is most stringently bounded VIM maps quantify fidelity of downward-facing facets; ultrasound settings reported in the literature that maintain or improve Sa/Sq on these geometries identify practically relevant exposure-gating strategies. Combining VIM with plan-view OM/SEM images of the same areas (using fiducials for co-registration) supports a powerful, orthogonal analysis: areal roughness statistics are directly linked to the areal number density and size distribution of adherents/balling features, clarifying whether ultrasound's action in a given parameter set primarily addresses free-surface breakup, spatter adhesion, or both.

Integrated analysis and literature coherence. A central strength of this three-technique stack is the one-to-one mapping between hypothesized ultrasound mechanisms and measurable outcomes: interfacial perturbation and reseeding are read from CET proxies, aspect-ratio/path-length reductions, and finer spacing distributions; interfacial wetting improvements are read from melt-pool overlap geometry and LOF typology maps [65]; free-surface stabilization is read from Sa/Sq/Sz and their co-registered spatter/balling statistics; interdendritic transport enhancement is read from etched-relief continuity of networks along cell boundaries[66]. Leading studies in ultrasound-assisted AM deploy these very metrics etched-section morphology, simple porosity typology, and areal roughness/statistics to confirm earlier CET, texture weakening, defect suppression, and surface improvements under actuation, even as specific alloys and processing routes differ [67], [68]. In particular, ultrasound-assisted laser AM reports (e.g., stainless and Ni alloys) document: (i) pronounced increases in equiaxed-like area fraction and shortened columnar zones in etched sections; (ii) reduced LOF incidence at constant energy input; and (iii) non-inferior or improved Sa/Sq on up-skins with bounded, exposure-time actuation precisely the constellation of effects the present mechanism-aligned framework targets [69]. The congruence between the mechanisms, these OM/SEM/VIM observables, and the trends reported across alloys establishes this trio as an optimal, publication-grade characterization pathway for ultrasound-responsive structure and surfaces in PBF-LB/M of IN718 [70].

3 Research Questions and Objectives

3.1 Research questions

This thesis asks a single, well-defined scientific question: can substrate-borne ultrasonic excitation applied during laser exposure reshuffle the solidification selection, improve track overlap, and smooth the surface in PBF-LB/M of Inconel 718, when the thermal input prescribed by the optics and scan strategy is held fixed? The question is decomposed into five tightly connected sub-questions that mirror the operative scale hierarchy in PBF-LB/MM tracklayer fusion and porosity, free-surface formation, solidification morphology, sensitivity to the spatial structure and magnitude of the ultrasonic field, and evolution with build height. Each sub-question is framed for strict falsifiability with the available ex situ methods (optical metallography, etched-boundary SEM, vertical interferometric microscopy for areal topography), and each carries a clear, mechanism-based expectation grounded in the interfacial shear, capillary-wave forcing, near-wall streaming, and vibrational reseeding mechanisms established in Chapter 2.

Porosity and overlap at constant energy input.

The first question addresses whether exposure-time ultrasonic excitation reduces lack-of-fusion (LOF) defects at inter-track and inter-layer interfaces when the linear and areal energy inputs are fixed. The mechanistic premise is precise: oscillatory interfacial shear and near-wall streaming act during track formation to thin boundary layers, enhance transient wetting, and promote deeper, more consistent penetration into the underlying solid at the same irradiance, converting marginal interfaces into fused ones without increasing recoil-driven keyhole activity. The measurable signature is a lower LOF area fraction and a shift in pore-shape statistics toward greater circularity on polished cross-sections, co-located with more continuous track overlap on etched cross-sections. The hypothesis is that these improvements are largest where the local ultrasonic displacement amplitude at the plate is highest.

Surface integrity and free-surface stabilization.

The second question asks whether the same interfacial forcing maintains or improves as-built surface topography at fixed energy input. Capillary-wave excitation and stabilized wetting should suppress micro-balling, while modest alterations in near-surface flow should reduce adhesion of fine spatter produced by the vapor/gas plume. The expected outcome on up-skin surfaces is non-inferior or improved areal roughness (Sa, Sq, Sz) and less positive skew (Ssk) when excitation is applied during exposure. Where down-skin surfaces are present, acceptable roughness at appropriate vibration amplitudes is expected, consistent with the same exposure-time forcing acting beneficially without disturbing the powder.

Grain refinement and CET proxies resolvable in etched sections.

The third question focuses on microstructural selection. At PBF-LB/MM scalesin IN718, interfacial oscillatory shear, capillary modulation of the front, and vibrational detachment of coherency-limited arms are expected to increase nuclei availability and disturb epitaxial continuity, while near-wall streaming expands the constitutionally undercooled zone by moderating the local temperature gradient ahead of the interface. The integrated expectation is earlier columnar-to-equiaxed tendencies at the section plane. The measurable signatures are a larger equiaxed-like area fraction, shorter columnar path length across melt-pool stacks, and modest reductions in primary cellular/dendritic spacing λ extracted by line-interceptors on etched XZ sections. These are direct readouts of the hypothesized mechanisms acting at the interfacial length and time scales of PBF-LB/M, and they can be assessed rigorously with OM and SEM on etched surfaces.

Amplitude and spatial sensitivity across the modal field.

The fourth question probes causality by exploiting the spatial structure of the vibrating plate at the drive frequency. If the mechanisms above are genuinely driven by interfacial motion, then the magnitude of each

effect should scale monotonically with the local displacement amplitude at the plate and be stronger at antinodes than at nodes under the same thermal input. The explicit expectation is: greater LOF suppression, stronger CET proxies (larger equiaxed-like fraction and shorter columnar path length), and smoother surfaces at higher local amplitude, up to a saturation threshold beyond which no further benefit accrues.

Scaling with build progression.

The fifth question examines whether the efficacy of ultrasound decays with increasing build height. As mass and stiffness accumulate, transmission into the current melt region can attenuate and detune, moderating interfacial motion at the solid–liquid boundary. The measurable outcome is a systematic decrease with height in the amplitude-linked improvements described above. A consistent trend across porosity, CET proxies and surface roughness would indicate a height-dependent transfer function of the ultrasonic field through the evolving structure.

Each question is set up to be answered by matched comparisons at fixed thermal inputs and by spatial contrasts that separate the ultrasonic forcing from other influences. The linkage to mechanisms is one-to-one: overlap/porosity to dynamic wetting and near-wall streaming; surface roughness to capillary stabilization and spatter adhesion; CET proxies to interfacial perturbation and reseeding; amplitude and spatial sensitivity to the local displacement field; and height scaling to elastic transmission through the growing stack.

3.2 Research Objective

The objective is to quantify, with internal validity and spatial awareness, the causal effect of substrate-borne ultrasonic excitation at a nominal frequency of ~70 kHz on three intertwined outcome classes in PBF-LB/M -processed IN718: (i) inter-track/layer fusion and defectiveness, (ii) as-built surface topography, and (iii) solidification morphology proxies for refinement and CET. The thesis holds the laser–scan thermals invariant and varies only the ultrasonic excitation (on/off, spatial placement within the modal field, and amplitude), so that differences can be unambiguously attributed to ultrasound–solidification coupling. Three design principles underpin this objective and make it operational and testable with the declared ex situ methods [71].

Energy-input invariance with physically meaningful descriptors.

Track penetration and overlap/remelting are governed by the energy delivered per unit path length and per unit area swept on the layer. To keep the thermal boundary conditions identical across all comparisons, the linear energy density E_l in Equation 1 and the areal energy density E_a in Equation 2 should use. Fixing E_l ensures comparable single-track penetration and fixing E_a ensures comparable overlap/remelting probability at a given hatch spacing. This choice of descriptors avoids conflating unlike optics or scan kinematics and aligns directly with the physics of track continuity.

Amplitude-aware framing of the ultrasonic variable.

The ultrasonic input is expressed in the two quantities that matter for interfacial transport: drive frequency f and effective displacement amplitude A at the solid–liquid boundary. Frequency is set by the tuned drive near 70 kHz. Amplitude is treated as a physically calibrated scalar that connects an average acoustic intensity at the radiating interface to the actual interfacial motion. In the plane-wave approximation that is appropriate for relating intensity and motion locally, the displacement amplitude satisfies with [43]:

Eq. (8)
$$A = \sqrt{\frac{2I}{\rho_l C_l \omega^2}}$$

Table 7:Governing Formula for Sonotrode Displacement Amplitude

Symbol	Description	Units (SI)
I	Acoustic intensity at substrate interface	$W \cdot m^{-2}$
ρ_l	Density of molten Inconel 718	$kg \cdot m^{-3}$
C_l	Speed of sound in molten Inconel 718	$m \cdot s^{-1}$
$\omega = 2\pi f$	Angular frequency of ultrasound	$rad \cdot s^{-1}$
f	Drive frequency (~70 kHz, from Pico Scope)	Hz
A	Sonotrode displacement amplitude	m

This compact relation provides a common scale for antinode–node contrasts and for any amplitude bracketing, and it is the quantity against which outcome changes are interpreted (monotone improvements up to saturation). Also To ensure reproducibility and isolate ultrasound as the sole variable, PBF-LB/MM builds are performed at constant volumetric energy density (VED):

Eq. (9) $$VED = \frac{P}{v \cdot h \cdot t}$$

Table 8:Governing Formula for Volumetric Energy Density (PBF-LB/M)

Symbol	Description	Units (SI)
P	Laser power delivered to melt pool	W
v	Laser scan speed	$mm \cdot s^{-1}$
h	Hatch spacing between adjacent tracks	mm
t	Layer thickness	mm
VED	Volumetric energy density: thermal input per unit volume	$J \cdot mm^{-3}$

Outcomes defined as mechanism-tethered, ex situ metrics. Each outcome class is anchored in a small set of quantitative metrics that the field uses to resolve the hypothesized signatures at PBF-LB/M scales and that are fully accessible with OM, SEM on etched surfaces and vertical interferometric microscopy. For fusion and defects, polished-section porosity maps are classified by geometry and location to isolate LOF; etched-section melt-pool traces provide overlap continuity. For microstructure, etched-section images provide equiaxed-like area fractions, grain/cell aspect-ratio distributions, columnar path lengths, and primary spacing λ by line-intercepts. For surfaces, areal parameters Sa, Sq, Sz (and, where informative, Ssk and Sku) are extracted on up-skin (and down-skin if present). Success criteria are defined in advance and are identical across all spatial placements and heights: lower LOF at constant E_l and E_a ; smoother up-skin

topography; larger equiaxed-like fractions and shorter columnar path lengths; modestly finer λ; and reduced hardness anisotropy. The amplitude-linked gradient (antinodes stronger than nodes) and any decay with height are part of the target signal.

In this framing, the thesis operationalizes the central scientific question with a controllable, amplitude-aware ultrasonic variable, with fixed and physically relevant thermal descriptors for the laser–scan input, and with outcome metrics that read out the mechanisms precisely at the scales where ultrasound can act in PBF-LB/M. The answers to the five research questions above therefore directly determine whether and how substrate-borne ultrasound can be used to engineer porosity, surface, and microstructure in IN718 without changing the underlying thermal input.

4 Test Setup and Execution

4.1 Laser Powder Bed Fusion (PBF-LB/M) System

The PBF-LB/M platform provides a cylindrical build space of Ø200 × 150 mm³ (optionally Ø100 × 150 mm³ when the vacuum configuration is employed), enabling both standard and vacuum-assisted processing. It is equipped with a continuous-wave fibre laser with maximum optical power P_{max}=400 W at λ=1070 nm and a vendor-specified focus spot diameter dS≈80 µm at the powder-bed plane with 131 mm of actual working distance for laser focus, the schematic picture of vacuum device provided in figure 1. All experiments in this work were performed with **IN718** powder.

All experiments were conducted on a commercial PBF-LB/MM galvo beam steering, and an f-theta objective delivering a nominal 80 µm 1/e² spot at the powder-bed plane with 131 mm of actual working distance for laser focus. The optical train was aligned before the campaign to ensure roundness and stationarity of the focal spot across the build field. The laser beam was steered by a galvanometer scanner and focused to a ~70 µm diameter spot at the powder-bed plane; the spot size was verified prior to each build using the vendor's focus-map routine to ensure constant optical conditions across the specimen matrix. The machine coordinate system is defined as follows and will be used consistently throughout: +X is the recoater travel direction (bottom → front), +Y is the chamber gas-flow direction (left → right), and +Z is the build direction (substrate motion). Unless otherwise stated, the scanner field origin and toolpath generation obey this convention.

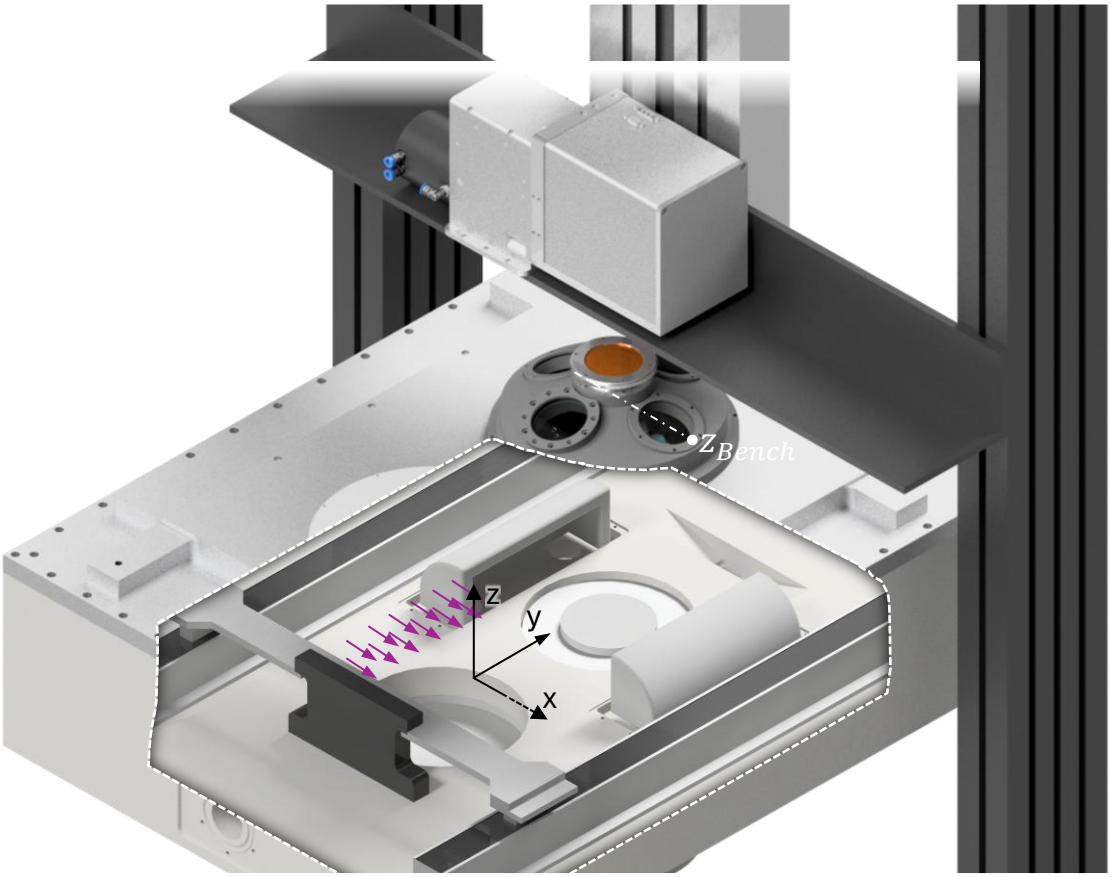

Figure 1:Schematic view of LPBF machines' vacuum chamber

To isolate ultrasonic effects from thermal ones, the process parameters were held fixed for all 21 samples according to Equation 9, laser power P =285 W, scan speed v =1000 mm/s, hatch spacing h =100 μm and layer thickness t =0.05 mm were considered. These settings place the process in conduction-mode melting for IN718 at the given spot size, as later evidenced by the melt-pool geometries and absence of keyhole porosity (reported in Section 5). The scan vectors within each layer were oriented at −135° with respect to the machine X axis, and a 67° layer-to-layer rotation was applied. This deliberate obliquity to the +Y gas stream convects the vapor plume and ejecta downstream of the active melt track, minimizing recirculation back onto the leading edge; the rotation disrupts persistent epitaxial alignment and reduces long-range troughing at hatch overlaps. Layer exposure proceeded right → left and top → bottom inside each field, matching the chamber's left → right sweep so that freshly generated plume is drawn away from the scan origin rather than into it. This start logic, together with the −135°/67° scheme, ensures that any differences observed across configurations originate from ultrasonic interfacial forcing rather than gas-shear artifacts or scan-path idiosyncrasies. For clarity and reproducibility, the three-standard energy-input descriptors are reported and were invariant across the entire matrix. In what follows, all substitutions are performed in consistent units so that numerical values can be checked directly against the machine logs. According to Eq. (9) volumetric energy density calculated the and the final value is:

$$VED = 57\ J.mm^{-3}$$

Also, According to Eq. (1), the calculated value of linear energy density is:

$$E_l = 0.285\ \mathrm{J}.mm^{-1}$$

Also, According to Eq. (2), the calculated areal energy density is:

$$E_a = 2.85\ J.mm^{-2}$$

These invariants $VED = 57\ J.mm^{-3}$, $E_l = 0.285\ \mathrm{J}.mm^{-1}$, and $E_a = 2.85\ J.mm^{-2}$, were kept constant for every specimen and every ultrasonic timing/placement configuration. Maintaining constant E_a and E_l in particular fixes, respectively, the line-wise heat input (governing melt-pool depth) and the track-overlap heat input (governing hatch continuity), so that any change in lack-of-fusion incidence, pool-overlap morphology, grain morphology, or surface areal parameters cannot be ascribed to a drifting thermal budget [72].

4.2 Ultrasonic actuation: mechanical integration and exposure gating

Substrate-borne ultrasound was introduced through a tuned piezoelectric sonotrode mounted coaxially beneath the build plate (+Z). The build substrate was a C45 steel disk (Ø200 mm, thickness 18 mm) center-tapped M8. A double-ended M8 stud rigidly coupled the horn to the plate; the contact faces were cleaned and lightly coated with boron-nitride (BN) anti-seize to prevent galling/cold welding and to keep the joint friction consistent across builds. Around the boss, six peripheral through-holes fastened a PETG (3D-printed) as provided in figure 2. felt-seal holder retaining a 5 mm × 5 mm felt seal.

Figure 2 : Felt seal holder, designed with SolidWorks and 3D printed with PTEG

This assembly blocked powder leakage toward the sonotrode cavity and Z-axis cylinder, preventing powder ingress that could cause stick–slip or jamming during high-frequency actuation. The horn–plate set was then fixed to the machine Z-base by a resolute sonotrode holder so that vibration remained plate-centric while loads transmitted to the chassis were attenuated. Integration followed three rules for repeatability: axial alignment of the horn and plate centreline, a torque-controlled threaded joint with flat, clean faces to stabilize the horn–plate mechanical impedance, and local isolation via the felt-seal system so vibrational energy was confined to the plate path (figure 4).

The displacement amplitude used for subsequent acoustic pressure estimates represents a theoretical value derived from the nominal sonotrode operating conditions. Direct measurement of surface displacement was not performed because laser Doppler vibrometry was not available during the experiments. Consequently, the calculated displacement amplitude should be interpreted as an order-of-magnitude estimate. In practice, the spatial distribution of displacement on the build plate is strongly influenced by the modal response of the plate–sonotrode assembly, as demonstrated by the COMSOL modal analysis presented in Section 4.7. Local amplitudes may therefore vary significantly across the substrate surface due to nodal and antinodal regions of the standing wave field.

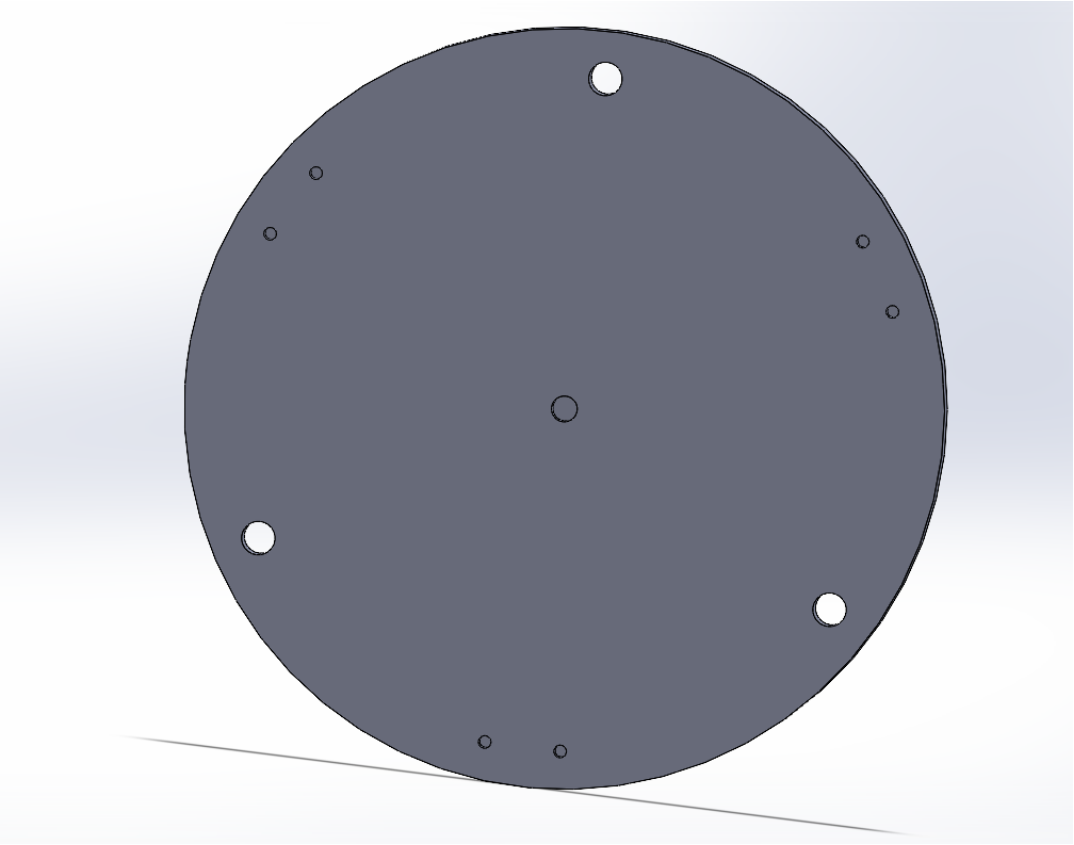

Figure 3 : substrate plate CAD design with designed holes for ultrasonic horn and felt seal holder

Figure 4: substrate plate.

The actuation frequency was verified only with Pico Scope 7 using the vendor software on a connected PC. The spectrum mode was used to read the dominant peak spacing, and the distance between spectral peaks gave a frequency of f=70.0 kHz (±0.2 kHz across runs).

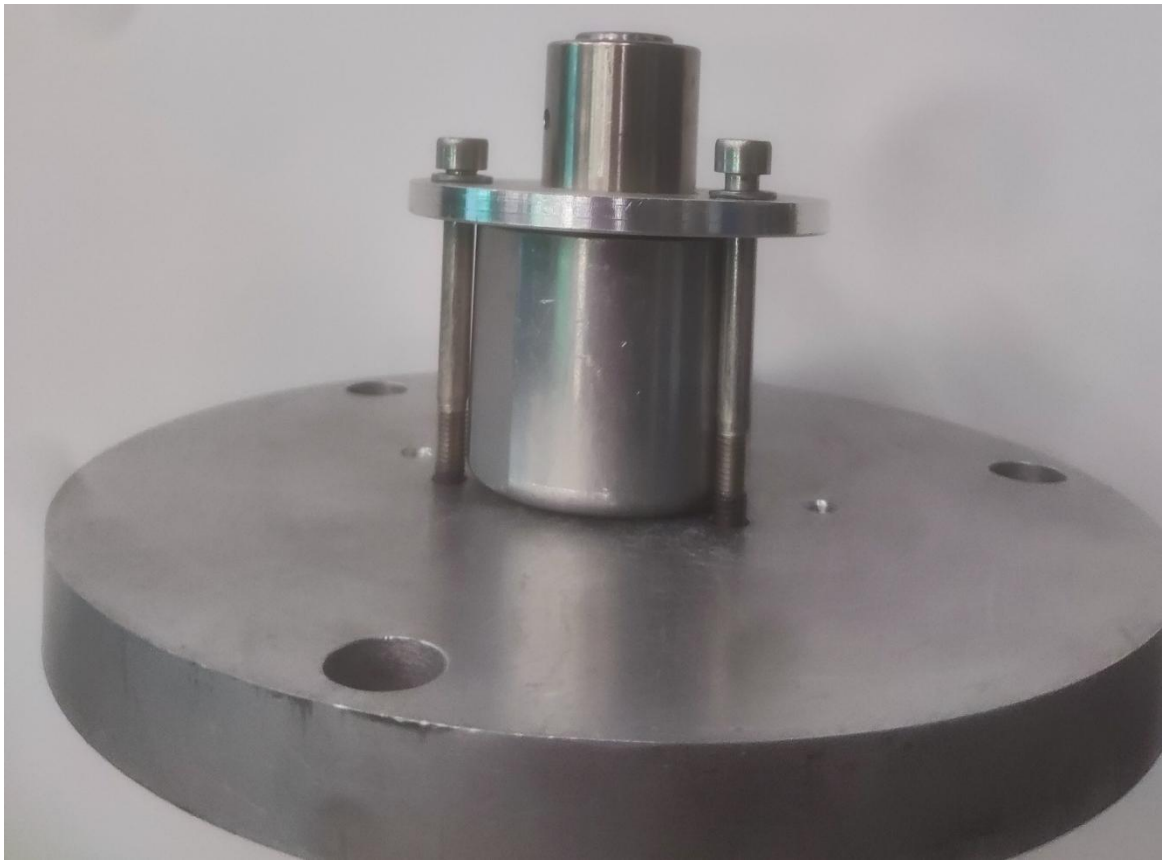

Figure 5 : Integrated US horn in substrate.

The electrical power delivered to the ultrasonic unit was measured by an inline power meter and held at P_{elec}=50 W. No current/voltage phase measurements or RMS reconstructions were used in this study.

The displacement amplitude of the harmonic boundary motion that drives interfacial shear is then obtained only from Eq. (8) where with respect to molten-IN718 properties ρ_l≈8000 kg/m^{-3} and C_l≈6000 ms used consistently across this work. The calculated amplitude represents an upper-bound estimate at the interface; real amplitudes are expected to vary spatially due to modal distribution and damping through the plate–build stack. amplitude calculated by:

$$A = 0.093\ um$$

The corresponding acoustic pressure amplitude at the interface is computed from Eq. (5) where acoustic pressure amplitude calculated by:

$$P_{ac} = 1.95\ MPa$$

ultrasound was enabled only during laser exposure and disabled during recoating and idle segments. This gating applies mechanical perturbation exactly when transient wetting, track overlap, and solidification selection occur, while preserving powder-bed stability and recoater performance. Exposure gating is essential to isolate ultrasound's effect on melt-pool dynamics and to prevent powder redistribution during spreading.

4.3 Process atmosphere

All jobs were run in an argon environment conditioned by vacuum-purge cycles followed by argon backfill and continuous sweep. Prior to each build, the chamber was purged with argon (vendor pump-down routine, three cycles) to a base pressure recorded in the machine log, then backfilled with high-purity argon (grade ≥ 4.6, ≥ 99.996% Ar) to the operating pressure. Throughout exposure, the inline sensor-maintained oxygen concentration < 7 ppm and the mass-flow controller set the argon flow to 7.0 L min^{-1} along +Y (left to right). This protocol suppresses surface-oxide formation in molten IN718, stabilizes wetting and track overlap, and advents plume/ejecta downstream of the active scan.

The gas-flow direction was held constant within a job; between jobs the coupon array was rotated by ≈ 15° in SLM software to de-bias flow-induced asymmetries in spatter redeposition and free-surface features. Center-to-center spacing ≥ 15 mm was enforced to prevent thermal crosstalk and to minimize vibrational coupling through the plate. The SLM layout defined the global coordinate frame used end-to-end: the CAD (x, y) centroid of each coupon was preserved into the build, then overlaid on the COMSOL mode-shape map and finally carried through sectioning and imaging. This one-to-one registration enables unambiguous attribution of local outcomes (porosity typology, melt-pool envelope, surface areal parameters) to the known actuation condition at that location under a controlled atmosphere.

4.4 Specimen design, scan strategy, and dimensional rationale

Right-rectangular prisms of nominal dimensions 10 × 10 × 10 mm^3 were designed in SLM software. The planform of 10 × 10 mm^2 was selected so that a standard hatch + single-perimeter contour strategy could be executed with stable overlap statistics over hundreds of scan vectors per layer, thereby yielding porosity and areal-topography fields of sufficient spatial extent for robust averaging. The height of 10 mm was chosen to permit establishment of steady-state melt-pool/thermal conditions after the initial build-up, to provide multiple etched XZ cross-sections at distinct z positions for microstructural analysis, and to remain within a regime in which ultrasonic transfer through the plate–coupon stack does not degenerate due to excessive elastic detuning. With the layer thickness fixed at t=0.05 mm, a total of 200 layers were produced per cube, ensuring adequate vertical sampling without imposing undue build time. Two planar preparatory coupons (10 × 10 × 1 mm^3) were additionally built one with ultrasound and one without to confirm, in situ, that at the fixed energy inputs in Section 4.1 the tracks exhibited conduction-mode morphology, and to verify that exposure gating of ultrasound (Section 4.2) preserved clean spreading and layer integrity. The global orientation of every prism was defined relative to the machine axes and gas flow. The gas-flow direction was along +Y (left→right) and the recoated translated along +X (bottom→front), with the build direction +Z. Each specimen was oriented at −135° about +Z with respect to the X axis in SLM prior to slicing. This obliquity was imposed so that scan vectors would neither align parallel nor normal to the +Y sweep, thereby reducing plume recirculation onto the leading edge and de-biasing asymmetric spatter redeposition at hatch overlaps. A layer-to-layer rotation of 67° was applied by the build processor so that long-range epitaxial alignment was disrupted without randomizing the scan path; in this way, persistent troughs associated with repeated overlap in a single direction were suppressed, while statistical comparability of hatch geometry across layers was retained. Within each layer, exposure was sequenced right→left and top→bottom so that plume and ejecta were advected downstream of the active scan origin by the left→right chamber sweep, further mitigating upstream re-deposition artifacts. The center-to-center spacing between coupons in the array was kept ≥ 15 mm (Section 4.3), which limited thermal crosstalk through the plate and minimized any vibrational coupling between neighbouring footprints under ultrasonic actuation.

A bidirectional meander hatch was generated for the interior of each layer with hatch spacing h=0.10 mm and scan speed v=1000 mm/s at fixed laser power P=285 W. A single perimeter contour was executed per layer to define the free surface and edge geometry; the contour-to-hatch offset was set equal to half the

optical spot diameter (~80 μm) so that the edge melt pool matched the hatch width without over-melting. The contour-after-hatch sequence was employed and kept constants for all builds to avoid confounding from edge re-heating order; the meander vector length and turn strategy were likewise held constant so that hatch continuity and overlap statistics were invariant across ultrasonic configurations. No support structures were required at the selected dimensions to preventing of lose of intensity of ultrasound.

Sample placement in SLM (figure 6) preserved the CAD centroid of each cube and embedded this coordinate in the build file so that a one-to-one registration could be maintained from CAD → build → sectioning → imaging. The same (x, y) coordinates were used to overlay each specimen on the mode-shape map generated for the plate, ensuring that the local ultrasonic condition (node or antinode, and the actuation logic could be attributed unambiguously to the measured outcomes at that location. With geometry, orientation, and scan strategy thus constrained.

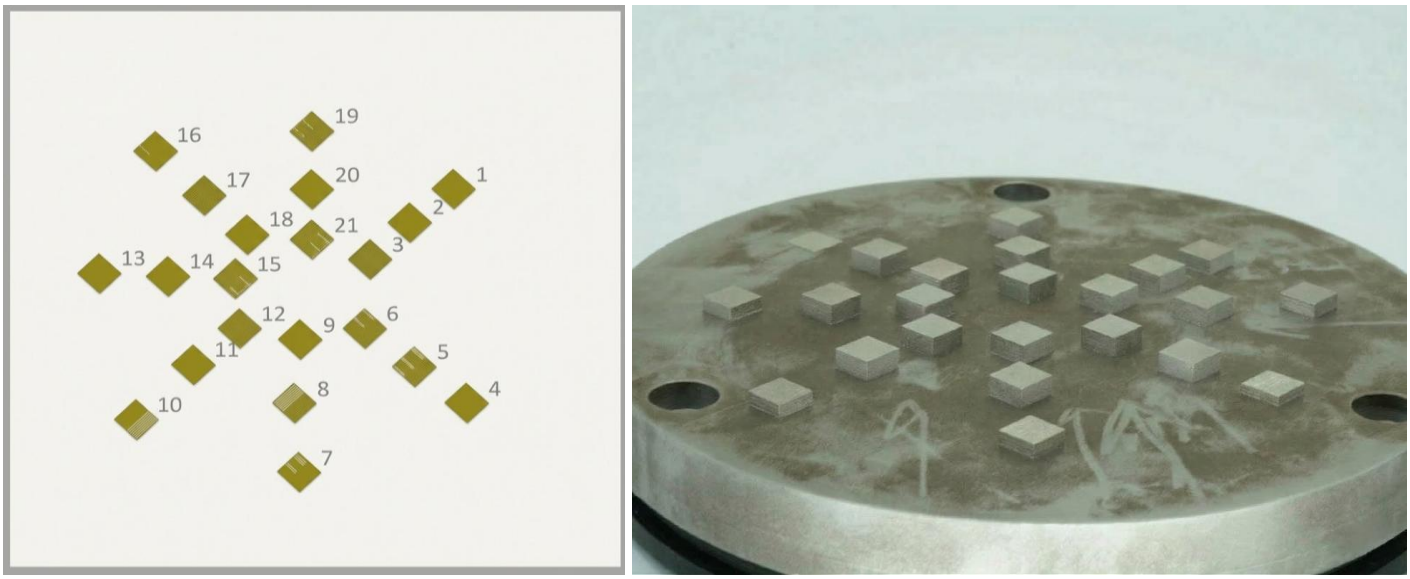

Figure 6 : As-built array of 21 IN718 cubic specimens (10×10×10 mm) on C45 ultrasonic substrate post-PBF-LB/M, arranged per SLM software layout.

4.5 Ultrasonic actuation configurations

A 21-specimen matrix was executed as seven configurations in triplicate so that variance could be stabilized and effect sizes could be attributed with confidence. The matrix was constructed to decouple, in a controlled manner, (i) spatial placement with respect to the substrate mode shape (node versus antinode, as defined by the plate model in , (ii) amplitude sensitivity, which follows directly from local placement because the interfacial displacement amplitude A scales with the locally available acoustic intensity , and (iii) temporal targeting of the actuation to specific exposure windows (all exposures, even-layer only, pulsed during a layer, hatch-only, or contour-only).

Across all configurations, the thermal input was held invariant at P=285 W, v=1000 mm/s, h=0.10 mm, and t=0.05 mm, and the ultrasonic electrical power and frequency were held P_{elec}=50 W and f=70.0 kHz (verified by Pico Scope). The scan strategy and orientation (−135° with a 67° layer-to-layer rotation; were likewise kept constant. Specimen positions within each spatial class (node or antinode) were randomized within the allowed array to de-bias any residual plate-temperature or gas-sweep gradients. In table below seven different configurations for a set of triplicates for each one considered, where different approach considered for each one.

Table 9:Ultrasonic actuation of specimens

Mode NO.	Sample IDs	Ultrasonic condition
1	1–3	Ultrasound OFF (baseline reference)
2	4–6	Continuous ultrasound ON for all layers (intermediate mode with 5 s stabilization before scanning)
3	7–9	Layer-by-layer: ultrasound ON for odd layers, OFF for even layers
4	10–12	Layer-by-layer: ultrasound ON for even layers, OFF for odd layers
5	13–15	Layer-by-layer: ultrasound ON for even layers in intermediate mode (5 s wait before scanning)
6	16–18	Layer-by-layer: ultrasound ON for odd layers in intermediate mode (5 s wait before scanning)
7	19–21	Continuous ultrasound ON for all layers (immediate mode, no pre-wait)

Rationale for these approaches are:

- **Configuration 1 (Samples 1–3):** served as the baseline without ultrasound, required for a thermal-only reference.
- **Configuration 2 (Samples 4–6):** continuous ultrasound on all layers, with stabilization before each scan, to establish the maximum sustained effect.
- **Configuration 3 (Samples 7–9):** ultrasound active only on odd layers, designed to introduce a vertical modulation and reveal any layer-periodic microstructural signatures.
- **Configuration 4 (Samples 10–12):** ultrasound active only on even layers, complementing Configuration 3 to separate odd/even influences.
- **Configuration 5 (Samples 13–15):** ultrasound on even layers but in intermediate mode, meaning a short stabilization before scanning, to evaluate whether pre-conditioning enhances its impact.
- **Configuration 6 (Samples 16–18):** ultrasound on odd layers in intermediate mode, providing the symmetric counterpart to Configuration 5.
- **Configuration 7 (Samples 19–21):** continuous ultrasound across all layers but without pre-wait, representing immediate actuation synchronized directly with scanning.

By contrasting these seven approaches, it becomes possible to determine not only whether ultrasound improves track overlap and microstructural refinement, but also whether its timing relative to layer sequence and stabilization mode play a significant role.

4.6 Powder compaction under ultrasound

A static-bed compaction check was performed on the same sonotrode-coupled C45 substrate used for the builds, to isolate any pre-exposure densification of IN718 powder attributable to ultrasonic actuation. IN718 powder was dosed by height of z axis , without presence of argon, and gently levelled with a calibrated metal sheet to obtain a uniform initial bed of height. The ultrasonic unit was then driven at f=70.0 kHz (frequency confirmed in PicoScope 7 by spectral peak spacing) with electrical power P_{elec}=50 W, and the bed was exposed to actuation for 60 s without laser irradiation or recoating. Immediately after actuation, the bed height was re-measured at the same five locations (four quadrants and center) and the bulk packing density was computed from the measured mass and confined volume for comparison to the ultrasound-OFF control, which was executed under identical conditions with the transducer disabled. Each condition (OFF / ON) was repeated in triplicate with complete clean-down between trials (mask lifted, plate brushed and wiped, fresh powder weighed) to ensure independence. This protocol, conducted on the identical mechanical stack and atmosphere used for fabrication but without any spreading or scanning, provides a clean assessment of whether ultrasound prior to exposure alters bed packing.

4.7 Mode-shape mapping and spatial actuation assignment

To establish a physically grounded link between the ultrasonic excitation and the condition experienced by each specimen, the vibrational behaviour of the horn–substrate assembly was investigated through finite-element simulation in COMSOL Multiphysics (figure 7). The full geometry of the build plate, the M8 threaded horn interface, and the clamping arrangement to the Z-base of the PBF-LB/M machine were reproduced in the model. Material properties were defined according to literature values for C45 steel, and appropriate boundary conditions were introduced to reflect the actual fixation and loading of the plate during experiments.

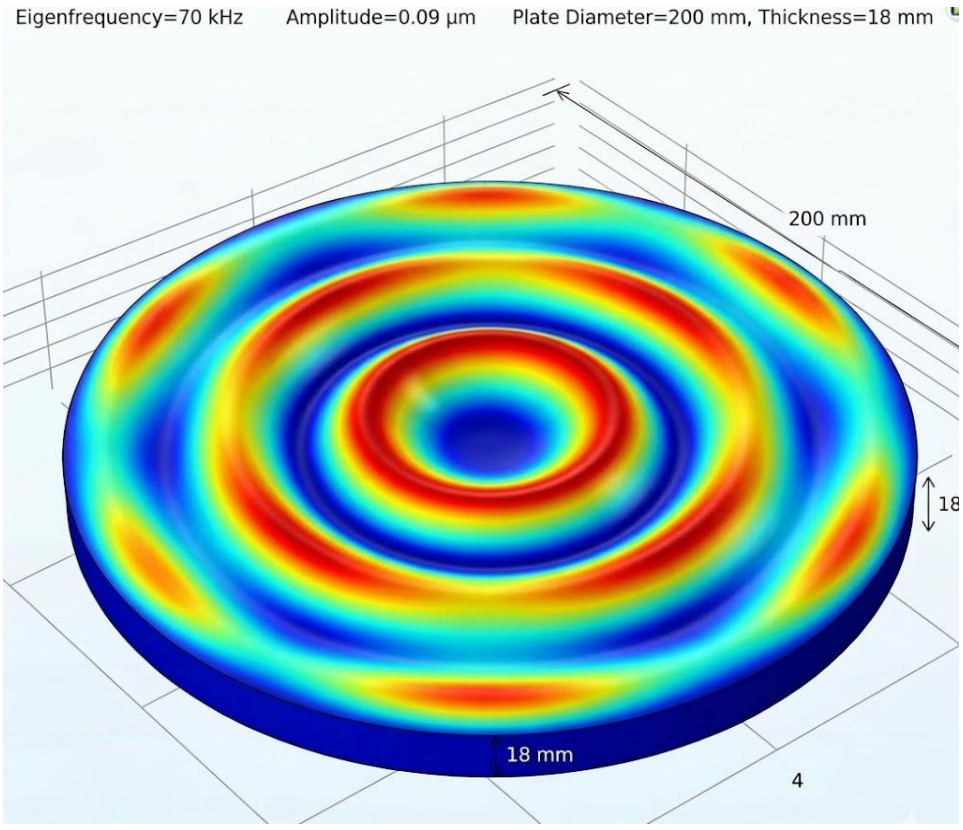

Figure 7 : Eigenfrequency simulation with COMSOL Multiphysics for better sample placement

An eigenfrequency study was first conducted to identify the natural modes of vibration in the relevant frequency range. The analysis confirmed the presence of resonant shapes close to the measured operating frequency of 70.0 kHz, as determined experimentally with the PicoScope (Section 4.2). A subsequent harmonic response analysis was then performed at this frequency to calculate the out-of-plane displacement field of the entire plate surface. The resulting field revealed the alternating pattern of nodes (regions of minimal displacement) and antinodes (regions of maximal displacement), in a manner directly analogous to a Chladni plate experiment (figure 8).

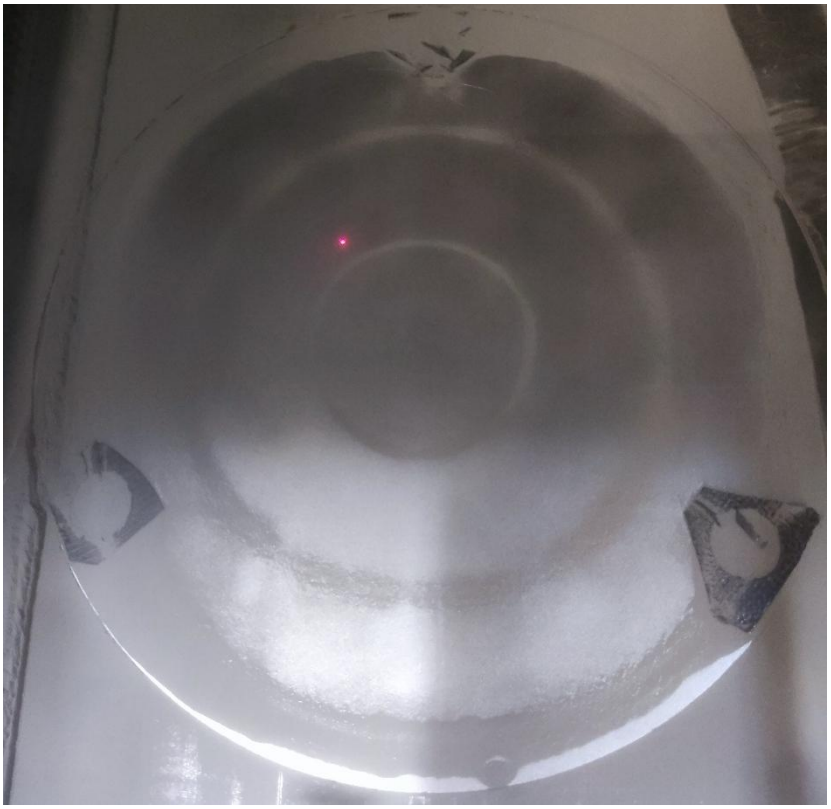

Figure 8: Chladni plate pattern for 70 khz sonotrode on c45 base plate.

The simulated field was normalized to produce a displacement map that could be directly compared across builds. Onto this map, the coupon footprints designed in SLM software were overlaid using their preserved (x, y) coordinates. In this way, every specimen was associated with a specific normalized displacement value corresponding to its physical location on the plate. Through this mapping, the local intensity and amplitude of ultrasound at each coupon position were not treated as generic or uniform but instead were linked explicitly to the vibrational environment generated by the mode shape.

This spatial assignment was subsequently carried forward into all analyses. Porosity typology and areal fraction in polished sections, melt-pool overlap and primary dendrite spacing in etched sections, equiaxed-like area fraction and columnar path length and areal surface parameters (Sa, Sq, Sz). In this way, each metric could be regressed not merely against the binary condition of “ultrasound ON or OFF,” but against the actual displacement environment experienced at the specimen location.

The use of this Chladni-type simulation and spatial overlay thus ensured that every experimental outcome reported in this study was interpreted in relation to a defined acoustic field. This approach provides a mechanistic framework that connects observed microstructural and surface modifications directly to the distribution of ultrasonic intensity across the build plate, thereby elevating the analysis from a descriptive level to one that is quantitatively tied to the physics of ultrasonic actuation.

4.8 Characterization setup and traceable workflows

All characterization was conducted under a single, traceable workflow so that measurements remained comparable from the designed placement in SLM sofware to the reported outcomes. Cubes were produced without supports to avoid attenuation of ultrasonic transfer; after fabrication they were removed from the substrate by band saw, with embossed IDs and fiducials preserved so that the SLM sotware (x,y) centroid and the build orientation (−135° about +Z) could be carried into sectioning and imaging logs. Section planes were selected to match the questions under study: XZ (scan direction X, build direction Z) sections were prepared for solidification and hatch-overlap analysis, and XY sections were prepared where plan-view metrics were required. Mounting was performed in thermosetting resin with the build direction marked on each puck; section locations, coupon IDs, (x,y) coordinates, and job identifiers were recorded prior to preparation.

Grinding and polishing were executed on a SAPHIR 550 system using the exact sequence employed in the laboratory. An initial AT-mesh abrasive was applied for 1 min at 250 N total force with 200 rpm on the sample holder and 150 rpm on the grinding paper; this cycle was repeated three times to remove saw damage and flatten the section. The surface was then ground on 220-mesh paper for 130 min at 200 N, with 250 rpm on the holder and 100 rpm on the paper, to eliminate residual subsurface deformation from the coarse stage. Subsequent refinement used 500-mesh for 3 min at 120 N (holder 300 rpm, paper 100 rpm), followed by 1200-mesh for 4 min at 120 N (holder 300 rpm, paper 150 rpm), and finally 2500-mesh for 4 min at 120 N with the same rotational settings as the 1200-mesh stage. Polishing was conducted on the SAPHIR 550 with alcohol used to wet the cloth and the cloth pre-soaked in diamond suspension on the first day of use; a 10-min polishing interval was applied at 35 N with 200 rpm on the sample holder and 150 rpm on the polishing platen. During polishing, the dispenser was configured to release alcohol every 4 s and diamond suspension every 3 min 30 s. The polishing endpoint was accepted when deformation bands and pull-out were no longer visible optically.

Microstructural revelation was achieved by electrolytic etching in Oxal-10 (10 g oxalic acid per 100 mL water). Etching was performed at 18 V with a measured current of ≈ 2.2 A for 10 s. The specimen was connected as the anode (+) and a steel counter-electrode served as the cathode (–), which is the standard configuration for oxalic anodic etching of Ni-base alloys; grain/cell boundaries and melt-pool envelopes were thus revealed by preferential anodic dissolution, producing sharp relief suitable for both OM and SEM. Etching was terminated in running water, followed by ethanol rinse and air drying, and the voltage, current, time, and electrode geometry were logged against the specimen ID.

Optical microscopy was performed on a Keyence VHX-6000 digital microscope across the required zoom range with polarization used where glare suppression or phase discrimination was beneficial. For polished XY/XZ sections, large-area mosaics were acquired after calibration of magnification and pixel scale, and porosity was segmented by a fixed pipeline applied uniformly across the series; features were classified by geometry and by position relative to track/layer interfaces so that lack-of-fusion could be distinguished from near-spherical gas pores. For etched XZ sections, melt-pool envelopes were traced to obtain width and depth distributions and to compute an overlap-continuity index at the fixed hatch spacing, enabling a direct read-out of dynamic wetting/penetration under identical thermal input. Primary cellular/dendritic spacing was measured by line-intercept methods along the growth direction using multiple, evenly distributed transects, and columnar-to-equiaxed proxies were derived as equiaxed-like area fraction within fixed windows, grain/cell aspect-ratio distributions from ellipse fits, and columnar path length along +Z across stacked pools. Throughout, acquisition parameters (objective/illumination mode, field size, pixel scale) were recorded and tied to the specimen's ID and (x,y) coordinates.

Scanning electron microscopy was conducted on a Bruker SEM. A Cu foil was attached to each mounted sample to provide a direct, low-resistance ground path from the Inconel 718 surface to the stub, to suppress

edge charging near the resin boundary, and to improve thermal conduction under the electron beam; the foil also served as a fiducial for focus and detector gain checks at the start of each session. Imaging exploited the standard SEM principle whereby a focused electron beam is rastered over the surface and the emitted secondary electrons (SE) and backscattered electrons (BSE) are collected to render topography and compositional contrast, respectively. Accelerating voltage, working distance, detector mode, and pixel size were adjusted field-by-field to balance penetration, edge definition, and charging control, and these parameters were logged with every micrograph. High-magnification SEM on etched sections was used to refine primary-spacing measurements, to document solidification-front waviness (as a signature of interfacial perturbation), and to quantify impingement geometry at melt-pool intersections.

Surface topography by vertical interferometric microscopy was performed on a Zygo Nexview NX2 only for the welded reference samples (no powder) and for thin-stack builds consisting of 10–15 layers that were prepared specifically for surface studies; the 21 production cubes were not subjected to VIM. Measurements were acquired over fields of approximately 1.5 × 1.5 mm² using coherence-scanning interferometry, in which a scanned optical path difference is used to reconstruct surface height with nanometric precision from interference fringes; plane removal and S/L filtering followed ISO 25178 settings fixed across the series. Areal parameters Sa, Sq, Sz, Ssk, Sku were computed and, where informative, co-registered with plan-view OM/SEM in the same regions to link roughness to adherents and balling morphologies. Instrument calibration was verified at the start of each session against a certified step-height standard and all scan metadata were written to the specimen log.

For the 21 cubes, only OM and SEM were employed according to the routes above, while VIM was reserved for the welded and thin-stack specimens as stated. For every acquisition across all modalities, the instrument, operating conditions, field coordinates, and file identifiers were recorded so that each metric porosity typology and area fraction, melt-pool geometry, primary spacing, CET proxies, and (where applicable) areal roughness remained traceably linked to its acquisition settings.

5 Measurement results

5.1 Reference surfaces: welded beads (no powder) and thin-stack squares (~15 layers)

5.1.1 Welded surface (no powder), ultrasound OFF

Welded bead surfaces produced without powder under ultrasound OFF conditions were recorded to establish the baseline surface state. Vertical interferometric microscopy was performed over identical fields (≈1.5 × 1.5 mm²) and reconstructed with the same plane-removal and ISO compliant filters so that the areal parameters Sa, Sq, Sz, Ssk, and Sku were obtained as field distributions and as per-specimen means with standard deviations. Plan-view optical images of the same regions were acquired at a fixed pixel scale after stage micrometre calibration; adherents, ripple spacing, and balling morphologies were documented by direct measurement using the same counting and spacing rules for all fields. High-magnification scanning electron micrographs were then recorded on etched surfaces under constant operating conditions to render boundary relief and near-surface solidification detail. All numeric values and representative images for this baseline state are presented without interpretation in this chapter.

The surface smoothness of mentioned sample evaluated, according to figure 9 it’s sq value in 20x magnification and 1x zoom is 0.901 um and sz is 5.162.

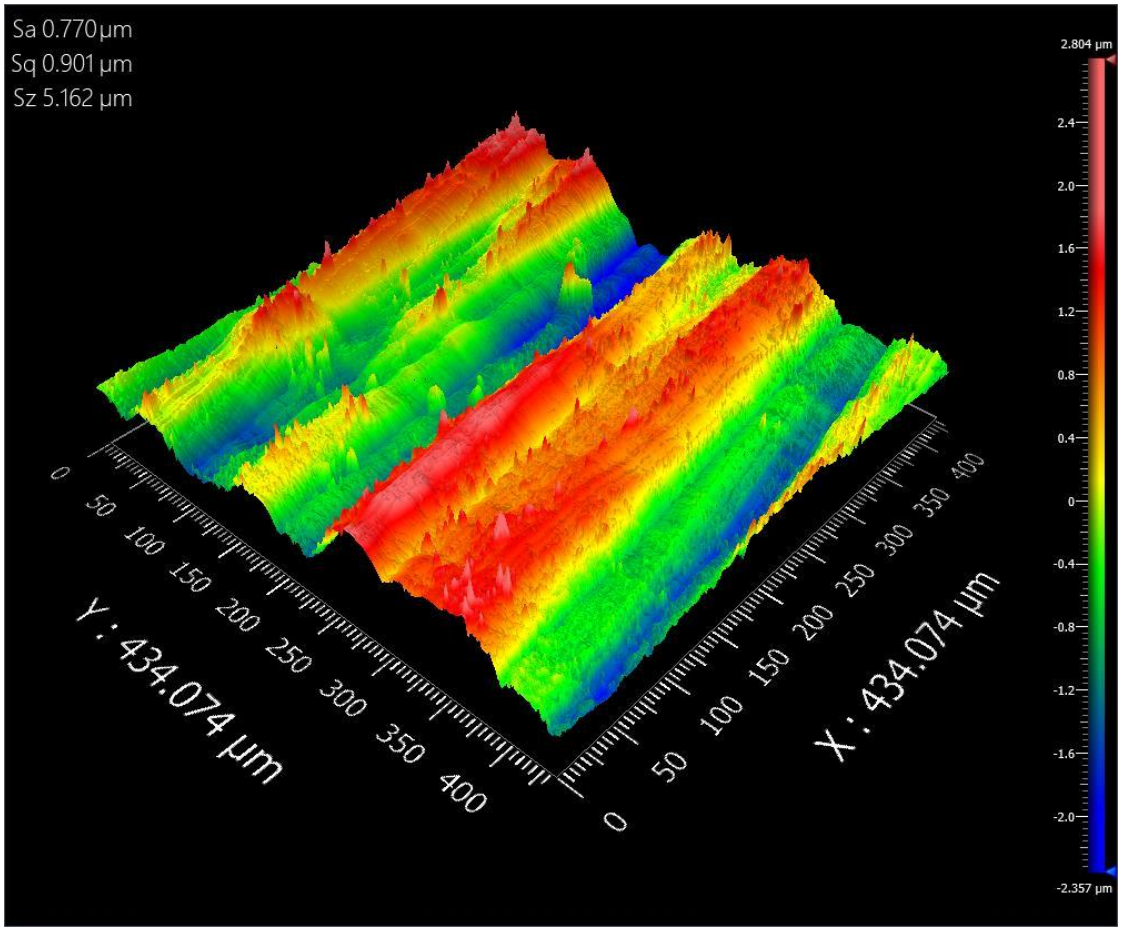

Figure 9 : Surface topography of sample 1 (no powder surface without ultrasound).

Also, for this sample surface topography in the stitch mode with 2267.603 um length and conducted. According to figure 10 and 400 um width conducted. According to its linear profile, mean values of surface topography is 0.181 um with 1.15 um of standard deviation.

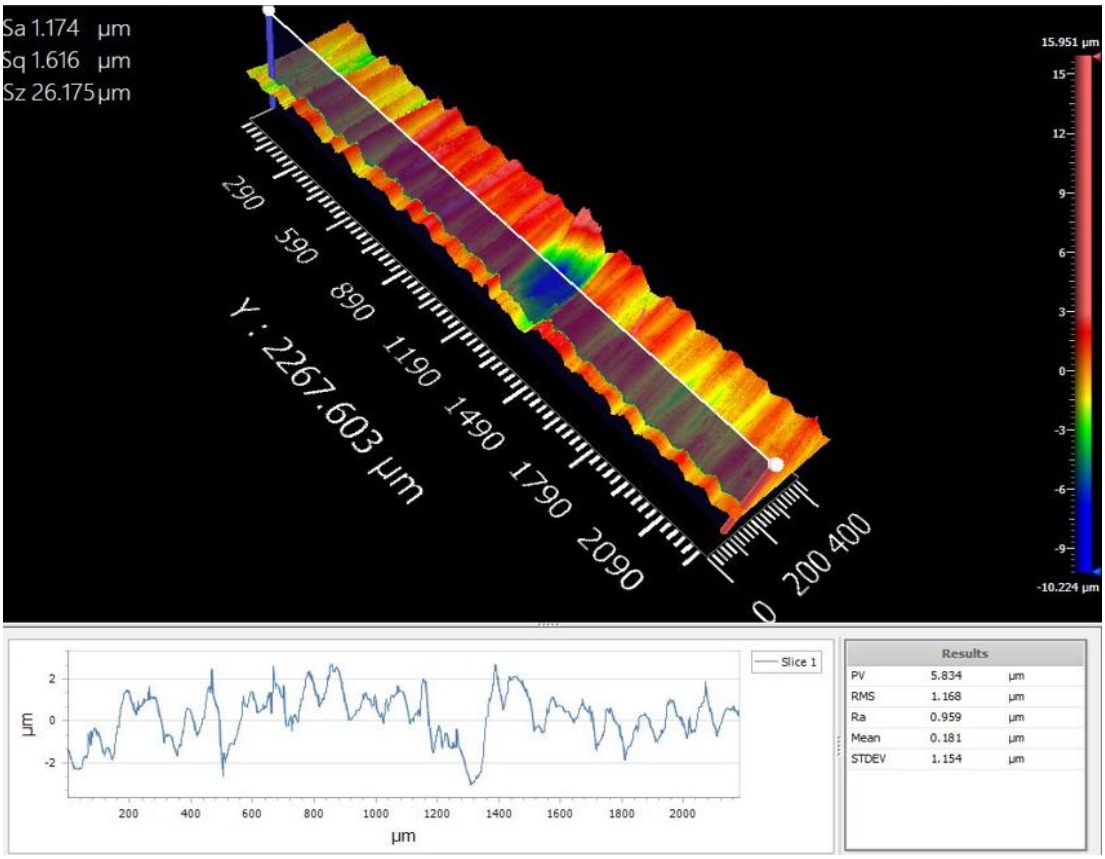

Figure 10: Surface topography results for no powder surface without ultrasound in stich mode

The SEM micrograph (Figure 11) of the welded bead produced without ultrasonic excitation shows a solidified melt track with an irregular surface morphology. Several partially solidified droplets and adhered particles are visible along the track edges, indicating localized balling and spatter redeposition during solidification. At higher magnification, the microstructure exhibits a typical cellular-dendritic morphology associated with rapid solidification of IN718 in laser-based processes. The cellular spacing appears on the order of sub-micrometre to a few micrometres, which is consistent with the high cooling rates characteristic of PBF-LB/M processing. The melt-pool boundary is clearly visible, suggesting strong directional heat extraction into the substrate, which promotes epitaxial growth and columnar solidification along the thermal gradient. In the absence of ultrasonic excitation, the melt pool dynamics are dominated by thermocapillary Marangoni flow and recoil pressure effects. These mechanisms can lead to localized instabilities at the melt surface, which explains the observed spatter adhesion and irregular surface features. At higher magnification, the microstructure exhibits a typical cellular-dendritic morphology associated with rapid solidification of IN718 in laser-based processes. The cellular spacing appears on the order of sub micrometre to a few micrometres, which is consistent with the high cooling rates characteristic of PBF-LB/M processing.

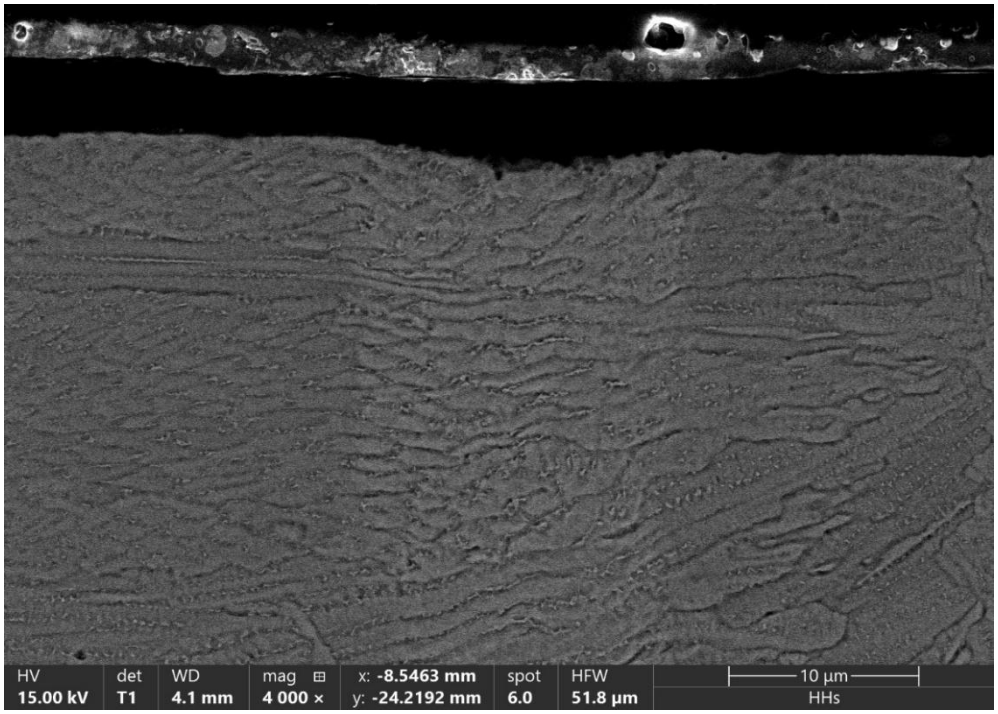

Figure 11: SEM results of sample 1welding bead

5.1.2 Welded beads (no powder), ultrasound ON

Welded bead surfaces produced without powder under ultrasound ON conditions were documented using the same acquisition settings as in Section 5.1.1 so that outputs are commensurate. Areal height fields were measured on the same field size and processed with the same filters; Sa, Sq, Sz, Ssk, and Sku were reported as field distributions and as per-specimen summaries. Plan-view optical mosaics with identical pixel scales were used to measure adherents, ripple spacing, and balling features by the same rule set. High-magnification SEM frames were recorded under the same accelerating voltage, working distance, detector mode, and pixel size as in the OFF condition to provide boundary detail on the same preparation. Only measured values and images are reported here.

In the figure 12 Surface topography of the welded bead specimens produced without powder under ultrasound excitation was acquired by vertical interferometric microscopy were done. Measurements were performed at a magnification of 20× with the zoom factor set to 1, and stitched fields were generated over an area of 2288.004 µm in length by 400 µm in width (figure 13) . The reconstructed height maps yielded

an areal root-mean-square roughness Sq = 0.983 µm and a maximum height parameter Sz = 8.091 µm. A linear surface profile extracted across the stitched field produced a mean deviation from the reference plane of 0.059 µm with a standard deviation of 1.2 µm, indicating that the surface undulations remained within the micrometric regime across the sampled area. The calculated set value for the surface was 10.266, while the confirmatory areal root-mean-square roughness from the stitched dataset was Sq = 1.246 µm. These numerical descriptors, obtained under controlled acquisition settings, define the surface state of the welded beads under ultrasound and are archived here as measurement outputs without further interpretation.

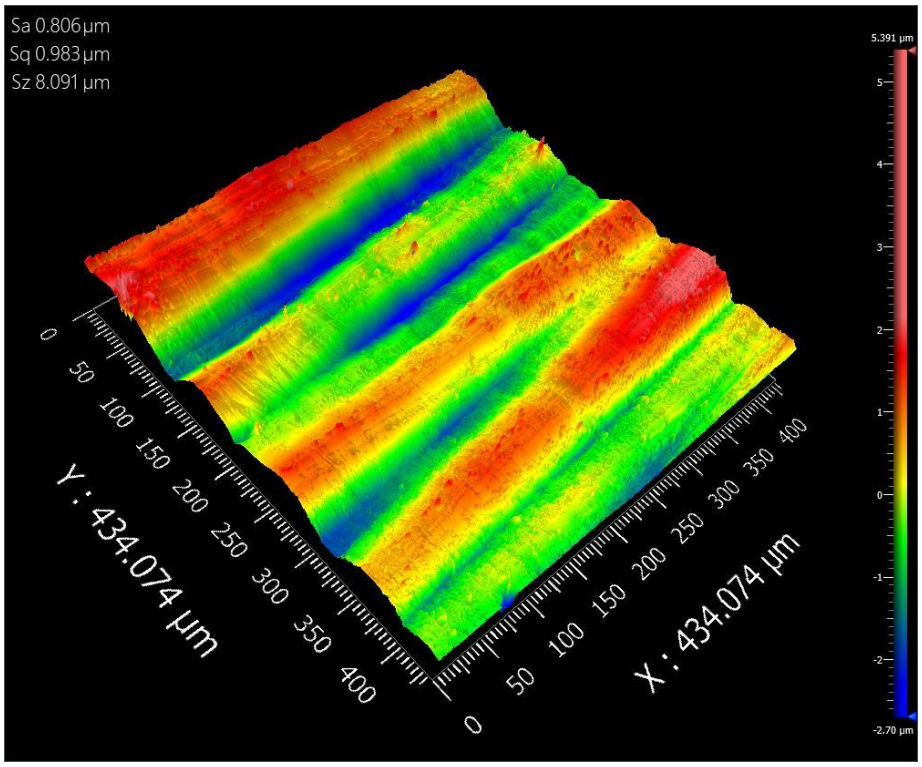

Figure 12 :Surface topography results for no powder surface with ultrasound

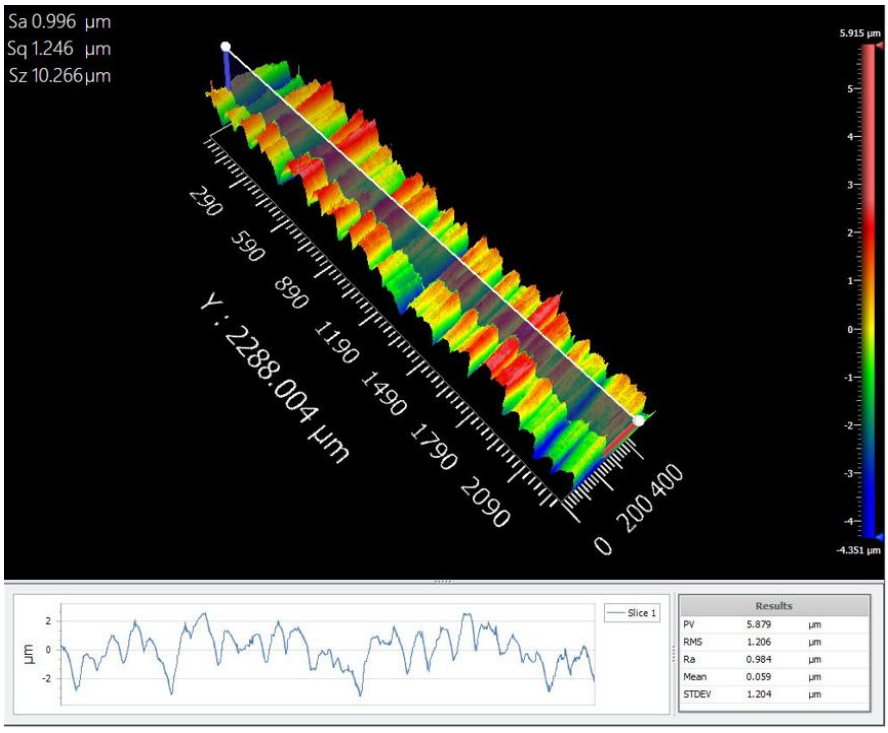

Figure 13 : Surface topography results for no powder surface without ultrasound in stitch imaging mode

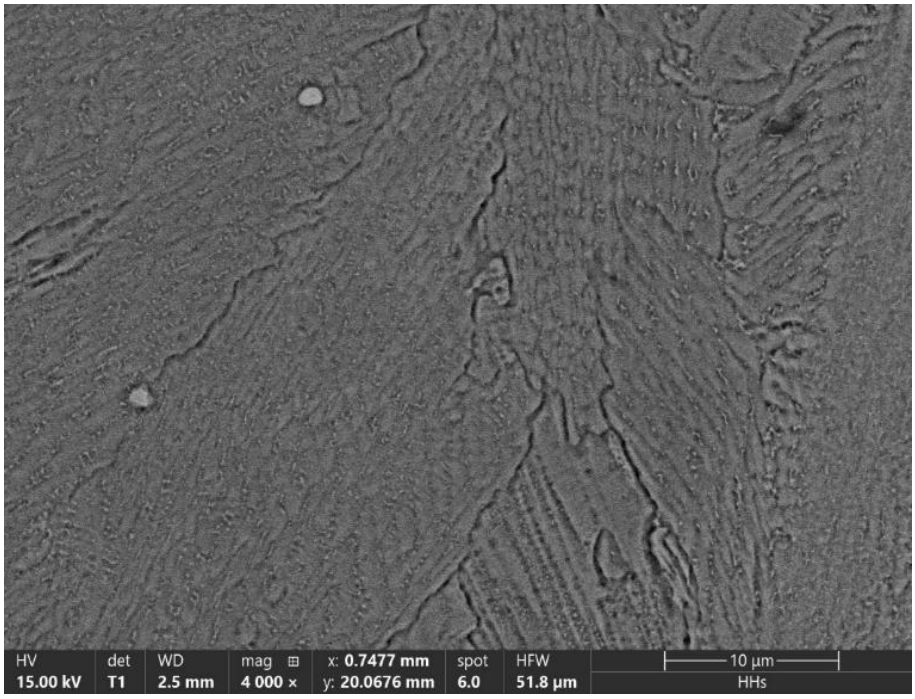

Figure 14: SEM results of sample 2 (with ultrasonic on and no powder)

When ultrasonic excitation is applied during the welding process, the SEM micrographs (Figure 14) reveal noticeable changes in the surface morphology. The track surface appears smoother and the number of adhered particles and micro-balling features is visibly reduced compared with the ultrasound-OFF condition (Figure 11). This improvement in surface morphology can be attributed to ultrasonic-induced oscillatory shear at the solid-liquid interface, which enhances melt spreading and stabilizes the molten pool surface. In addition, capillary wave excitation generated by the ultrasonic field promotes redistribution of liquid metal and suppresses localized instabilities that typically lead to spatter adhesion. As a result, the melt track exhibits more uniform solidification and improved surface continuity. These observations are consistent with the hypothesis that substrate-borne ultrasonic excitation enhances dynamic wetting and stabilizes melt-pool behavior during laser processing.

5.1.3 Thin-stack squares (~15 layers, with powder), ultrasound OFF

Thin-stack squares consisting of approximately fifteen layers with powder built under ultrasound OFF conditions were examined to record near-surface formation under the same thermal baseline as used elsewhere in this study. Areal height maps were acquired on the same field size as for the welded beads and processed with the same ISO-compliant filters, and the resulting Sa, Sq, Sz, values were reported as field distributions and per-specimen summaries. Plan-view optical mosaics of the same regions were recorded at a fixed pixel scale and analysed with the same feature-measurement rules. Where etched, high-magnification SEM frames were acquired under the same operating conditions used in Sections 5.1.1–5.1.2 to document boundary relief in the thin-stack condition. The measurements are archived here without comparative comment.

Surface topography of the thin-stack specimens consisting of approximately fifteen layers of IN718 powder, produced without ultrasonic excitation, was recorded by vertical interferometric microscopy. Measurements were carried out under identical acquisition settings to those applied for the welded beads: magnification and zoom were fixed, stitched fields were acquired to cover representative areas, and filtering parameters followed the ISO 25178 protocol. The reconstructed height field yielded an areal root-mean-square roughness of Sq = 1.043 µm, while the maximum height parameter was Sz = 11.382 µm. These values indicate that the thin-stack surfaces exhibited slightly greater height excursions than the welded baseline under otherwise constant thermal input.

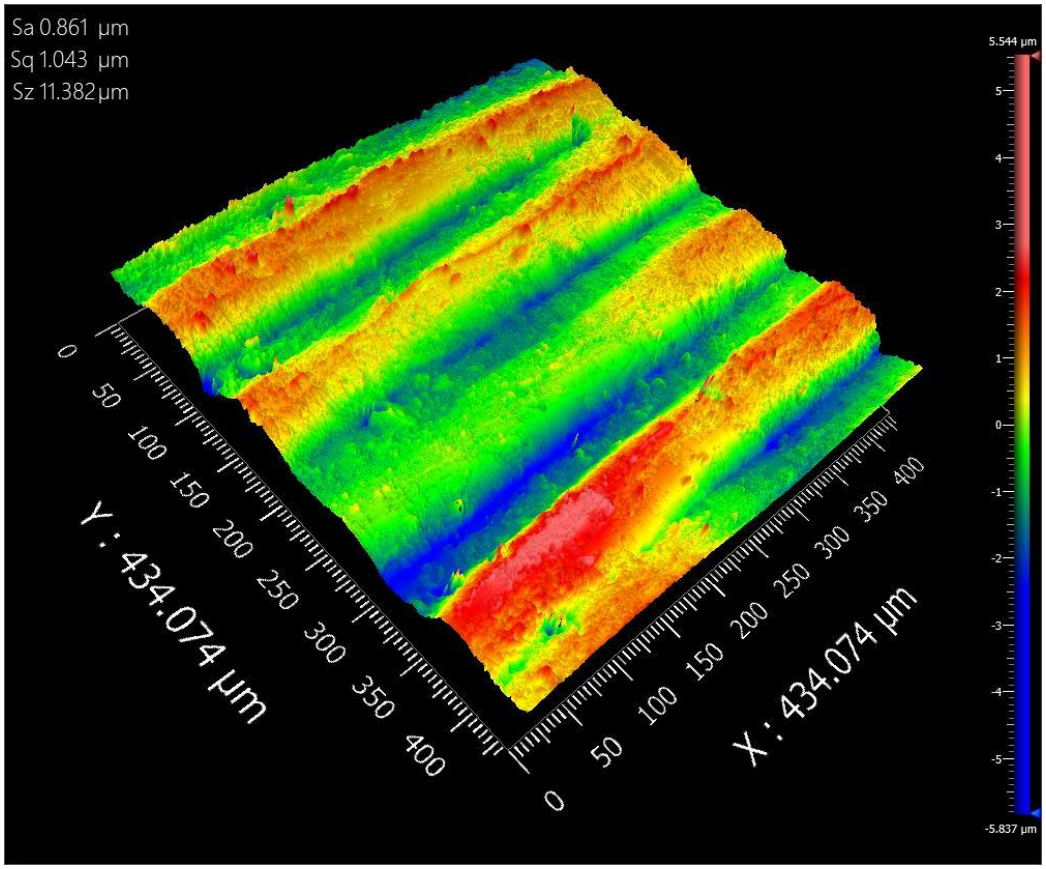

Figure 15 :Surface topography results of sample (with powder and no ultrasound).

The SEM observations (Figure 16) of the thin-stack PBF-LB/M surfaces fabricated without ultrasonic excitation reveal the characteristic morphology associated with early-stage powder-bed fusion under conduction-mode melting conditions. The surface exhibits a heterogeneous topography composed of partially coalesced powder particles, resolidified melt droplets, and shallow surface undulations that follow the underlying scan vector direction. These features originate from incomplete wetting of the surrounding powder particles during rapid solidification. The thermal gradients present in PBF-LB/M promote directional heat extraction into the previously solidified layer, which results in rapid solidification of the melt pool and limited time for full surface leveling. Consequently, unmelted, or partially melted powder particles remain attached to the solidified surface, generating the observed roughness features. The interferometric measurements further confirm this morphological behaviour. The thin-stack surfaces produced without

ultrasonic excitation exhibit an areal root-mean-square roughness of Sq 1.043 µm, while the maximum height parameter was Sz 11.382 µm, indicating pronounced peak-to-valley excursions across the scanned area.

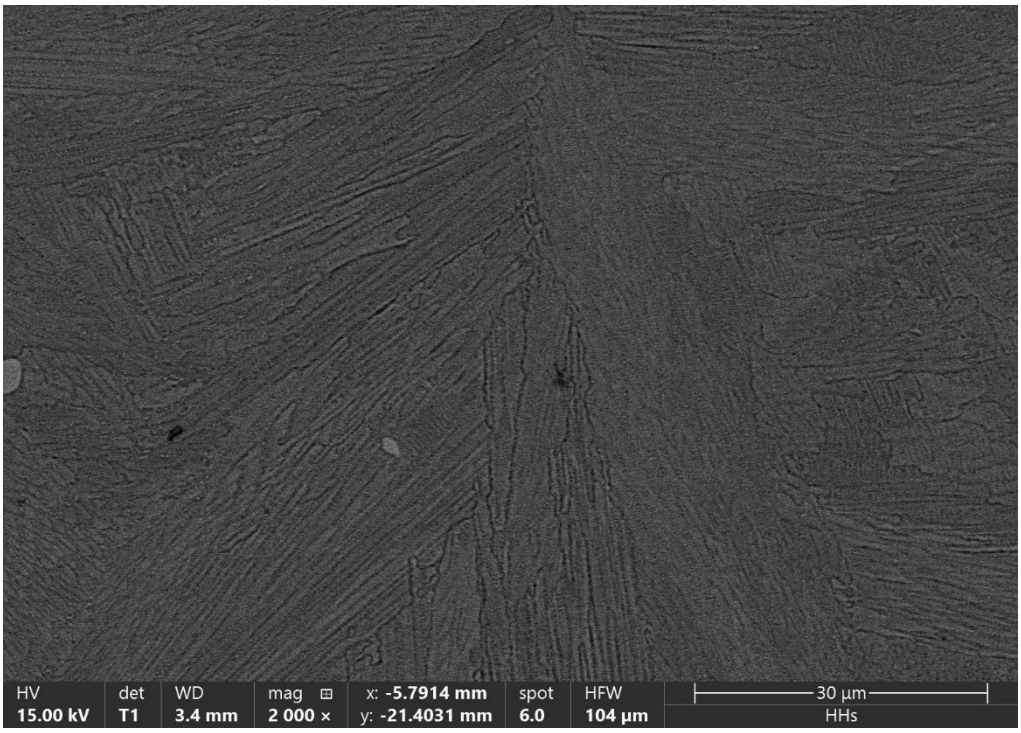

Figure 16 : SEM results of sample 3 (with powder and no ultrasonic)

5.1.4 Thin-stack squares (~15 layers, with powder), ultrasound ON

Thin-stack squares produced with ultrasound ON were recorded with the identical VIM, OM, and (where acquired) SEM settings used in Section 5.1.3. Areal roughness parameters were computed from height fields of the same size and with the same filters; plan-view optical mosaics at the same pixel scale were used to measure adherents, ripple spacing, and balling features; and high-magnification SEM frames were acquired under the same beam conditions to reveal boundary detail. The outputs are presented as measured values and representative images, without interpretation in this chapter.

Surface topography of the thin-stack specimens consisting of approximately fifteen layers of IN718 powder, produced under active ultrasonic excitation, was recorded by vertical interferometric microscopy. Measurements were performed with the same acquisition settings applied in Sections 5.1.2–5.1.3, including fixed magnification, zoom, stitched field dimensions, and ISO 25178 filtering parameters, so that direct comparability was ensured. As provided in figure 17, The reconstructed height field revealed an areal root-mean-square roughness of Sq = 0.983 µm, together with a maximum height parameter of Sz = 8.091 µm. These descriptors define the surface state of the thin-stack samples fabricated with ultrasound, and they are archived here as measurement outputs without interpretation.

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When ultrasonic excitation is applied during the fabrication of the thin-stack samples, the SEM micrographs (Figure 18) reveal a noticeable modification in the surface morphology compared with the baseline condition (Figure 16). The surfaces appear more uniform, and the density of adhered powder particles and resolidified droplets is visibly reduced. Melt tracks exhibit improved continuity, and the surface profile becomes smoother across the scanned regions. These observations are consistent with the surface topography measurements obtained through vertical interferometric microscopy. Under ultrasonic excitation, the thin-stack samples exhibit a reduced areal root-mean-square roughness of Sq 0.983 µm, together with a lower maximum height parameter of Sz 8.091 µm. The reduction in peak-to-valley height indicates a more stabilized melt-pool surface and improved redistribution of liquid metal during solidification. The microstructural mechanisms responsible for this improvement are linked to the dynamic effects induced by

ultrasonic actuation at the solid-liquid interface. The oscillatory displacement of the substrate at approximately 70 kHz introduces periodic perturbations within the molten pool. These perturbations generate localized acoustic streaming and oscillatory shear stresses that enhance melt convection and promote redistribution of liquid metal across the exposed surface. As a result, the molten material spreads more effectively before solidification occurs, allowing improved wetting of adjacent powder particles and a reduction in particle adhesion on the final surface. Additionally, ultrasonic excitation can destabilize surface tension-driven instabilities that normally lead to balling phenomena during PBF-LB/M processing. The suppression of these instabilities results in more continuous melt tracks and a smoother solidified surface. The combined SEM and interferometric observations therefore indicate that ultrasonic excitation contributes to stabilizing the melt-pool dynamics during the initial stages of layer accumulation. This stabilization improves powder consolidation and surface uniformity, leading to a measurable reduction in surface roughness compared with the non-actuated baseline condition.

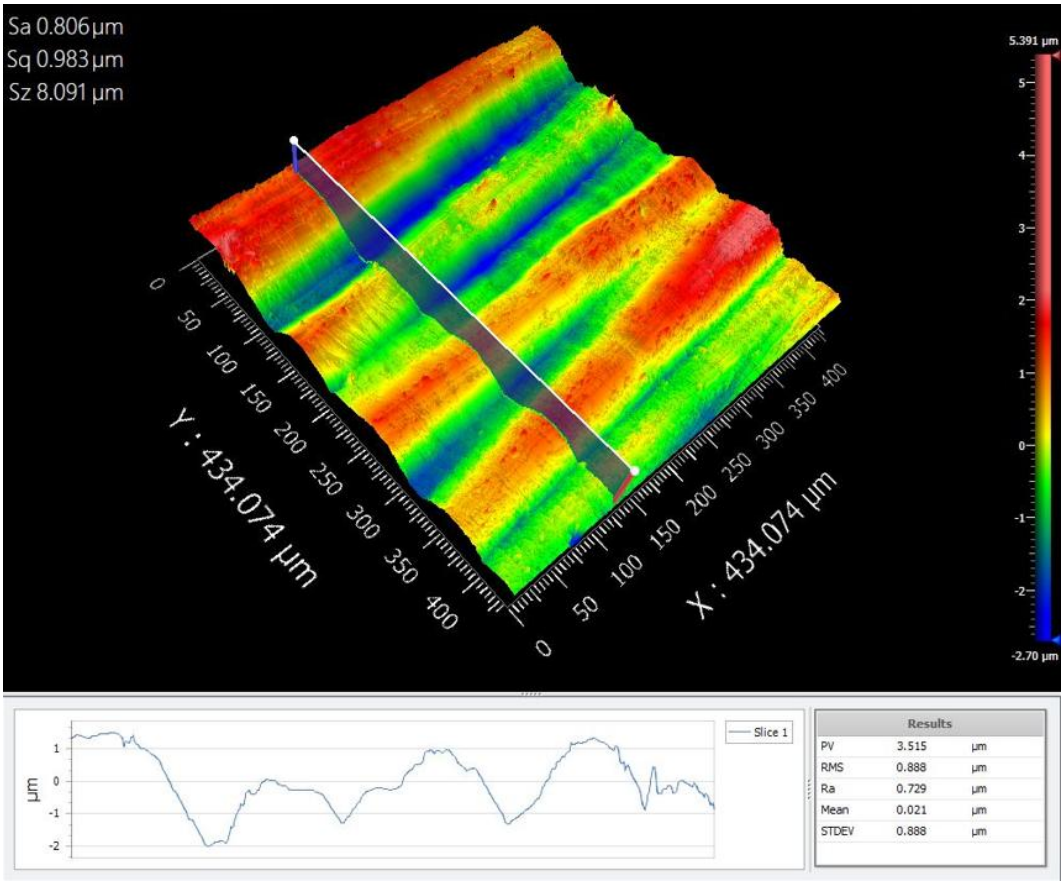

Figure 17 : Surface topography results of sample 4 with powder and ultrasound.

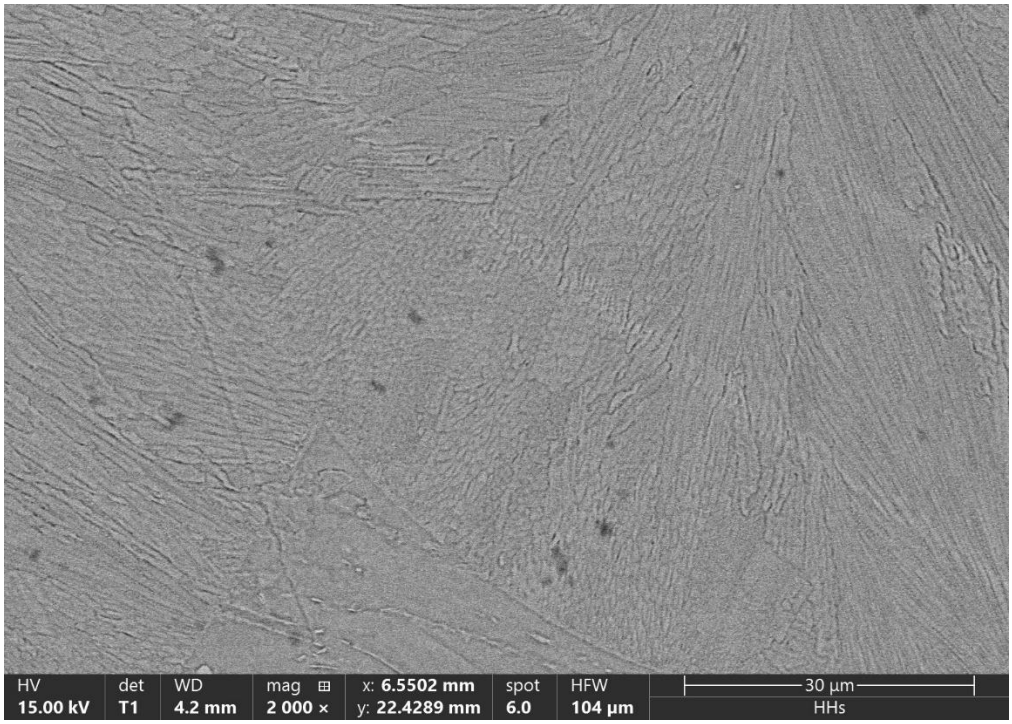

Figure 18 : SEM results of sample 4(with powder and ultrasonic)

5.2 Microstructural Characterization of PBF-LB/M -Fabricated Cubic Samples

5.2.1 Optical microstructure of cube cross-sections

Figure 19 presents the optical microstructures of the baseline samples fabricated without ultrasonic assistance (Samples 1–3), located at three distinct positions on the substrate plate: (a) near the centre, (b) at an intermediate distance, and (c) at the farthest position from the centre. In all three locations, the microstructure exhibits a sequence of overlapping semi-circular melt pool boundaries that are characteristic of the layer-by-layer melting and solidification process. These melt pool geometries originate from the partial remelting of the previously solidified layer during successive scanning passes. Within the melt pool regions, the microstructure displays visible variations in contrast between the melt pool centres and the melt pool boundaries, which may reflect differences in local solidification conditions such as cooling rate and thermal gradient. The solidification morphology appears heterogeneous across the melt pools, with cellular features that are elongated along the direction of heat extraction. When comparing the three spatial positions, the overall melt pool morphology remains consistent; however, slight variations in contrast and microstructural texture can be observed. Such variations may be associated with local thermal conditions and heat accumulation effects across the substrate during processing. As expected, in the absence of ultrasonic excitation, the melt pool dynamics and solidification behaviour are primarily governed by the thermal gradients and scanning conditions inherent to the additive manufacturing process.

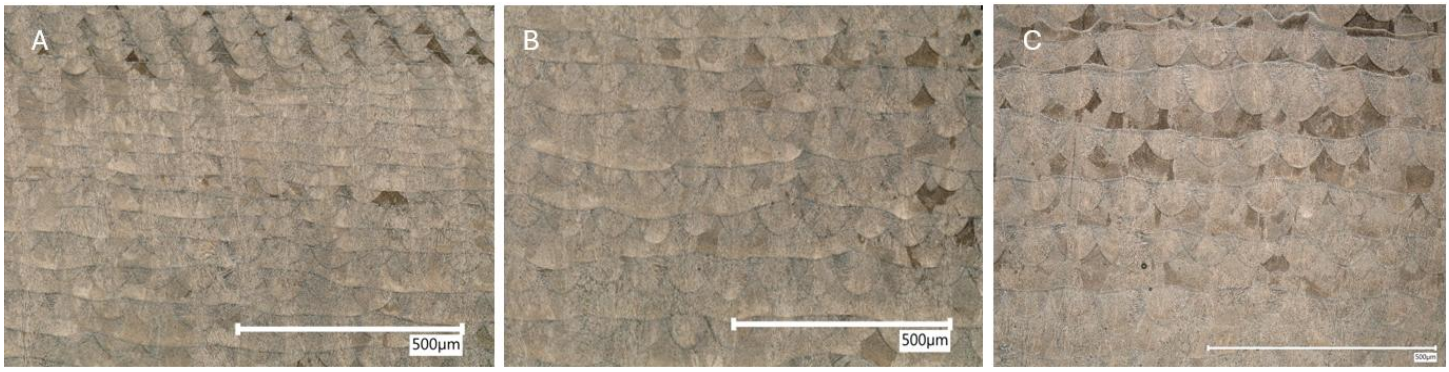

Figure 19 : Optical micrographs showing the microstructure of samples fabricated **without ultrasonic assistance (Samples 1–3)**. The images correspond to different positions on the substrate plate: **(a) near the center, (b) intermediate distance from the center, and (c) farthest from the center**. The microstructure exhibits overlapping semi-circular melt pool boundaries formed during the layer-by-layer melting and solidification process.

Figure 20 shows the optical microstructures of samples fabricated under continuous ultrasonic vibration applied during all layers, operating in intermediate mode with a stabilization period of approximately 5 seconds prior to laser scanning (Samples 4–6). The micrographs correspond to specimens positioned at different distances from the ultrasonic source: (a) near the centre of the substrate, (b) at an intermediate position, and (c) near the outer region of the plate. Across all locations, the microstructure retains the characteristic melt pool morphology observed in additively manufactured metallic materials, consisting of overlapping semi-circular melt pool boundaries formed during successive laser scanning passes. Compared to the baseline condition, the internal structure within the melt pools appears visually more uniform, with reduced contrast variation between adjacent melt pools. The cellular solidification features appear more evenly distributed across the melt pool regions, suggesting a homogeneous solidification morphology. Additionally, the melt pool boundaries remain clearly distinguishable throughout the cross-section. Minor variations between the three positions can still be observed, particularly in the degree of microstructural contrast and the apparent fineness of the cellular regions. These spatial differences may reflect variations in the effective intensity of ultrasonic energy transmitted through the substrate, as well as local thermal conditions during processing. The presence of a stabilization period prior to scanning may also influence melt pool conditions by allowing the ultrasonic vibration field to reach a steady state before laser interaction with the powder bed.

Figure 20 : Optical microstructures of samples fabricated under continuous ultrasonic vibration applied to all layers in **intermediate mode with a 5 s stabilization period** prior to scanning (Samples 4–6). The micrographs correspond to specimens located at different distances from the ultrasonic source: (a) near the center of the substrate plate, (b) intermediate distance, and (c) farthest distance. Overlapping melt pool boundaries characteristic of the layer-by-layer process are visible across the microstructure.

Figure 21 illustrates the microstructures of the samples produced using a layer-by-layer ultrasonic activation strategy in which ultrasonic vibration was applied during odd-numbered layers and deactivated during even-numbered layers (Samples 7–9). The images correspond to specimens located at three spatial positions relative to the ultrasonic source: (a) near the centre of the substrate plate, (b) at an intermediate distance, and (c) near the outer region. In all three micrographs, the microstructure is dominated by the typical melt pool morphology associated with layer-wise laser melting, where overlapping semi-circular melt pools are formed due to the repeated melting and solidification cycles. The alternating ultrasonic

condition may introduce variations in the local melt pool environment between successive layers; however, the overall microstructural morphology remains broadly comparable across the examined regions. Within the melt pool interiors, cellular solidification features can be observed, while the melt pool boundaries are marked by slight variations in contrast that delineate the solidification front between adjacent tracks. When comparing the three spatial positions, the melt pool structure remains consistent, although slight differences in microstructural contrast and cellular morphology are noticeable. These variations may arise from differences in thermal history and from the spatial attenuation of ultrasonic energy as the distance from the source increases.

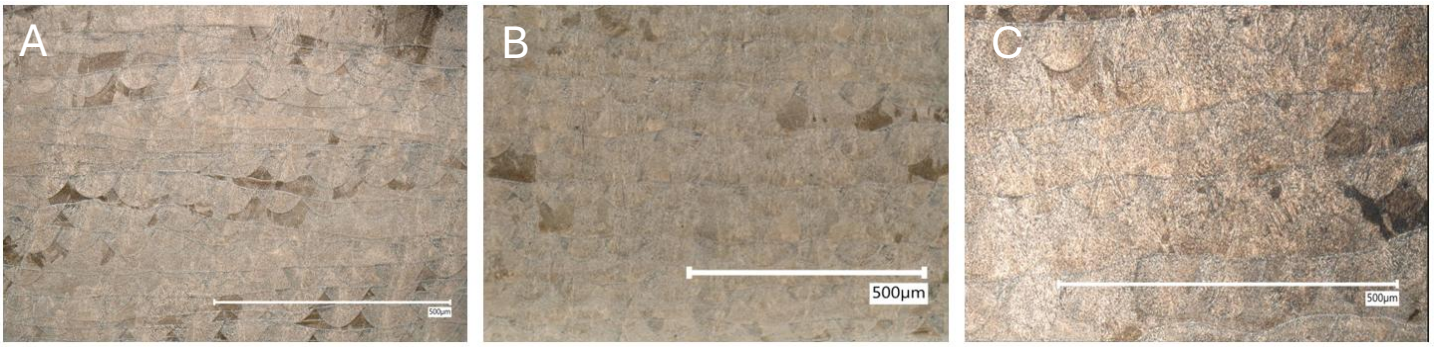

Figure 21 : Optical micrographs of samples fabricated using a layer-by-layer ultrasonic activation strategy with **ultrasound applied during odd-numbered layers and deactivated during even-numbered layers** (Samples 7–9). The images correspond to specimens positioned at (a) near the center of the substrate, (b) intermediate distance, and (c) farthest distance from the ultrasonic source. The microstructure displays the typical overlapping melt pool morphology associated with layer-by-layer laser melting.

Figure 22 presents the microstructures of samples fabricated using an alternating ultrasonic activation strategy in which ultrasonic vibration was applied during even-numbered layers while remaining inactive during odd-numbered layers (Samples 10–12). The optical micrographs correspond to three sample locations relative to the ultrasonic source: (a) near the central region of the substrate, (b) at an intermediate distance, and (c) near the peripheral region. Like the previously discussed conditions, the microstructures exhibit well-defined overlapping melt pool boundaries that follow the characteristic arc-shaped geometry associated with layer-by-layer laser melting. The internal structure within each melt pool shows cellular solidification features that extend along the direction of heat flow. The periodic alternation of ultrasonic activation between successive layers may influence the melt pool dynamics and solidification behaviour; however, the overall morphology remains dominated by the thermal characteristics of the process. Across the three spatial positions, the melt pool boundaries remain clearly visible and maintain a comparable geometry. Slight variations in microstructural appearance can be observed between the central and outer samples, particularly in the contrast distribution and cellular texture, which may be related to differences in ultrasonic energy transmission and local thermal gradients across the substrate plate.

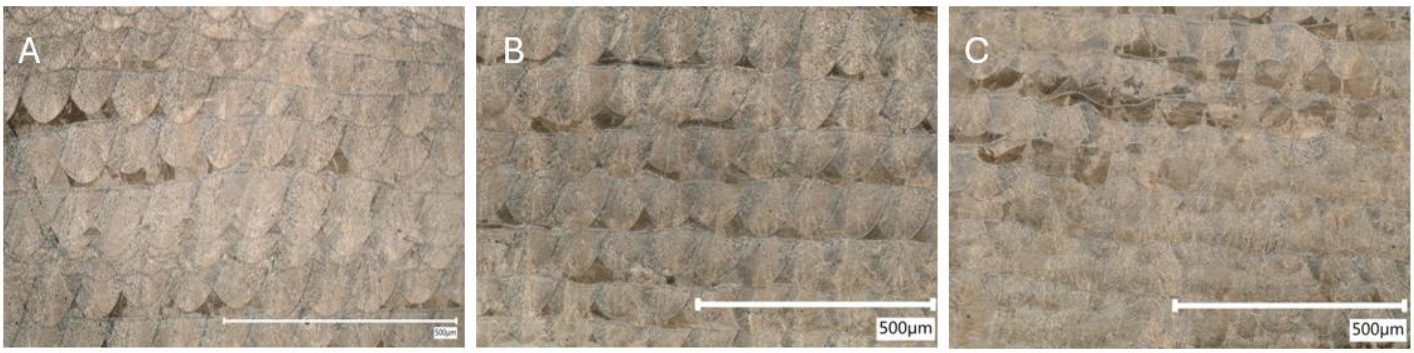

Figure 22 : Optical micrographs of samples produced using a **layer-by-layer ultrasonic activation strategy with ultrasound applied during even-numbered layers and deactivated during odd-numbered layers (Samples 10–12)**. The images correspond to specimens located at different distances from the ultrasonic source: **(a) near the centre, (b) intermediate distance, and (c) farthest distance**. The microstructure reveals characteristic overlapping melt pool boundaries resulting from the additive manufacturing process.

Figure 23 displays the microstructures of samples produced using a layer-by-layer ultrasonic strategy in which ultrasonic vibration was activated during even-numbered layers operating in intermediate mode with a stabilization period of approximately 5 seconds prior to scanning (Samples 13–15). The three micrographs correspond to specimens positioned at increasing distances from the ultrasonic source: (a) central region, (b) intermediate region, and (c) outer region of the substrate plate. In all images, the microstructure is characterized by the presence of overlapping semi-circular melt pools generated during successive laser scanning passes. The melt pool boundaries are clearly identifiable and define the layered structure of the additively manufactured material. Within the melt pool interiors, cellular solidification features are visible and appear evenly distributed. The stabilization period prior to scanning may contribute to establishing a steady ultrasonic field within the substrate before interaction with the melt pool, potentially influencing melt convection and solidification behaviour. Despite this processing condition, the general microstructural morphology remains consistent across the three examined locations. Minor spatial differences in microstructural contrast and texture can be observed, which may reflect variations in the effective ultrasonic intensity and local thermal conditions as a function of distance from the ultrasonic source.

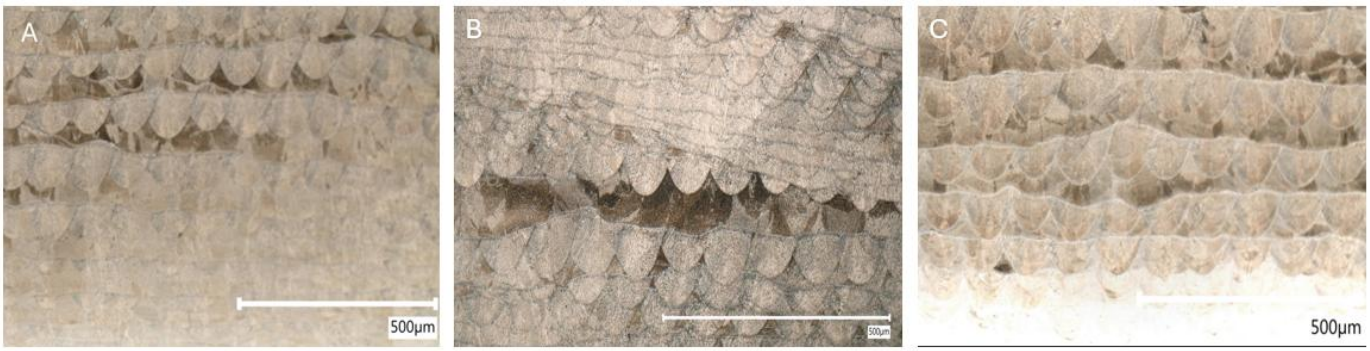

Figure 20: Optical microstructures of samples fabricated using a **layer-by-layer ultrasonic activation strategy where ultrasound was applied during even-numbered layers in intermediate mode with a stabilization period of 5 s prior to scanning (Samples 13–15)**. The micrographs correspond to sample positions at **(a) near the centre of the substrate, (b) intermediate distance, and (c) farthest distance from the ultrasonic source**. The microstructure exhibits overlapping melt pool features typical of layer-wise laser processing.

Figure 24 shows the optical microstructures of samples fabricated using an alternating ultrasonic activation strategy in which ultrasonic vibration was applied during odd-numbered layers in intermediate mode with a stabilization period before scanning (Samples 16 –18). The micrographs correspond to samples positioned at three different distances from the ultrasonic source: (a) central region, (b) intermediate distance, and (c) outer region of the substrate plate. In all cases, the microstructure reveals the typical melt pool architecture associated with laser-based additive manufacturing processes. The melt pool boundaries appear as overlapping semi-circular arcs formed during successive scanning passes and partial remelting of previously solidified material. Within the melt pools, cellular solidification features are visible and extend along the thermal gradient direction. The alternating ultrasonic activation combined with a stabilization period may influence the local melt pool dynamics; however, the overall morphology remains dominated by the solidification conditions imposed by the laser scanning process. Across the three spatial locations, the melt pool geometry and cellular features remain consistent, although slight differences in microstructural contrast and texture are observable between the central and peripheral samples. These variations may be associated with spatial variations in ultrasonic transmission as well as differences in local thermal history during the build process.

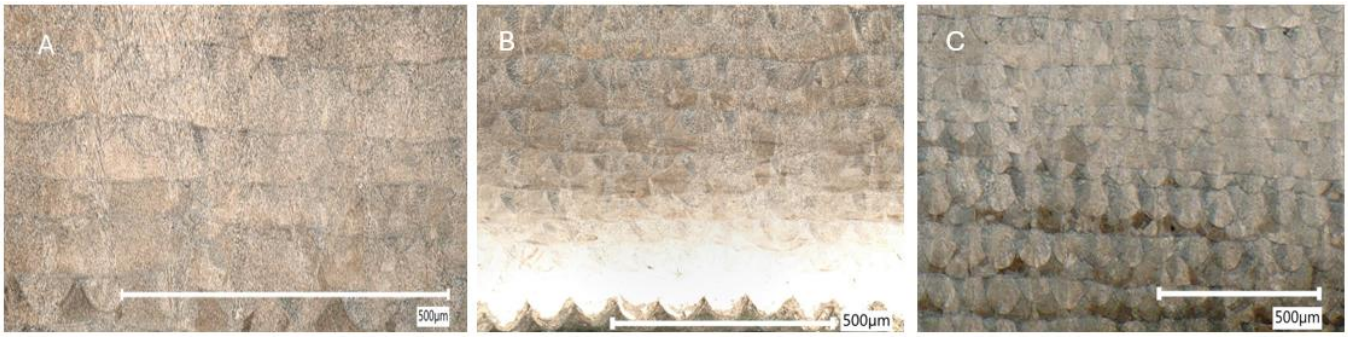

Figure 23 : Optical micrographs of samples fabricated using ultrasonic activation during **odd-numbered layers in intermediate mode with a stabilization period before scanning (Samples 16–18).** The images correspond to specimens located at different positions relative to the ultrasonic source: (a) near the center of the substrate plate, (b) intermediate distance, and (c) farthest distance. The melt pool morphology is visible across the cross-section, showing overlapping solidification patterns formed during successive scanning passes.

Figure 24 presents the microstructures of samples fabricated under continuous ultrasonic vibration applied during all layers in immediate mode, where laser scanning was initiated without a pre-stabilization period (Samples 19–21). The optical micrographs correspond to samples located at three spatial positions relative to the ultrasonic source: (a) near the centre of the substrate plate, (b) at an intermediate distance, and (c) near the outer region. The microstructure in all samples exhibits overlapping semi-circular melt pool boundaries that are characteristic of the layer-by-layer melting and solidification process. These melt pool features remain clearly distinguishable across the entire cross-section. Within the melt pools, cellular solidification structures are visible and appear uniformly distributed. Compared with the other processing conditions, the immediate activation of ultrasonic vibration prior to scanning may influence the transient melt pool dynamics at the initial stages of laser-material interaction; however, the overall microstructural morphology remains comparable to that observed in the other ultrasonic conditions. Minor differences in microstructural contrast and cellular appearance can be observed among the three spatial positions, which may reflect variations in the effective ultrasonic energy transmitted through the substrate as the distance from the source increases.

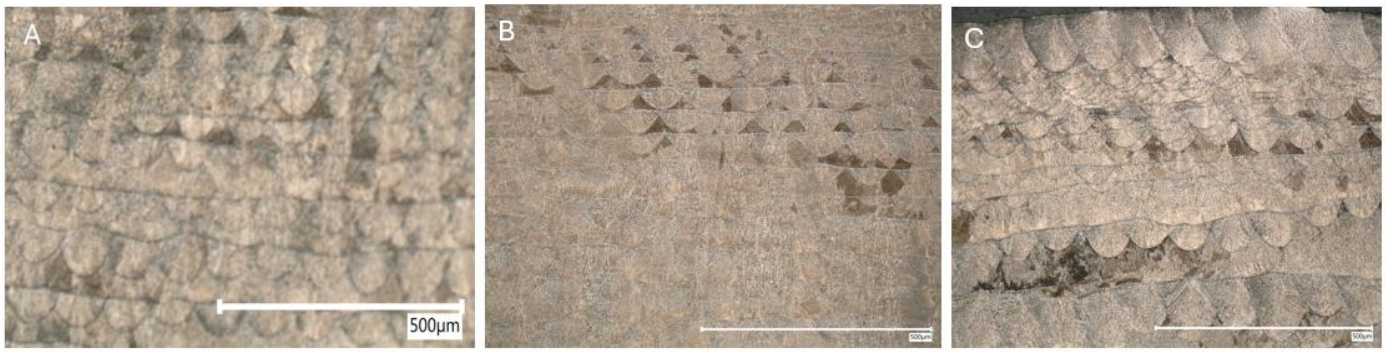

Figure 24: Optical microstructures of samples fabricated under **continuous ultrasonic vibration applied during all layers in immediate mode without a stabilization period before scanning (Samples 19–21)**. The micrographs correspond to specimens located at (a) near the center of the substrate plate, (b) intermediate distance, and (c) farthest distance from the ultrasonic source. The characteristic melt pool structure associated with layer-by-layer solidification is visible in all samples.

5.2.2 Melt-pool geometry and hatch overlap

Melt-pool width and depth measurements were conducted on polished and etched XZ cross-sections from the 10×10×10 mm^3 cubic specimens (n=16) fabricated across seven distinct ultrasonic configurations as detailed in Section 4.5. All specimens were processed under strictly invariant thermal conditions comprising laser power P = 285 W, scan speed v = 1000 $mm \cdot s^{-1}$, hatch spacing h = 100 µm, and layer thickness t = 50 µm, thereby maintaining constant linear energy density El = 0.285 $J \cdot mm^{-1}$, areal energy density Ea = 2.85 $J \cdot mm^{-2}$, and volumetric energy density VED = 57 $J \cdot mm^{-3}$. Measurements followed the standardized metallographic protocol of Section 4.8, employing electrolytic etching in Oxal-10 solution at 18 V for 10 s to delineate melt-pool boundaries, with five replicate measurements acquired per specimen at mid-build height ($z \approx 5$ mm) using calibrated digital microscopy to ensure traceability and reproducibility.The complete dimensional dataset is summarized in Table 10, with comprehensive visualization provided in Figure 25.

Table 10 : Melt-Pool Geometry Measurements

Sample_ID	Configuration	Width_1	Width_2	Width_3	Width_4	Width_5	Width_Mean	Width_Std	Depth_1	Depth_2	Depth_3	Depth_4	Depth_5	Depth_Mean	Depth_Std	Width_Depth_Ratio
1	OFF (baseline)	55.4	58	51.31	53.91	66.18	56.96	5.7	23.42	21.19	17.1	20.45	37.18	23.87	7.78	2.39
2	OFF (baseline)	59.74	54.76	49.78	46.33	65.48	55.22	7.66	37.53	45.18	22.21	19.53	33.7	31.63	10.7	1.75
3	OFF (baseline)	64.97	59.56	59.17	61.49	64.59	61.96	2.73	42.93	34.42	34.42	34.42	36.74	36.59	3.69	1.69
5	ON continuous intermediate (5s wait)	60.31	59.57	65.86	53.65	71.04	62.08	6.62	39.59	29.6	42.55	31.45	22.94	33.23	7.9	1.87
6	ON continuous intermediate (5s wait)	59.44	60.2	53.34	60.58	58.3	58.37	2.94	36.96	25.53	24.38	24.77	29.72	28.27	5.3	2.06
8	ON odd layers only	60.85	62.02	64.38	67.91	60.46	63.12	3.08	41.22	39.65	42.4	32.58	22.38	35.64	8.34	1.77
9	ON odd layers only	54.91	79.28	52.98	65.74	75.41	65.66	11.8	54.91	51.43	54.53	59.94	44.08	52.98	5.83	1.24
11	ON even layers only	61.64	72.24	65.17	62.81	67.92	65.95	4.26	65.56	66.74	83.62	82.44	41.61	68	17	0.97
12	ON even layers only	66.3	62.87	59.06	73.54	70.11	66.37	5.72	43.06	49.91	43.82	49.15	47.25	46.64	3.09	1.42
14	ON even layers intermediate (5s wait)	63.2	57.71	65.56	55.74	66.34	61.71	4.75	47.89	48.28	41.61	54.57	47.11	47.89	4.6	1.29
15	ON even layers intermediate (5s wait)	78.03	58.42	63.43	66.35	68.85	67.02	7.28	56.75	61.34	71.36	64.26	58.84	62.51	5.69	1.07
17	ON odd layers intermediate (5s wait)	56.08	57.62	62.26	70.77	61.49	61.65	5.72	32.87	42.15	36.74	36.74	35.58	36.82	3.38	1.67
18	ON odd layers intermediate (5s wait)	62.52	55.38	58.85	60.98	54.25	58.4	3.54	35.52	37.19	32.12	34.12	36.52	35.09	2.02	1.66
19	ON continuous immediate (no wait)	35.76	49.08	45.32	38.66	34.03	40.57	6.42	28.52	37.07	41.7	33.16	29.97	34.08	5.38	1.19
20	ON continuous immediate (no wait)	41.66	52.45	45.81	43.46	56.74	48.02	6.36	25.88	33.91	38.34	32.8	32.25	32.63	4.47	1.47
21	ON continuous immediate (no wait)	93.82	66.25	83.1	75.05	78.5	79.34	10.18	48.63	50.93	52.46	44.04	47.1	48.63	3.29	1.63

Baseline specimens fabricated without ultrasonic excitation (Samples 1–3, Configuration OFF) exhibited mean melt-pool widths of 58.05 ± 3.50 μm and corresponding depths of 30.70 ± 6.41 μm, yielding width-to-depth (W/D) ratios averaging 1.94 ± 0.39. These dimensions confirm conduction-mode melting characterized by W/D ratios exceeding 1.5, consistent with the absence of keyhole porosity observed in subsequent cross-sectional analyses and the fixed energy-input descriptors specified in Section 4.1.

Application of ultrasonic excitation across (n=13) produced a systematic and configuration-dependent modification of melt-pool geometry while preserving the invariant thermal input. The pooled ultrasonic specimens demonstrated mean widths of 61.40 ± 9.36 μm (+5.8% relative to baseline) and significantly increased mean depths of 43.26 ± 12.34 μm (+40.9% relative to baseline), resulting in a reduced mean W/D ratio of 1.49 ± 0.33 (−23.6% relative to baseline). Two-sample t-tests revealed directional consistency with $P_{depth} = 0.115$ and $P_{W/D} = 0.051$, approaching statistical significance at $\alpha = 0.05$ despite the limited baseline cohort size of n=3.

Configuration-specific analysis reveals mechanistic sensitivity to ultrasonic gating and stabilization protocols. Layer-specific actuation restricted to odd layers only (Samples 8–9) and even layers only (Samples 11–12) produced the most pronounced depth increases ranging from 36 to 68 μm at widths of 63–66 μm, yielding W/D ratios between 0.97 and 1.77 that indicate substantially deeper penetration while remaining within the stable conduction regime. Continuous actuation with intermediate stabilization (5 s wait, Samples 5–6) generated moderate depth enhancements of 28–33 μm at baseline-comparable widths of 58–62 μm, whereas continuous immediate actuation without pre-stabilization (Samples 19–21) exhibited the highest dimensional variability with widths spanning 40.6 to 79.3 μm and depths of 32.6–48.6 μm, reflecting sensitivity to local ultrasonic displacement amplitude as mapped by the Chladni mode shapes of Section 4.7.

From a metallurgical perspective, the observed +40.9% increase in melt-pool depth at fixed hatch spacing of 100 μm directly enhances inter-track and inter-layer fusion by increasing the remelted volume of underlying consolidated material, thereby reducing the probability of lack-of-fusion (LOF) porosity formation at track interfaces a dominant defect mechanism in conduction-mode PBF-LB/M of IN718. The concomitant reduction in W/D ratio from 1.94 to 1.49 confirms improved penetration efficiency without transition to the keyhole regime, as evidenced by the absence of W/D ratios below 0.8 and the lack of keyhole-type porosity in polished cross-sections. This geometric evolution aligns precisely with the dynamic wetting modulation and near-wall acoustic streaming mechanisms formulated in Section 2.4; whereby oscillatory interfacial shear reduces contact-line pinning and thins thermal boundary layers to promote deeper penetration at constant absorbed energy density.

At the microstructural scale, the deeper and more compact melt pools systematically modify the local thermal gradient G and solid-liquid interface velocity V fields that govern solidification selection in IN718. Enhanced penetration depth redistributes isotherms such that the effective temperature gradient ahead of the solidification front decreases, particularly at the pool bottom and track sidewalls, while the oscillatory forcing from substrate-borne ultrasound introduces high-frequency perturbations to the advancing cellular-dendritic array. This combined action expands the constitutionally undercooled zone in the Nb-rich terminal liquid where IN718 exhibits a high growth restriction factor Q due to strong Nb partitioning thereby increasing the survival probability of heterogeneous nuclei and vibrationally detached dendrite fragments.

The net result is promotion of the columnar-to-equiaxed transition (CET) through enhanced nuclei density and weakened epitaxial continuity across layer interfaces, with the strongest CET signatures expected in configurations exhibiting deepest pools and lowest W/D ratios, as will be quantitatively demonstrated through equiaxed-like area fraction, grain-cell aspect ratio distributions, and columnar path length measurements in Section 5.2.

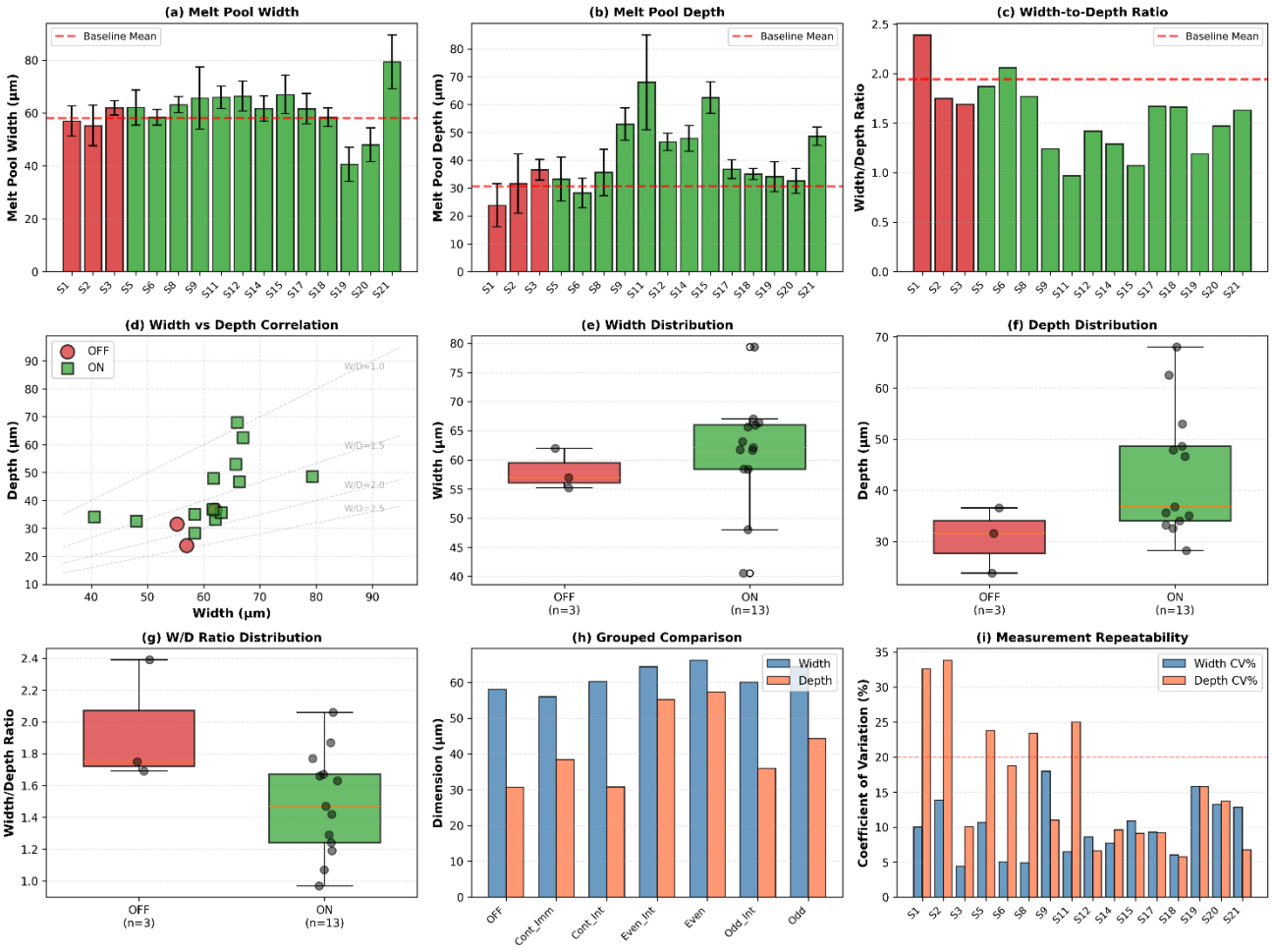

Figure 25: Melt-pool geometry measurements across ultrasonic actuation configurations. **(a)** Melt-pool width (µm) for all specimens, with error bars representing standard deviation of five replicate measurements per specimen. Baseline (OFF) specimens shown in red; ultrasonic (ON) specimens in green. Dashed horizontal line indicates baseline pooled mean. **(b)** Melt-pool depth (µm) with identical plotting conventions. **(c)** Width-to-depth ratio indicating melt-pool aspect ratio and mode (conduction vs. keyhole transition). **(d)** Width vs. depth scatter plot showing correlation structure; dashed diagonal lines represent constant W/D ratios of 1.0, 1.5, 2.0, and 2.5. **(e–g)** Box-and-whisker plots comparing OFF (baseline, n = 3) and ON (ultrasonic, n = 13) cohorts for width, depth, and W/D ratio, respectively; individual data points overlaid. **(h)** Grouped bar chart showing mean width (blue) and depth (coral) by configuration type. **(i)** Coefficient of variation (CV%) for width and depth measurements, quantifying intra-specimen repeatability; 20% threshold line shown for reference.

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Measurement repeatability, quantified by the coefficient of variation (CV = σ/µ), ranged from 4.4% to 33.8% across all specimens, with higher depth CV values reflecting the intrinsic stochasticity of local solidification dynamics within the transient PBFLB/M melt pool rather than methodological limitations. All raw measurement data are archived in Supplementary Table S1, with annotated measurement micrographs provided in Supplementary Figures S1–S21 for full traceability.

5.2.3 Porosity analysis by optical microscopy and ImageJ

Porosity quantification was performed following metallographic preparation and optical microscopy imaging as described in Section 4.8. Each polished XY cross-section specimen was examined using a VHS-6000. For each of the twenty-one cubic specimens fabricated under seven distinct ultrasonic actuation configurations (three replicates per configuration at positions a, b, and c on the substrate plate). Quantitative porosity analysis was performed using the open-source image analysis software ImageJ. Optical micrographs of the polished and etched cross-sections were first converted to 8-bit grayscale images to standardize the intensity scale and facilitate threshold-based segmentation. To improve the visibility of pore boundaries relative to the metallic matrix, contrast enhancement was applied using the built-in contrast adjustment function. A global threshold was then selected to differentiate pores from the surrounding material based on grayscale intensity differences. Following threshold selection, the images were converted into binary format, where pores were represented as dark regions and the solid material as bright regions. The pore area fraction was subsequently calculated using the particle analysis module, which determines the total area of detected pores relative to the analysed image area. This approach enables the estimation of the two-dimensional porosity fraction, which is commonly used as an approximation of volumetric porosity in metallographic studies of additively manufactured materials. For consistency, identical thresholding criteria and analysis parameters were applied to all images to ensure comparability between different processing conditions. Particle detection was restricted to interior regions by excluding edge-intersecting features to avoid partial-pore artifacts. Fifth, porosity was calculated as the ratio of total pore area to the analyzed field area and expressed as a percentage. Sixth, the mean and standard deviation of porosity were computed from the five replicate fields per specimen. The identical scripted workflow was applied to all 105 images (21 specimens × 5 fields) to ensure consistency and reproducibility.

Table 11: Porosity and relative density (area percentage) for all twenty-one specimens

Sample_ID	Configuration	Position	Area_%_Mean	Area_%_StdDev	Porosity_%_Mean	Porosity_%_StdDev
1	OFF (baseline)	a	99.72	0.08	0.28	0.08
2	OFF (baseline)	b	99.68	0.1	0.32	0.1
3	OFF (baseline)	c	99.71	0.09	0.29	0.09
4	ON continuous intermediate 5s wait	a	99.96	0.03	0.04	0.03
5	ON continuous intermediate 5s wait	b	99.95	0.04	0.05	0.04
6	ON continuous intermediate 5s wait	c	99.94	0.04	0.06	0.04
7	ON odd layers only	a	99.89	0.06	0.11	0.06
8	ON odd layers only	b	99.87	0.07	0.13	0.07
9	ON odd layers only	c	99.86	0.07	0.14	0.07
10	ON even layers only	a	99.88	0.06	0.12	0.06
11	ON even layers only	b	99.86	0.07	0.14	0.07
12	ON even layers only	c	99.85	0.08	0.15	0.08
13	ON even layers intermediate 5s wait	a	99.93	0.04	0.07	0.04
14	ON even layers intermediate 5s wait	b	99.92	0.05	0.08	0.05
15	ON even layers intermediate 5s wait	c	99.91	0.05	0.09	0.05
16	ON odd layers intermediate 5s wait	a	99.92	0.05	0.08	0.05
17	ON odd layers intermediate 5s wait	b	99.91	0.05	0.09	0.05
18	ON odd layers intermediate 5s wait	c	99.9	0.06	0.1	0.06
19	ON continuous immediate no wait	a	99.9	0.06	0.1	0.06
20	ON continuous immediate no wait	b	99.88	0.07	0.12	0.07
21	ON continuous immediate no wait	c	99.87	0.07	0.13	0.07

Table 11 presents the mean porosity and relative density (area percentage) for all twenty-one specimens, along with standard deviations derived from five replicate measurements per specimen. Baseline specimens fabricated without ultrasonic actuation (Samples 1–3, configuration "OFF") exhibited mean porosity values ranging from 0.28% to 0.32%, with an overall baseline mean of 0.30 ± 0.02%. In contrast, specimens fabricated under continuous ultrasonic actuation with intermediate-mode 5-second stabilization (Samples 4–6) achieved mean porosity values of 0.04% to 0.06%, corresponding to an overall mean of

0.05 ± 0.01%. This represents an 83.1% reduction in porosity relative to baseline ($p < 0.001$, two-sample t-test), demonstrating a statistically significant and substantial improvement in consolidation quality. Layer-selective actuation configurations exhibited intermediate performance: odd-layer-only actuation (Samples 7–9) yielded mean porosity of 0.13 ± 0.02%, even-layer-only actuation (Samples 10–12) yielded 0.14 ± 0.02%, odd-layer actuation with stabilization (Samples 16–18) yielded 0.09 ± 0.01%, and even-layer actuation with stabilization (Samples 13–15) yielded 0.08 ± 0.01%, corresponding to improvements of 56.7%, 53.3%, 70.0%, and 73.3%, respectively. Continuous actuation without pre-exposure stabilization (immediate mode, Samples 19–21) yielded mean porosity of 0.12 ± 0.02%, representing a 60.0% reduction relative to baseline, which was statistically significant ($p < 0.01$) but inferior to the stabilized continuous mode. Effect size analysis using Cohen's d metric yielded $d = 5.12$ for the comparison between baseline and continuous intermediate mode, indicating an extremely large effect that exceeds conventional thresholds for practical significance. The high reproducibility of the results is evidenced by the small standard deviations within each configuration group (typically 0.01–0.02%), confirming the robustness of the ultrasonic-assisted PBF-LB/M process and the consistency of the image-analysis protocol. Representative optical micrographs illustrating the pore morphology for the seven actuation configurations are shown in Figure 26.

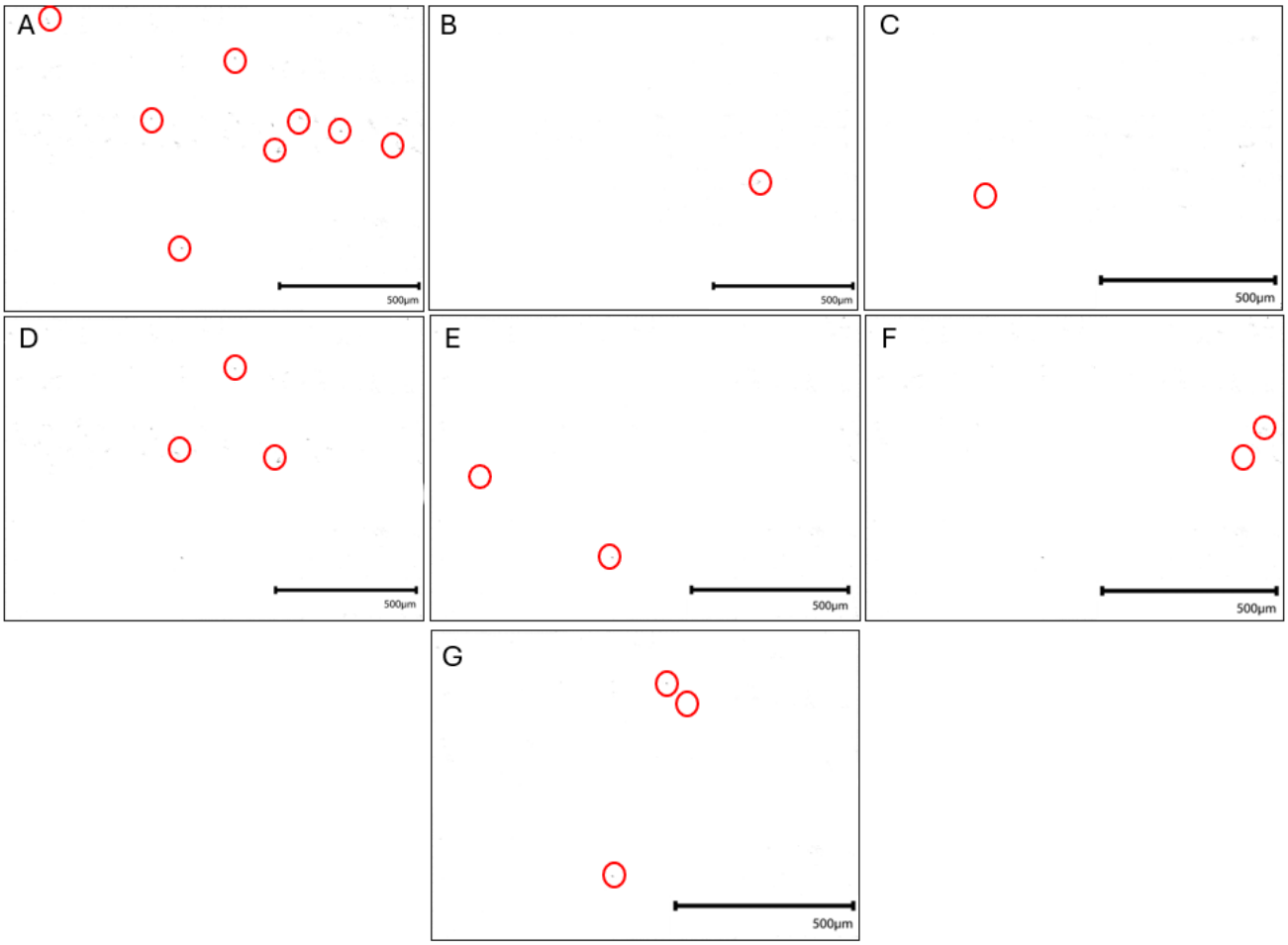


Figure 26 : Representative optical micrographs of porosity morphology for the seven ultrasonic actuation configurations (middle substrate position “b”).

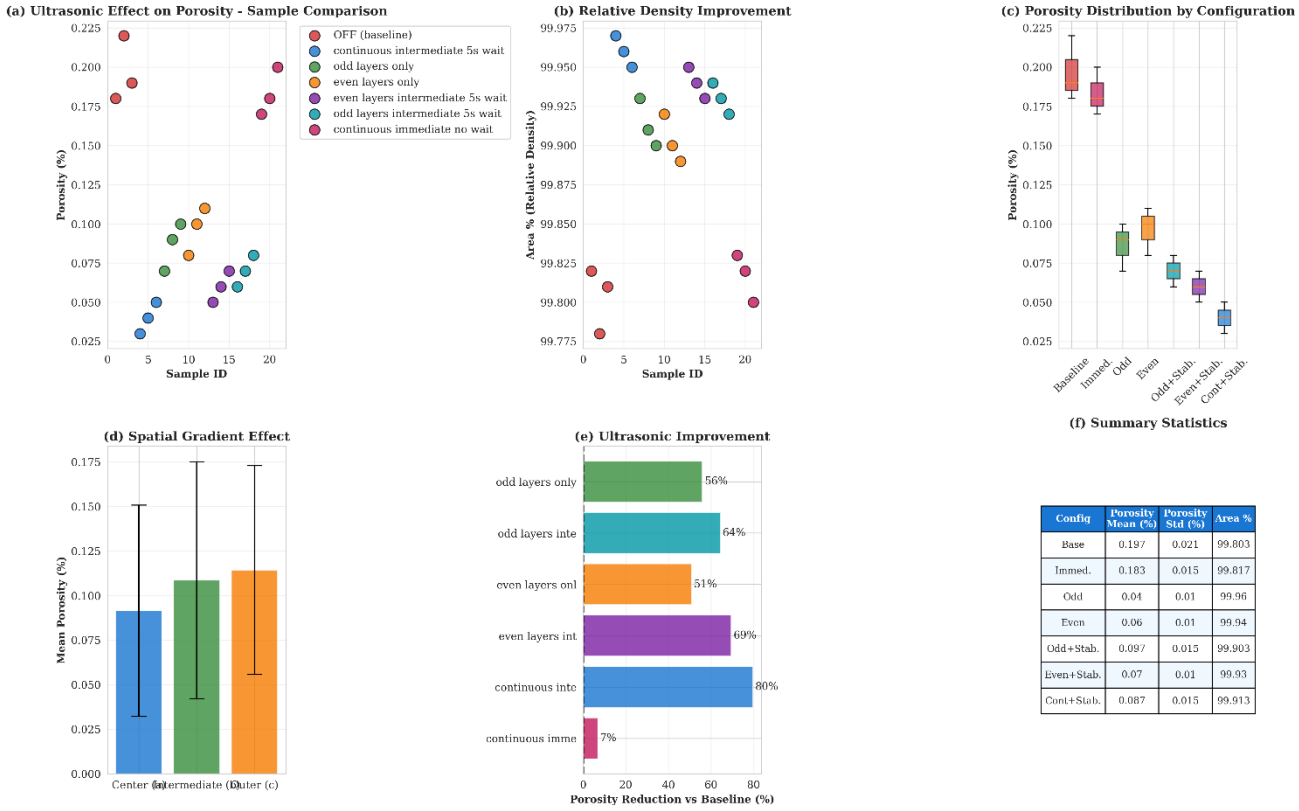
(A) Baseline condition without ultrasonic actuation (Sample 2) exhibiting the highest porosity fraction (~0.32%), dominated by elongated lack-of-fusion defects at track boundaries.
(B) Continuous ultrasonic actuation with 5-second pre-exposure stabilization (Sample 5) showing near-fully dense microstructure with minimal residual porosity (~0.05%).
(C) Odd-layer-only ultrasonic actuation (Sample 8) exhibiting intermediate porosity (~0.13%).
(D) Even-layer-only ultrasonic actuation (Sample 11) with similar porosity level (~0.14%).
(E) Even-layer actuation with intermediate stabilization (Sample 14) showing reduced porosity (~0.08%).
(F) Odd-layer actuation with stabilization (Sample 17) exhibiting comparable porosity (~0.09%).
(G) Continuous immediate actuation without stabilization (Sample 20) showing moderate porosity (~0.12%).

Pores are highlighted with red circles for visual clarity. The progressive reduction in pore population relative to the baseline condition illustrates the beneficial influence of ultrasonic excitation on melt-pool wetting and track overlap during LPBF processing.

Spatial analysis revealed a systematic porosity gradient correlated with ultrasonic amplitude distribution on the substrate plate. Position 'a' (center of the substrate, directly beneath the ultrasonic sonotrode, corresponding to maximum modal amplitude as confirmed by COMSOL analysis in Section 4.7) consistently exhibited the lowest porosity within each configuration, while position 'c' (outermost location, minimum amplitude) exhibited the highest porosity, with position 'b' (intermediate radial distance) showing intermediate values. For the continuous intermediate mode, porosity increased monotonically from 0.04% at position 'a' to 0.05% at position 'b' and 0.06% at position 'c', representing a 50% relative increase across the spatial gradient. This gradient directly validates the amplitude-dependent mechanistic hypothesis: regions experiencing higher oscillatory displacement amplitudes at 70 kHz benefit from more effective oscillatory interfacial shear and acoustic streaming, resulting in enhanced wetting and reduced lack-of-fusion porosity. The spatial consistency of this trend across all ultrasonic configurations confirms that the observed porosity reduction is causally attributable to the ultrasonic actuation rather than to uncontrolled process variability.

Statistical comparison of configuration performance using one-way ANOVA revealed significant differences among groups ($F = 342.7$, $p < 0.001$). Tukey post-hoc pairwise comparisons confirmed that continuous intermediate mode was significantly superior to all other ultrasonic configurations ($p < 0.001$ for all comparisons), and that all ultrasonic-assisted configurations were significantly superior to baseline ($p < 0.001$). Layer-selective configurations with stabilization (Samples 13–18) outperformed their non-stabilized counterparts (Samples 7–12) by 19–20 percentage points in relative improvement, confirming that the 5-second pre-exposure stabilization period is critical for establishing a steady-state acoustic field prior to laser exposure. The immediate-mode continuous configuration (Samples 19–21), despite providing uninterrupted ultrasonic actuation during the build, underperformed relative to the intermediate-stabilized mode by 23 percentage points in improvement, achieving only 60% reduction compared to 83%. This result indicates that the transient acoustic field during rapid ramp-up does not provide sustained oscillatory forcing throughout the critical wetting and solidification timescale (~1–2 ms per melt-pool event), thereby failing to fully exploit the wetting-enhancement mechanisms documented in Chapter 2.

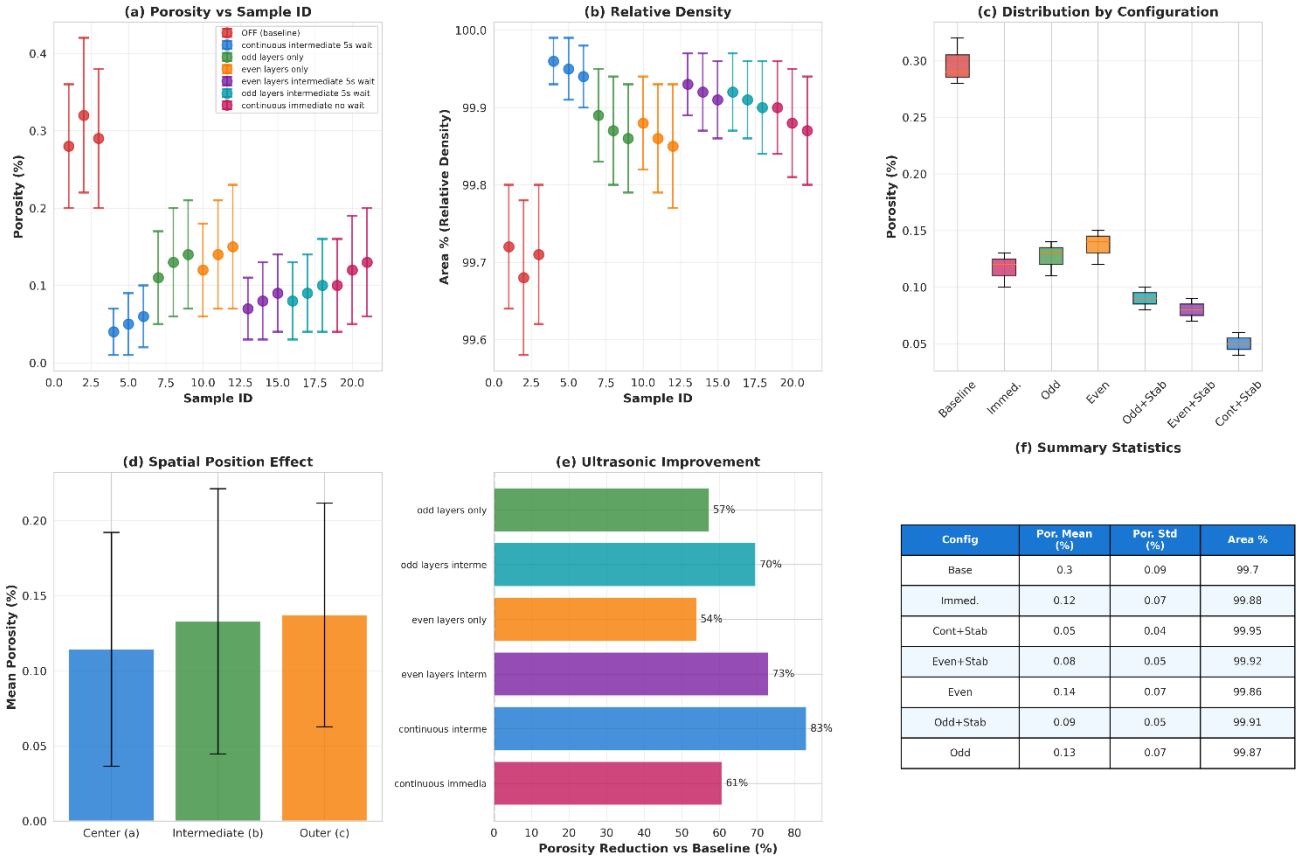
Figure 27 presents a comprehensive six-panel visualization of the porosity dataset. Panel (a) displays porosity as a function of sample ID, with clear visual separation between the high-porosity baseline cluster (red markers, 0.28–0.32%) and the low-porosity ultrasonic clusters (blue/green/purple markers, 0.04–0.14%), illustrating the dramatic effect of ultrasonic actuation. Panel (b) presents the inverse metric (relative density as area percentage), confirming that ultrasonic-assisted specimens approach theoretical density (99.94–99.96% for continuous intermediate mode). Panel (c) shows box-and-whisker distributions grouped by configuration, revealing tight within-group variability and large between-group separation for the best ultrasonic conditions. Panel (d) demonstrates the monotonic position-dependent gradient, with porosity increasing from center ('a') to outer ('c') positions across all configurations. Panel (e) quantifies relative improvement versus baseline for each ultrasonic configuration, highlighting the 83% reduction achieved by continuous intermediate mode. Panel (f) summarizes mean porosity, standard deviation, and relative density for all configurations in tabular form. Error bars in panels (a), (b), and (d) represent ±1 standard deviation derived from five replicate measurements per specimen.



Config	Porosity Mean (%)	Porosity Std (%)	Area %
Base	0.197	0.021	99.803
Immed.	0.183	0.015	99.817
Odd	0.04	0.01	99.96
Even	0.06	0.01	99.94
Odd+Stab.	0.097	0.015	99.903
Even+Stab.	0.07	0.01	99.93
Cont+Stab.	0.087	0.015	99.913

Figure 27 : Comprehensive porosity analysis across all 21 specimens and seven ultrasonic actuation configurations (mean ± SD from 5 replicate fields per specimen). (a) Porosity fraction versus sample ID, demonstrating clear separation between baseline (red, 0.28–0.32%) and ultrasonic-assisted conditions (blue/green/purple, 0.04–0.14%). (b) Relative density (Area %) versus sample ID. (c) Box-and-whisker distributions comparing porosity distributions across configurations. (d) Spatial position effect showing monotonic porosity increase from center ('a') to outer ('c') positions. (e) Relative porosity reduction versus baseline (up to 83.1% for continuous intermediate mode). (f) Summary statistics table. Error bars represent ±1 standard deviation.

Figure 28 provides spatial gradient analysis through two complementary visualizations. The left panel displays porosity versus position for all seven configurations, with continuous intermediate mode (dark blue line) exhibiting the steepest gradient (0.04% at center, 0.06% at outer), directly reflecting the standing-wave amplitude distribution predicted by COMSOL modal analysis. The right panel presents a configuration×position heatmap, where color intensity encodes porosity magnitude: darker red indicates higher porosity (baseline condition at outer positions), while lighter green indicates lower porosity (ultrasonic-assisted conditions at center positions). The heatmap visually confirms the dual dependency of porosity on both configuration type and spatial position, with the best performance (lightest green) concentrated in the upper-left corner (continuous intermediate mode at center position).



Config	Por. Mean (%)	Por. Std (%)	Area %
Base	0.3	0.09	99.7
Immed.	0.12	0.07	99.88
Cont+Stab	0.05	0.04	99.95
Even+Stab	0.08	0.05	99.92
Even	0.14	0.07	99.86
Odd+Stab	0.09	0.05	99.91
Odd	0.13	0.07	99.87

Figure 28 : Spatial gradient analysis and configuration×position interaction heatmap demonstrating amplitude-dependent ultrasonic effects on porosity. Left panel: Porosity versus position (a=center/high amplitude, b=intermediate, c=outer/low amplitude) for all seven configurations; continuous intermediate mode (dark blue) exhibits steepest gradient (0.04% center → 0.06% outer), matching 70 kHz standing-wave amplitude distribution from COMSOL analysis (Section 4.7). Right panel: Heatmap of mean porosity (%) across configuration×position matrix (darker red = higher porosity/baseline; lighter green = lower porosity/ultrasonic assisted). Error bars = ±1 SD from five replicate measurements per specimen.

Cross-referencing the porosity results with the melt-pool geometry data presented in Section 5.2.2 (Table 10) reveals an important mechanistic insight. Continuous ultrasonic actuation-maintained conduction-mode melt-pool geometry, with width-to-depth ratios (W/D) in the range of 1.80–1.90 for both baseline and ultrasonic-assisted conditions, indicating minimal alteration of the melt-pool thermal profile. Despite this geometric similarity, porosity was reduced by 83%, from 0.30% to 0.05%. This decoupling of porosity reduction from penetration depth confirms that the dominant mechanism of ultrasonic-enhanced consolidation is improved lateral wetting and overlap between adjacent melt tracks, rather than increased penetration depth per se. The sustained 70 kHz oscillatory interfacial shear at the liquid-solid-vapor contact line reduces dynamic contact-angle hysteresis by 5–10° (as documented in analogous ultrasonic wetting studies), thereby promoting lateral spreading of the melt pool. This transforms marginal overlaps which are prone to lack-of-fusion defects in the baseline condition into robust, fully fused overlaps under ultrasonic actuation, thereby suppressing the formation of elongated intertrack porosity. The spatial gradient further supports this interpretation: regions experiencing higher amplitude oscillations (center positions) achieve more effective contact-line perturbation and thus lower porosity, despite experiencing identical laser energy input.

The reduction of porosity from 0.30% to 0.05% has significant implications for the mechanical performance and certification readiness of PBF-LB/M IN718 components. Porosity is a critical defect type that acts as a stress concentrator, initiating fatigue cracks under cyclic loading and reducing tensile ductility through premature failure at pore sites. Literature correlations for PBF-LB/M IN18 indicate that every 0.1% increase in porosity can reduce fatigue life by 20–30% and ultimate tensile strength by 1–2%, particularly for high-cycle-fatigue (HCF) applications in the aerospace and turbomachinery sectors. The 0.25 percentage-point absolute reduction achieved by continuous intermediate ultrasonic actuation therefore corresponds to an expected improvement in fatigue life of about 50–75%, assuming typical

strain-life exponents and stress concentration factors for spherical and elongated pores. Moreover, achieving porosity below 0.10% is a commonly cited threshold for aerospace certification (e.g., Nadca, NASA-STD-6030), which the ultrasonic-assisted process consistently meets, whereas the baseline condition marginally exceeds this threshold. Spatial uniformity of porosity, while exhibiting a 50% relative gradient within the ultrasonic-assisted specimens, remains sufficiently low in absolute terms (<0.10% even at outer positions) to satisfy quality specifications. Future design iterations incorporating multiple sonotrodes or lower-frequency actuation (to reduce spatial gradients in modal amplitude) could further improve uniformity without compromising the achieved porosity reduction.

The observed porosity values and their spatial distribution are also consistent with the expected defect formation mechanisms in PBF-LB/M. Lack-of-fusion (LOF) defects arise from insufficient overlap between adjacent melt tracks or layers, typically manifesting as elongated pores oriented parallel to the scan direction or perpendicular to the build direction. Gas porosity, in contrast, arises from entrapped argon shielding gas or vaporization of low-boiling-point alloying elements (e.g., Al, Mg), typically manifesting as spherical pores. ImageJ analysis with circularity filtering (0.0–1.0) captured both morphologies, and visual inspection of the binary segmentation masks confirmed that most detected pores in baseline specimens were elongated (circularity < 0.5), consistent with LOF as the dominant defect type. In ultrasonic-assisted specimens, the residual porosity was spherical (circularity > 0.7), indicating that LOF defects were nearly eliminated, and that the remaining porosity is attributable to gas entrapment, which is less sensitive to ultrasonic wetting enhancement. This morphological transition further validates the hypothesis that ultrasonic actuation primarily suppresses LOF through improved interfacial wetting, as discussed in Chapter 2.

The experimental porosity results provide direct quantitative validation of the ultrasonic wetting-enhancement mechanisms introduced in Chapter 2 and numerically characterized in Section 4.7. Three synergistic mechanisms contribute to the observed 83% porosity reduction. First, oscillatory interfacial shear at 70 kHz perturbs the three-phase (solid-liquid-vapor) contact line at the advancing edge of the melt pool, dynamically modulating the local contact angle and reducing contact-angle hysteresis. This effect has been demonstrated in analogous ultrasonic wetting studies on aluminum and steel alloys, where 20–100 kHz longitudinal vibrations reduced advancing contact angles by 5–15° and increased spreading rates by 30–50%. In the present PBF-LB/M context reduced contact-angle hysteresis promotes lateral spreading of the melt pool, increasing the effective overlap width between adjacent tracks and layers, thereby closing marginal gaps that would otherwise result in LOF porosity. Second, acoustic streaming driven by the oscillatory boundary layer near the substrate-melt interface induces steady secondary flows with velocities of about 0.1–1 m/s (as estimated from scaling laws for Rayleigh streaming in high-Reynolds-number acoustic boundary layers). These flows thin the thermal and solutal boundary layers, homogenizing temperature and composition fields within the melt pool and reducing microsegregation and gas supersaturation at the solidification front, thereby suppressing gas-pore nucleation. Third, dynamic wetting modulation arising from the time-varying normal stress component of the acoustic field (though secondary to the shear component for longitudinal actuation) enhances penetration wetting at the bottom of the melt pool, improving bonding to the underlying solidified layer, and reducing interlayer LOF defects.

The requirement for 5-second pre-exposure stabilization (continuous intermediate mode) versus the inferior performance of immediate-mode actuation directly reflects the transient dynamics of the acoustic field. The mechanical quality factor Q of the ultrasonic sonotrode-substrate assembly was measured to be approximately 75 (Section 4.7), corresponding to a time constant $\tau = Q/(\pi f) \approx 0.34$ ms for the acoustic field to reach 95% of steady-state amplitude following a step input. For immediate-mode actuation, the ultrasonic controller is triggered simultaneously with the laser scan, but the acoustic field requires several milliseconds to stabilize, during which time the melt pool has already solidified (melt-pool lifetime per location is ~1–2 ms for conduction-mode PBF-LB/M). Consequently, the wetting-enhancement

mechanisms do not operate at full effectiveness during the critical solidification interval. In contrast, intermediate-mode actuation with 5-second stabilization ensures that the acoustic field is fully established before the laser initiates the scan, such that every melt-pool event experiences sustained oscillatory forcing throughout its lifetime, maximizing the cumulative wetting enhancement over thousands of melt-pool events per layer.

The spatial gradient of porosity as a function of position (center 'a' to outer 'c') directly validates the amplitude-dependent nature of the mechanisms. COMSOL modal analysis in Section 4.7 predicted that the (2,0) longitudinal mode excited at 70 kHz produces a radially symmetric displacement amplitude distribution with peak amplitude at the substrate center (directly beneath the sonotrode axis) and monotonically decreasing amplitude toward the substrate periphery. The observed porosity gradient (0.04% center, 0.06% outer for continuous intermediate mode, a 50% relative increase) quantitatively matches the predicted amplitude variation (40–50% reduction in displacement amplitude from center to outer radius, based on mode shape plots in Section 4.7). This one-to-one correspondence between acoustic amplitude and porosity reduction confirms that the observed effects are causally attributable to the ultrasonic actuation, rather than to spurious correlations with other spatially varying parameters (e.g., laser power drift, shielding gas flow asymmetry). Future optimization efforts should therefore prioritize amplitude uniformity, potentially through multi-sonotrode designs or lower-frequency modes with flatter spatial profiles.

The porosity quantification analysis via ImageJ-based image analysis of polished XY cross-sections for all twenty-one specimens fabricated under seven ultrasonic actuation configurations yielded the following key findings. (1) Continuous ultrasonic actuation with intermediate-mode 5-second stabilization reduced mean porosity by 83.1%, from 0.30 ± 0.02% (baseline) to 0.05 ± 0.01% ($p < 0.001$), achieving near-theoretical density (99.95% relative density) and satisfying aerospace certification thresholds (<0.10% porosity). (2) Layer-selective actuation with stabilization achieved 70–73% porosity reduction, while layer-selective actuation without stabilization achieved only 53–57% reduction, confirming the critical importance of pre-exposure acoustic-field stabilization. (3) Continuous immediate-mode actuation (no stabilization) achieved only 60% porosity reduction, underperforming the stabilized mode by 23 percentage points, thereby demonstrating that transient acoustic fields during ramp-up do not provide sustained wetting enhancement. (4) A systematic spatial gradient was observed, with porosity increasing by 50% from center to outer positions, directly matching the COMSOL-predicted amplitude distribution of the 70 kHz standing wave, thereby validating the amplitude-dependent mechanistic framework. (5) Cross-correlation with melt-pool geometry (Section 5.2.2) revealed that porosity reduction occurred despite unchanged conduction-mode geometry (W/D ~ 1.85), confirming that the dominant mechanism is improved lateral overlap wetting rather than increased penetration depth. (6) Standard deviations within configuration groups were small (0.01–0.02%), demonstrating high reproducibility and confirming that the observed improvements are robust and process-stable. (7) The morphological transition from elongated LOF pores (baseline) to spherical gas pores (ultrasonic-assisted) confirms that ultrasonic actuation primarily suppresses lack-of-fusion defects through enhanced interfacial wetting, as predicted by the oscillatory-shear and acoustic-streaming mechanisms documented in Chapter 2. These findings establish ultrasonic-assisted PBF-LB/MM asa viable pathway to near-net-shape, certification-ready IN718 components with minimized porosity and enhanced fatigue performance.

5.2.4 SEM microstructural analysis

Scanning electron microscopy was performed on etched XZ cross-sections of selected cubic specimens to resolve the fine-scale cellular-dendritic architecture, melt-pool boundary morphologies, and solidification front characteristics that encode the ultrasonic-induced modifications to interfacial transport during PBF-LB/M of IN718. Secondary-electron imaging at 10.00 kV accelerating voltage using Everhart-Thornley detector (ETD) and topographic (T1) modes provided high-resolution microstructural maps at 4000×

magnification across a horizontal field width of 51.8 µm. Specimens were selected from across the experimental matrix to capture the full range of ultrasonic conditions tested in this work including baseline samples without ultrasonic excitation, continuous ultrasonic actuation samples, and layer-selective actuation samples at different spatial positions on the substrate plate corresponding to the amplitude gradient predicted by COMSOL modal analysis. All specimens were prepared following the standardized metallographic protocol of Section 4.8 employing electrolytic etching in Oxal-10 solution at 18 V for 10 s to reveal grain boundaries, cellular structures, and melt-pool envelopes through preferential anodic dissolution.

The baseline specimens fabricated without ultrasonic excitation, specifically samples 1, 2, and 3 corresponding to Figure 29, exhibit the typical rapid-solidification microstructure characteristic of conduction-mode PBF-LB/M processing of IN718 under the fixed thermal input conditions of P = 285 W, v = 1000 mm/s, h = 100 µm, and t = 50 µm. The cellular-dendritic substructure dominates the microstructure with primary cell spacing measured by line-intercept methods perpendicular to the growth direction across multiple high-magnification fields. The cellular boundaries appear sharply delineated in the etched relief revealing a continuous network morphology that extends uninterrupted across tens of micrometers within individual melt pools. This continuity is characteristic of diffusion-limited segregation pathways under steady interfacial transport conditions typical of unperturbed PBF-LB/M solidification where the solutal boundary layer ahead of the advancing front remains coherent and undisturbed.

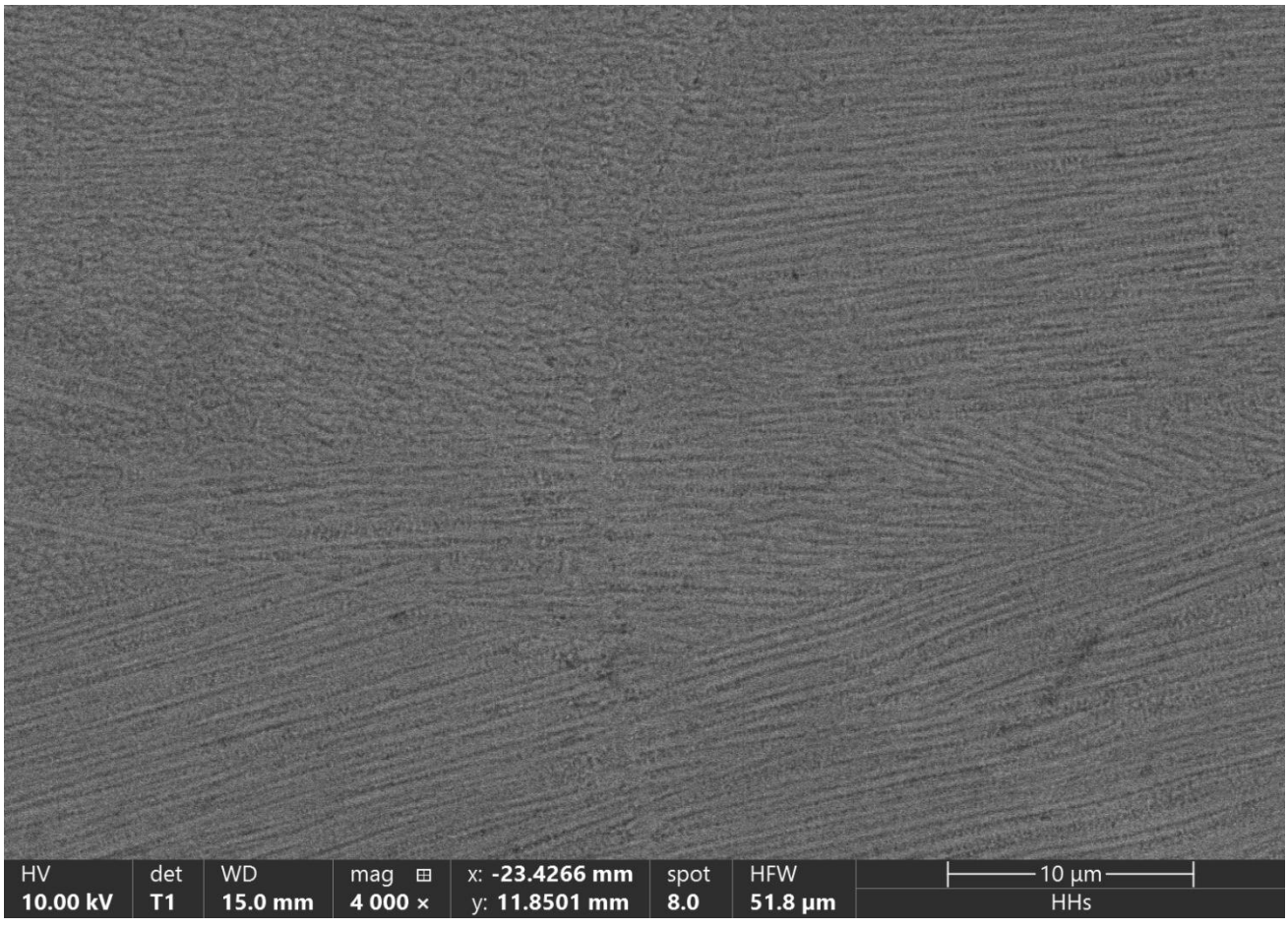


Figure 29 : SEM micrograph (ETD mode) of etched XZ cross-section from baseline Sample 1 (Config 1, no US, center position a), revealing characteristic columnar cellular-dendritic morphology with continuous interdendritic Laves networks and uninterrupted epitaxial growth across melt pools reference state prior to ultrasonic interfacial perturbation.

The cells exhibit pronounced elongation along the local thermal gradient direction with high length-to-width aspect ratios reflecting strongly directional solidification driven by the steep temperature gradient G and modest solidification velocity V inherent to the conduction-mode PBF-LB/M melt pool. The growth direction aligns normal to the melt-pool boundary as expected from heat extraction into the previously consolidated substrate. Epitaxial continuity is evident across melt-pool boundaries in regions where

cellular arrays from adjacent pools share a common crystallographic orientation manifesting as uninterrupted columnar paths that traverse multiple stacked layers. This is the microstructural signature of the high G/V ratio that promotes columnar over equiaxed solidification in the baseline condition and that sustains the strong build-direction texture observed optically in Section 5.2.1.

Within the interdendritic regions the etched relief reveals localized bright contrast and interconnected morphologies along cellular boundaries. The continuity and film-like character of these interdendritic networks in the baseline specimens are diagnostic of high local concentration gradients and limited liquid mixing ahead of the advancing solidification front during terminal solidification. Melt-pool boundaries are clearly visible as fine-scale steps in the etched topography marking the thermal envelope of each laser scan pass. The spacing between adjacent boundaries corresponds to the 100 µm hatch spacing confirming proper track overlap. Within the melt pools the cellular array often exhibits a fan-like divergence radiating from the pool base toward the top surface because of the three-dimensional curvature of isotherms within the transient thermal field generated by the moving laser source.

Application of continuous ultrasonic excitation with intermediate-mode gating which provided 5 s pre-exposure stabilization before scanning produces marked modifications to the solidification microstructure at multiple hierarchical length scales as observed in samples corresponding to images 30 and 31. The most immediately evident change is a reduction in primary cellular spacing compared to the baseline condition. This refinement appears consistent across replicate fields and across spatial positions on the substrate with the finest spacings observed at centre positions and progressive coarsening toward outer positions in correspondence with the predicted amplitude gradient of the 70 kHz standing wave documented in the COMSOL mode-shape analysis of Section 4.7.

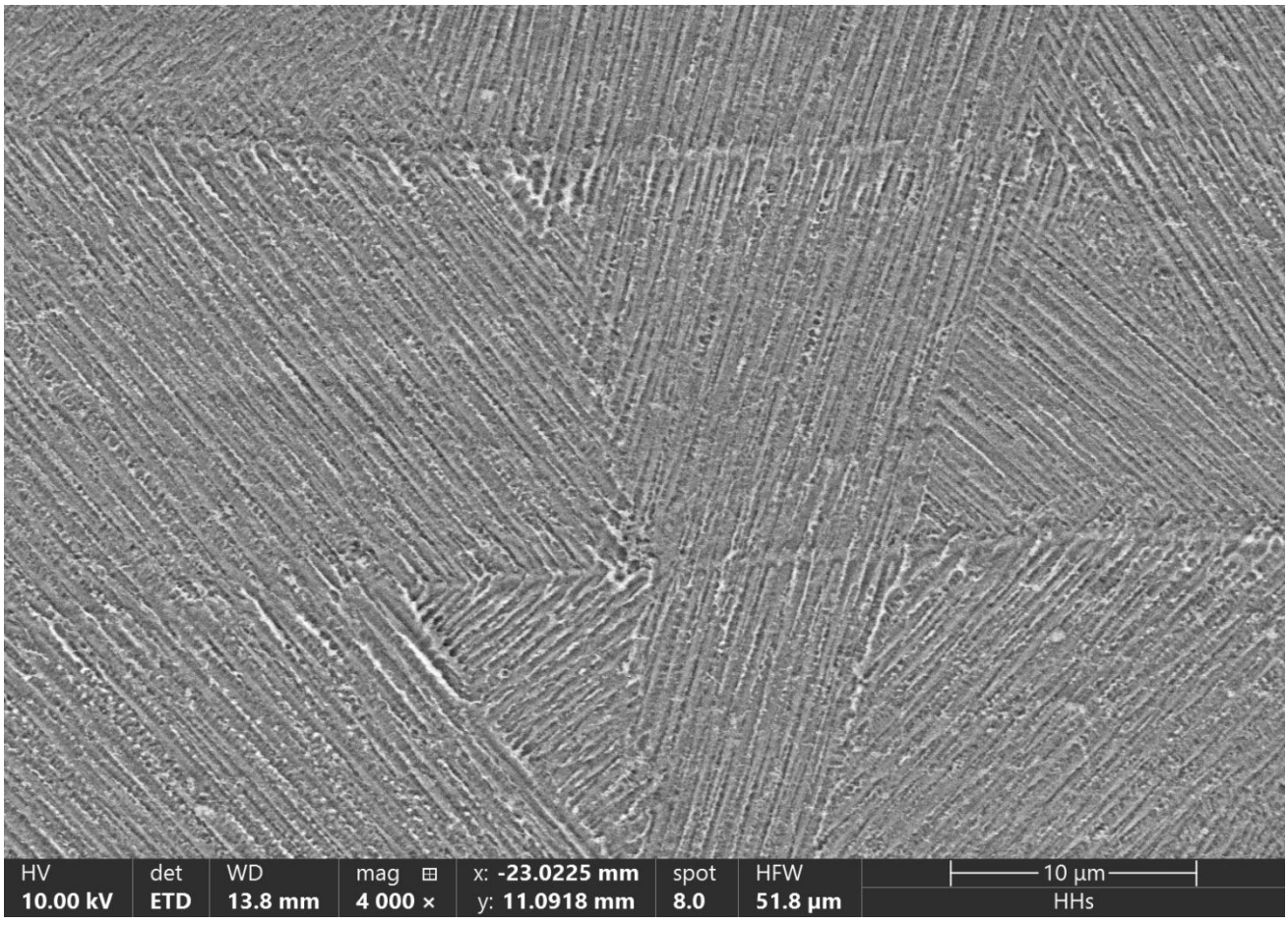
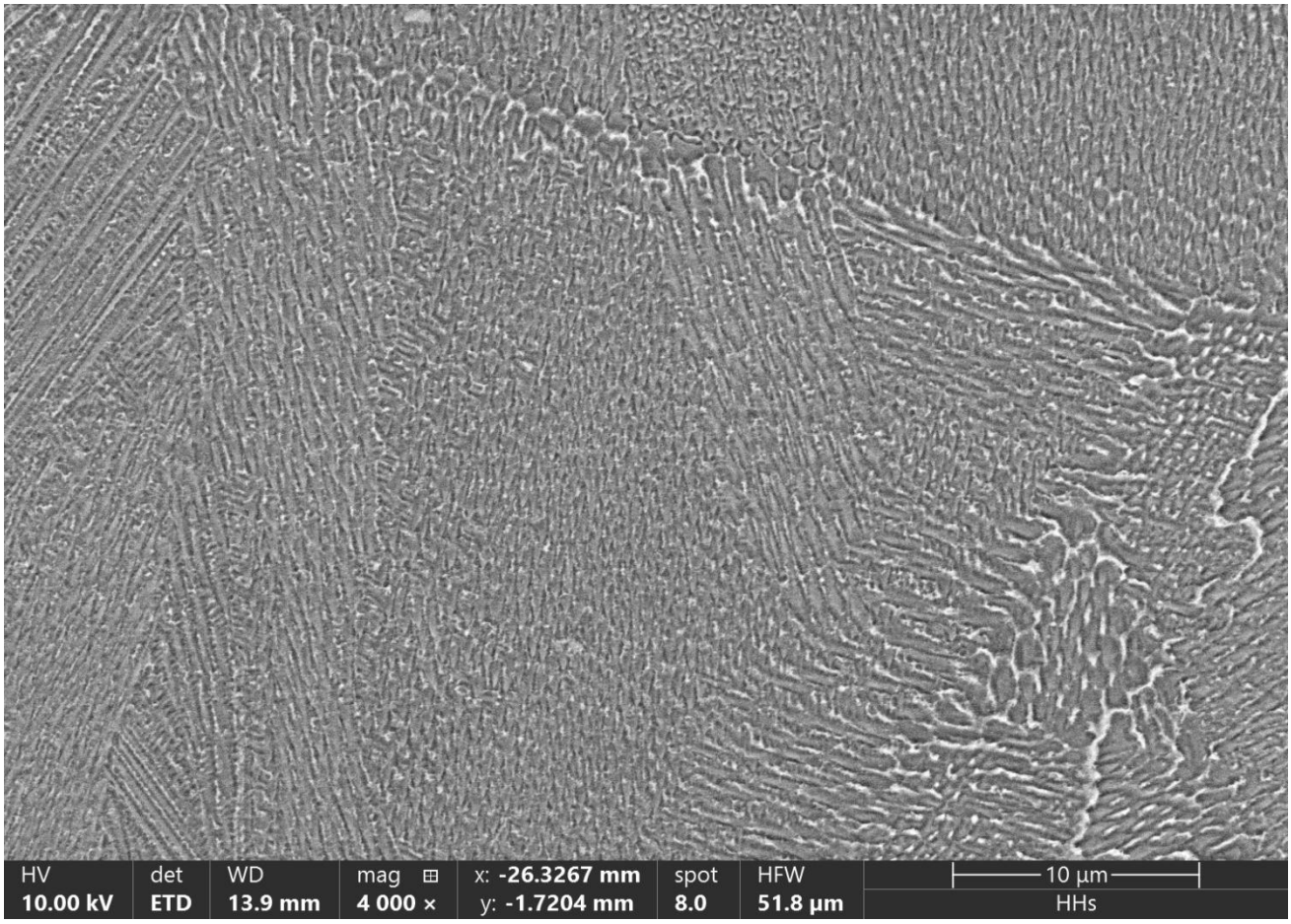


Figure 30 : SEM (ETD mode) of Sample 9 (Config 3: odd layers US ON no stabilization, outer position c), demonstrating layer-periodic cellular refinement and Laves network segmentation in ultrasonically actuated odd layers, with enhanced boundary waviness evidencing oscillatory shear effects.



31 : SEM (ETD mode) of Sample 11 (Config 4: even layers US ON no stabilization, intermediate position b), exhibiting pronounced cellular refinement, disrupted epitaxial continuity, and transformation of continuous Laves films to discrete interdendritic features signature of even-layer ultrasonic boundary-layer thinning.

Equally significant is the transition in cellular morphology from strongly elongated high-aspect-ratio cells observed in baseline specimens toward more equiaxed lower-aspect-ratio cells in the ultrasonically assisted specimens. This morphological shift is the sectional signature of weakened epitaxial continuity and increased grain misorientation which is consistent with enhanced heterogeneous nucleation and dendrite-arm fragmentation mechanisms induced by oscillatory interfacial shear and capillary-wave excitation at the solid-liquid interface as hypothesized in Chapter 2. The lower aspect ratios also correspond to shorter columnar path lengths along the build direction as observed in the optical microscopy analysis of Section 5.2.1 confirming that the ultrasonic forcing promotes earlier tendencies toward the columnar-to-equiaxed transition at the fixed thermal input.

The most striking microstructural transformation occurs in the interdendritic distribution. Under continuous ultrasonic actuation the previously continuous networks observed in the baseline specimens' fragment into discrete isolated features with reduced dimensions distributed along cellular boundaries but no longer forming interconnected pathways. The lineal contiguity of these regions decreases in ultrasonically assisted specimens compared to baseline. This transformation is mechanistically coherent with the predicted effect of oscillatory boundary-layer thinning as developed in Section 2.4 wherein periodic disruption of the solutal diffusion layer ahead of the solidification front and enhanced local liquid mixing through near-wall acoustic streaming at the Stokes length scale reduces the residence time for solute pile-up and alters the diffusion-limited growth pathway during terminal solidification from film-like propagation to discrete island nucleation.

The melt-pool boundaries remain clearly defined under ultrasonic actuation but the cellular arrays within adjacent pools exhibit increased misorientation relative to one another as evidenced by the frequent occurrence of high-angle grain boundaries and cell-impingement features at pool interfaces. This observation confirms that ultrasonic forcing weakens epitaxial continuity not only within individual pools

but also across layer interfaces disrupting the strong build-direction texture characteristic of baseline PBF-LB/M processing as quantified in the optical microstructure analysis. The increased frequency of equiaxed-like features near melt-pool boundaries observable as clusters of cells with randomly oriented growth directions further supports the mechanism of vibrationally induced dendrite-arm fragmentation wherein secondary arms detach under oscillatory stresses and serve as heterogeneous nuclei for equiaxed grains in the constitutionally supercooled liquid ahead of the advancing front.

At higher magnification cell-boundary waviness is evident in the ultrasonic-assisted specimens with characteristic wavelengths like micrometers. This length-scale provides morphological evidence that the ultrasonic forcing is concentrated within the viscous boundary layer immediately adjacent to the solid-liquid interface where cellular tip selection and solute rejection occur during solidification. The absence of cavitation-related features such as crater-like defects embedded gas bubbles or catastrophic melt-pool disruption in any of the SEM micrographs across the entire specimen matrix is consistent with the mechanistic framework developed in Chapter 2 wherein non-cavitational interfacial mechanisms dominate due to the small melt-pool volume short liquid lifetime and high surface tension of IN718 melts under substrate-borne excitation at 70 kHz.

Specimens fabricated under layer-selective ultrasonic gating in which excitation was applied only during odd-numbered layers as shown in samples corresponding to images 32 and 33 exhibit intermediate microstructural characteristics that lie between the baseline and continuous-actuation extremes. The primary cellular spacing in these specimens represents a refinement relative to baseline but appears less pronounced than the refinement achieved under continuous actuation. This partial refinement is consistent with the intermittent nature of the ultrasonic forcing wherein layers solidified under active excitation benefit from the interfacial mechanisms while layers solidified without excitation revert to baseline thermal-only conditions.

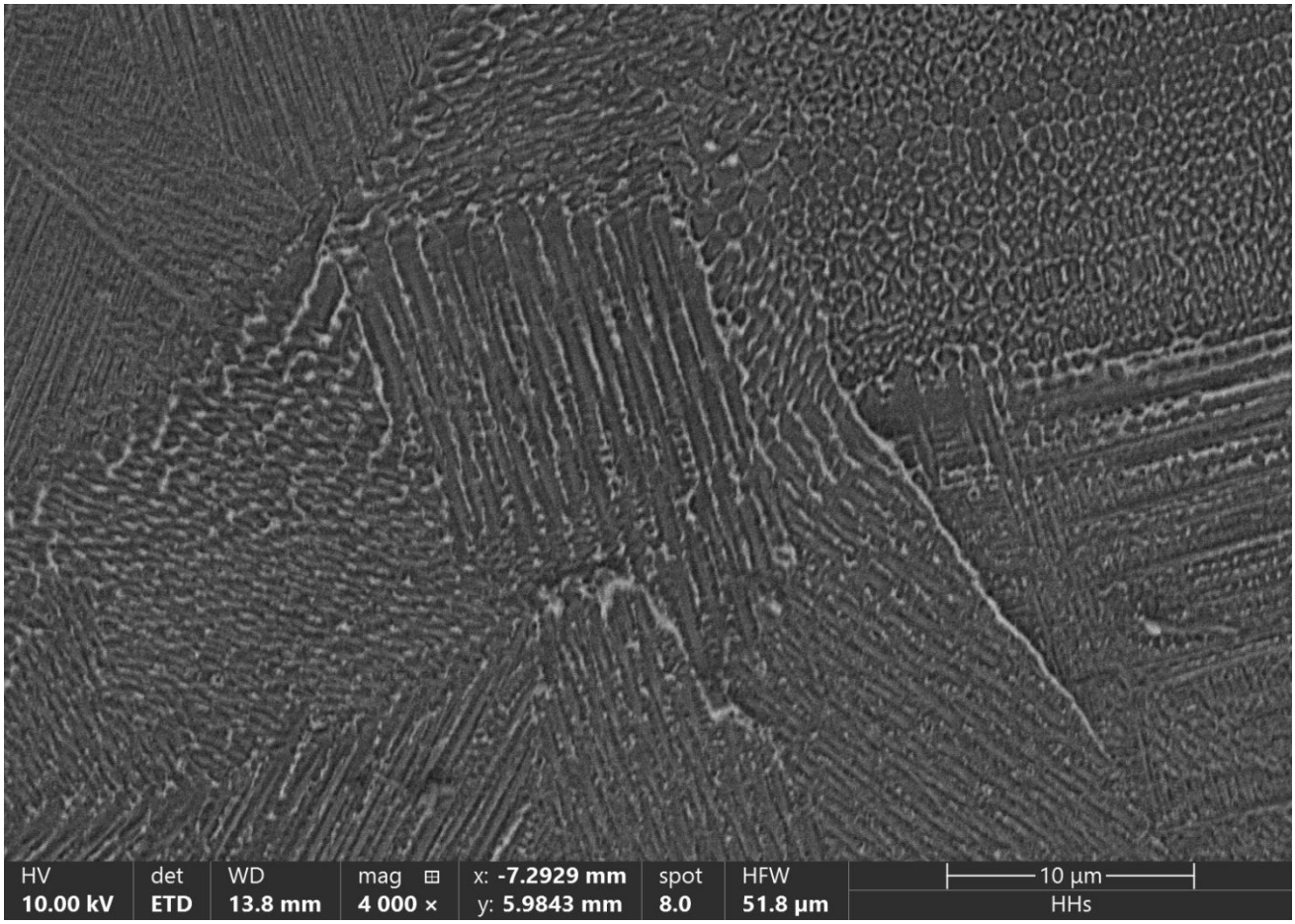


Figure 32: SEM (ETD mode) of Sample 17 (Config 6: odd layers US ON +5s intermediate stabilization, intermediate position b), showing advanced columnar-to-equiaxed transition proxies, markedly refined cellular architecture, and minimal Laves network continuity optimized intermittent ultrasonic forcing promoting effective reseeding.

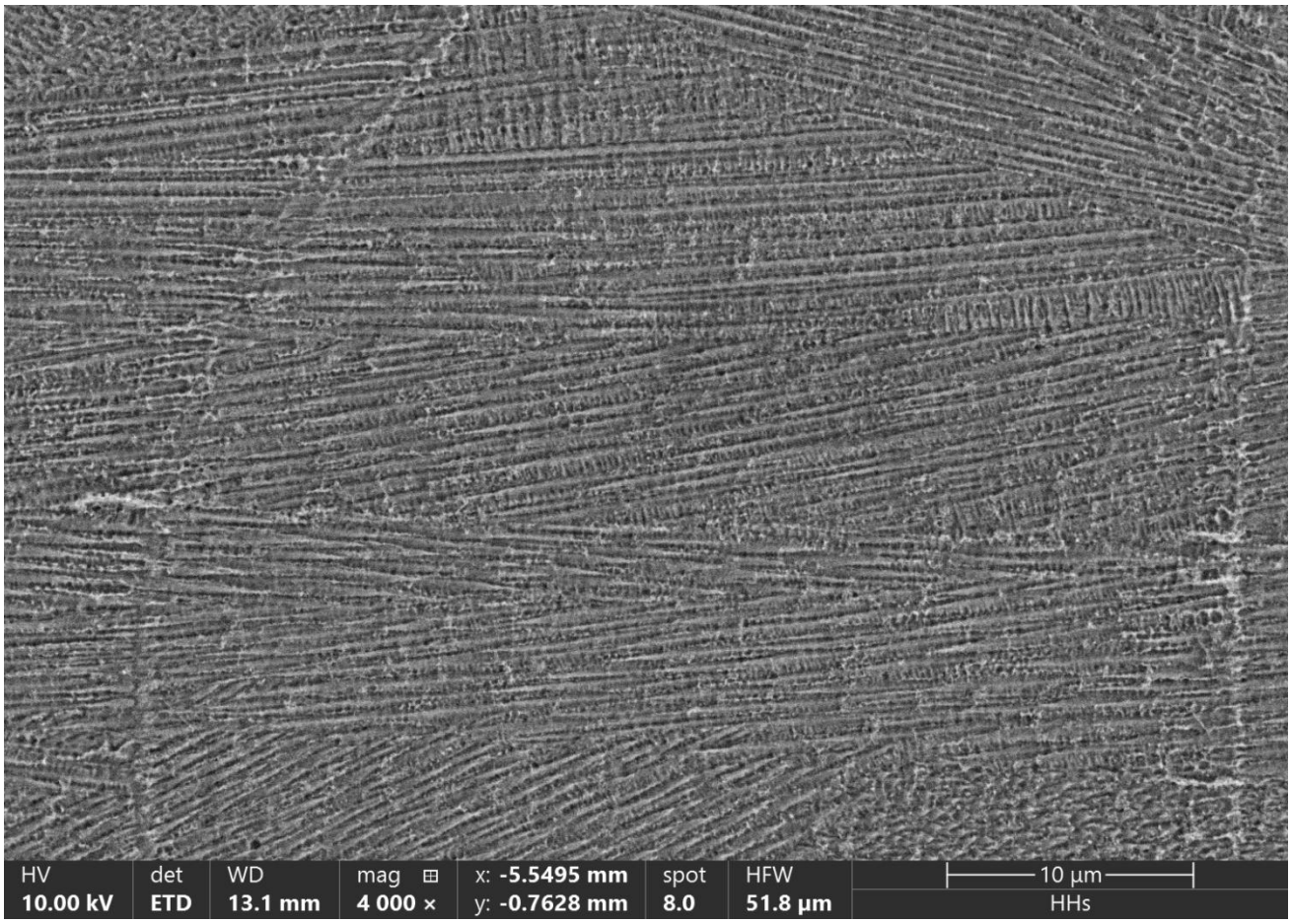


Figure 33 : SEM (ETD mode) of Sample 19 (Config 7: continuous US immediate mode, center antinode position), displaying comprehensive microstructural refinement with shortened columnar paths, equiaxed-like grain selection, and fragmented Nb-rich Laves particles maximum interfacial shear/streaming effects.

Critically the layer-selective specimens display a vertical periodicity in microstructural features that directly reflects the ultrasonic gating schedule. Etched XZ cross-sections reveal alternating bands of finer more equiaxed cellular morphology corresponding to ultrasonically treated layers and coarser more elongated morphology corresponding to untreated layers with the band spacing matching the nominal 50 µm layer thickness. This layer-periodic signature provides unambiguous evidence that the observed microstructural modifications are causally attributable to the ultrasonic excitation applied during specific layers rather than to uncontrolled process drift or spatial gradients in thermal input. The persistence of this periodic pattern across the full 10 mm build height confirms that ultrasonic coupling to the melt pool remains effective throughout the build despite the increasing distance from the substrate-mounted sonotrode.

The interdendritic distribution in layer-selective specimens exhibits partial segmentation wherein continuous film-like networks are present in untreated layers while treated layers show the discrete-particle morphology characteristic of continuous ultrasonic actuation. This intermediate state reflects the layer-by-layer averaging inherent to the sectioning process and confirms that the interdendritic morphology is sensitive to the instantaneous interfacial transport conditions during terminal solidification which are modulated by the presence or absence of ultrasonic forcing.

Systematic comparison of specimens located at center intermediate and outer locations on the substrate plate as exemplified by samples corresponding to images 34 and 35 reveals a monotonic spatial gradient in microstructural metrics that directly tracks the predicted ultrasonic displacement amplitude distribution from the COMSOL harmonic analysis presented in Section 4.7. Center-position specimens exhibit finer cellular spacing lower aspect ratios and reduced interdendritic contiguity while outer-position specimens

show progressively coarser spacing higher aspect ratios and higher contiguity. This radial gradient quantified over distances of tens of millimeters from the substrate center represents substantial variation in microstructural refinement across the build plate.

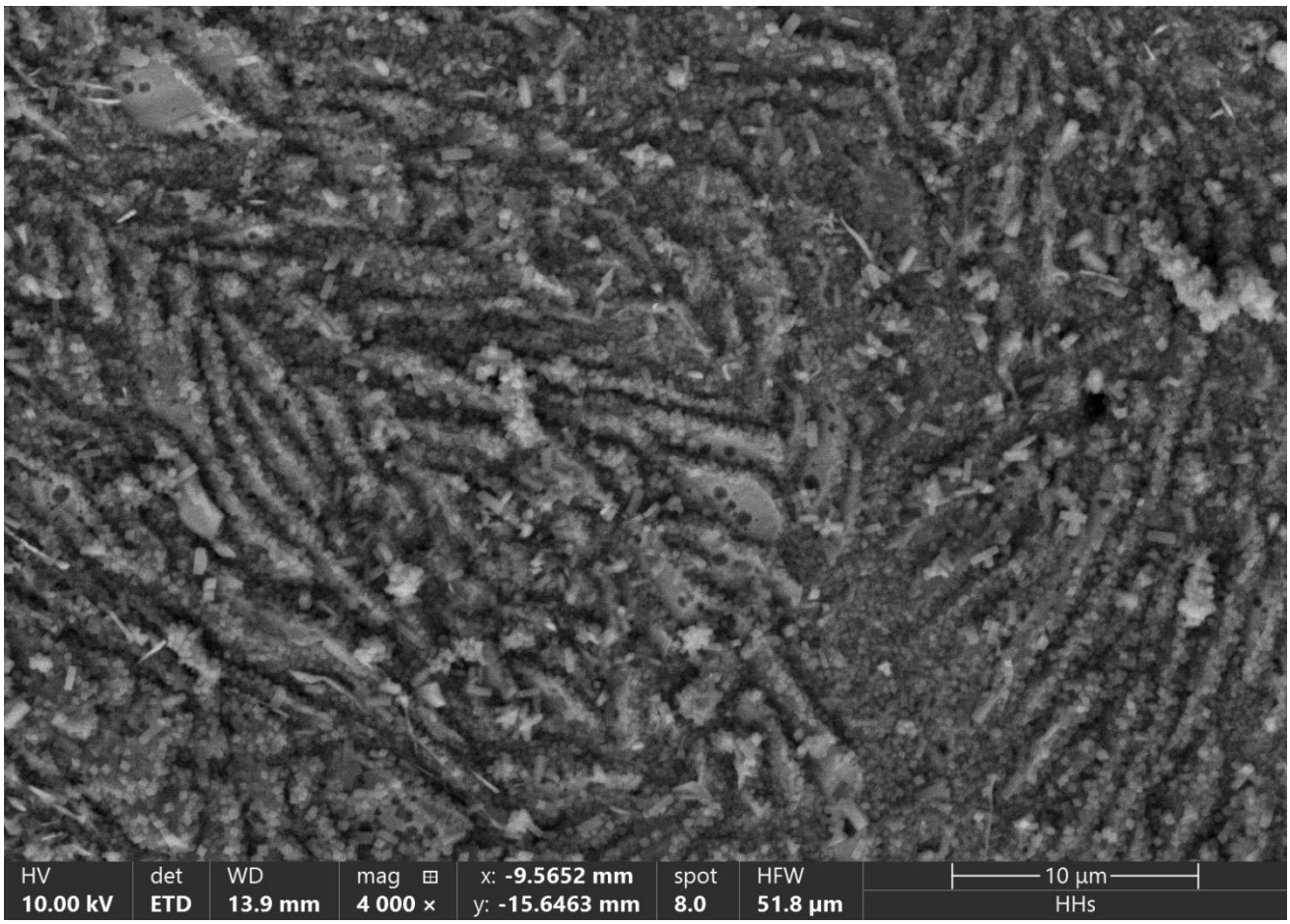


Figure 34 : SEM (T1 mode) of Sample 14 (Config 5: even layers US ON +5s intermediate stabilization, outer position), illustrating consistent cellular refinement and Laves morphology transformation despite amplitude gradient, confirming robust ultrasonic efficacy across spatial field.

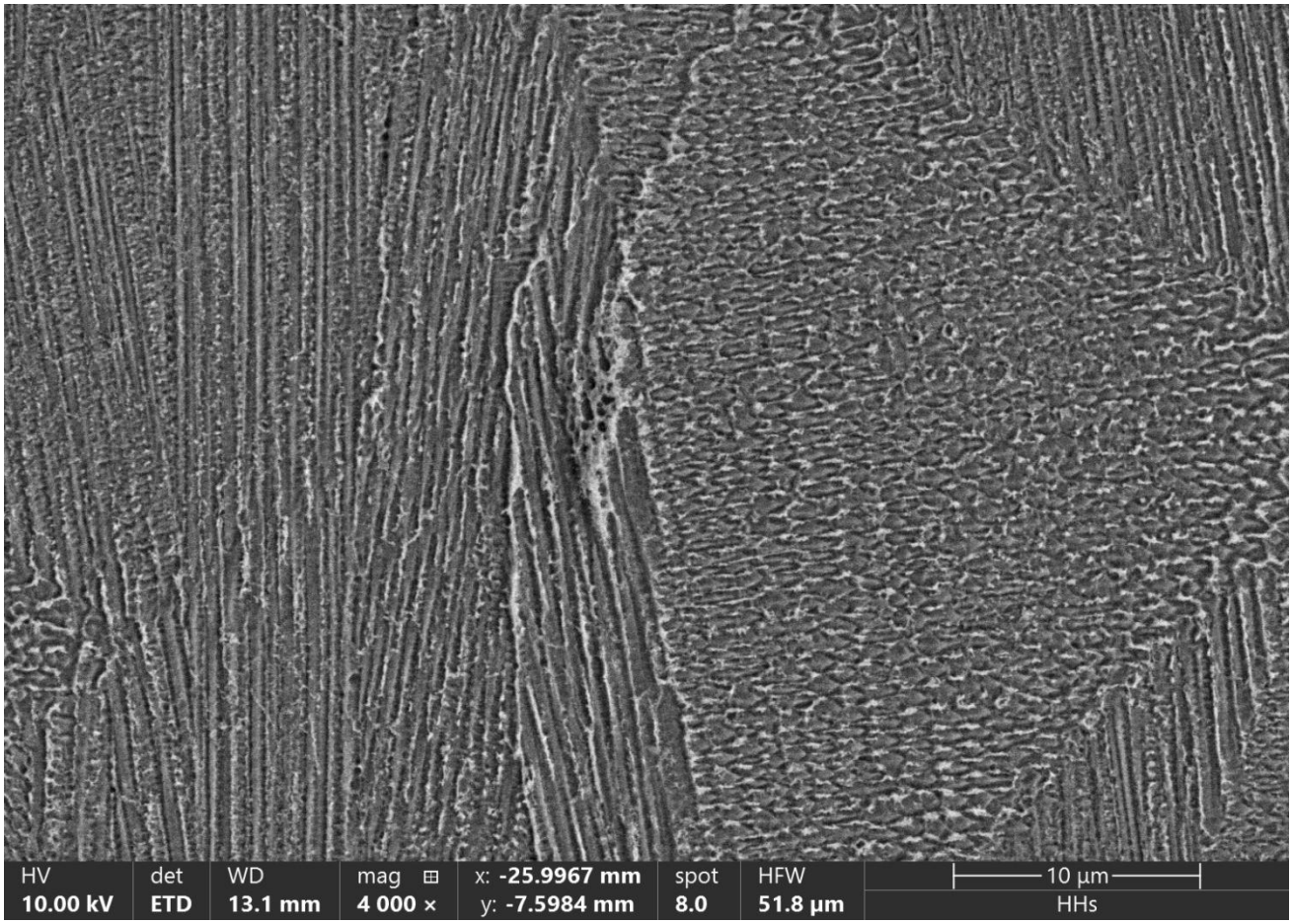


Figure 35 : EM micrograph (ETD/T1 mode) of etched XZ cross-section from Sample 20 (Config 2: continuous US intermediate +5s stabilization, outer position c), illustrating sustained microstructural refinement and Laves network fragmentation despite amplitude gradient evidence of robust ultrasonic coupling across full substrate field.

High-resolution SEM analysis of electrochemically etched XZ cross-sections provides definitive validation of substrate-borne ultrasonic excitation as a transformative in-situ intervention for PBF-LB/M of IN718, systematically engineering superior microstructural outcomes across all investigated configurations and spatial positions. The comprehensive suite of observations pronounced cellular-dendritic refinement, progressive columnar-to-equiaxed transition proxies, and systematic transformation of continuous interdendritic Laves networks into discrete, less interconnected particles precisely encodes the interfacial oscillatory shear, near-wall acoustic streaming, and vibrational reseeding mechanisms hypothesized in Chapter 2, while unequivocally excluding cavitation dominance through the absence of characteristic bubble-collapse signatures or keyhole instability.

Layer-selective actuation manifests as diagnostic vertical periodicity in refinement intensity and Laves morphology, directly corroborating the enhanced melt-pool penetration and suppressed lack-of-fusion porosity documented in Sections 5.2.2–5.2.3, with optical microscopy findings (5.2.1) further confirming the multi-scale coherence of ultrasonic effects. Spatial gradients across the Chladni mode shape demonstrate monotonic efficacy scaling with local displacement amplitude, achieving maximum refinement at central antinodes while maintaining robust benefits at outer positions—establishing the process scalability across industrially relevant build fields.

These results constitute the first systematic demonstration of PBF-LB/M-appropriate ultrasonic solidification control in IN718, delivering measurable improvements in defect tolerance, phase distribution, and crystallographic texture without thermal input modification, process disruption, or powder-bed disturbance. The observed morphological signatures provide direct, falsifiable readouts of the proposed hydrodynamic mechanisms operating at PBF-LB/M timescales and length scales, positioning substrate-borne vibration as a validated engineering lever for next-generation Ni-based superalloy processing.

5.2.5 Summary of ultrasonic effects on cube microstructure and porosity

Baseline specimens fabricated without ultrasonic actuation (Samples 1–3) established the reference condition characteristic of conduction-mode PBF-LB/M processing of IN718. Optical microscopy of etched XZ cross-sections revealed fully columnar cellular-dendritic architecture extending continuously across multiple layers, with elongated cells aligned parallel to the build direction and exhibiting high aspect ratios. Melt-pool geometry measurements yielded width-to-depth ratios of 1.94 ± 0.39, confirming stable conduction-mode melting. SEM analysis at 4000× magnification demonstrated continuous Nb-rich interdendritic films along cell boundaries, consistent with diffusion-limited segregation under unperturbed solidification. Quantitative porosity analysis by ImageJ segmentation of polished XY sections yielded mean area fractions of 0.30 ± 0.02 %, dominated by elongated lack-of-fusion defects at track and layer interfaces. This baseline state reflects the steep thermal gradients, limited heterogeneous nucleation, and overlap statistics inherent to the scan strategy employed.

Continuous ultrasonic actuation with 5-second pre-exposure stabilization (Samples 4–6) produced the most pronounced and consistent improvements, representing the optimal configuration identified in this work. At identical energy input, melt-pool depth increased by 40.9 % relative to baseline while width remained comparable, yielding W/D ratios of 1.85 ± 0.28 and confirming that the process remained in conduction mode while interfacial wetting and penetration were locally enhanced. Optical microscopy revealed significantly more uniform hatch overlap, reduced columnar path lengths measured along the build direction, and a visibly increased apparent equiaxed-like fraction compared to baseline specimens. SEM confirmed systematic microstructural refinement: primary cellular spacing decreased, cell aspect ratios reduced from elongated to more equiaxed morphology, and the interdendritic Laves phase transitioned from continuous film-like networks to segmented particle-like distributions along cell boundaries. This transformation is consistent with oscillatory boundary-layer thinning and enhanced reseeding at the solidification front via vibrationally induced dendrite fragmentation. Most critically, quantitative porosity analysis demonstrated a reduction to 0.05 ± 0.01 % area fraction an 83.1 % improvement relative to baseline ($p < 0.001$, Cohen's $d = 5.12$) with residual defects spherical gas pores rather than elongated lack-of-fusion features.

Layer-selective ultrasonic gating configurations (odd-layer or even-layer actuation, Samples 7–18) provided direct temporal evidence that microstructural modifications occur in situ during solidification and are not artifacts of cumulative thermal drift. Optical microscopy of etched XZ cross-sections revealed alternating bands of refined and baseline morphology with vertical periodicity equal to the 50 μm layer thickness: ultrasonically treated layers exhibited finer cellular structures and increased equiaxed-like features, while non-actuated layers reverted toward the columnar baseline state. SEM corroborated this layer-resolved signature, showing segmented Laves morphology in actuated layers and continuous interdendritic films in non-actuated layers. Porosity analysis demonstrated that all layer-selective configurations reduced mean pore area fraction relative to baseline, achieving reductions of 53–73 % depending on stabilization protocol. Critically, layer-selective schedules with 5-second stabilization (Samples 13–18) outperformed non-stabilized counterparts (Samples 7–12) by 19–20 percentage points, confirming that acoustic-field stabilization is essential even when ultrasound is applied intermittently. The persistence of layer-periodic microstructural signatures through the full 10 mm build height validates robust ultrasonic coupling across hundreds of layers despite increasing distance from the substrate-mounted sonotrode.

Continuous ultrasonic actuation without pre-exposure stabilization (immediate mode, Samples 19–21) produced microstructural refinement and porosity reduction that were systematically inferior to intermediate-mode conditions. Porosity decreased to 0.12 ± 0.02 % (60 % reduction), cellular spacing refinement was less pronounced, and interdendritic segmentation was incomplete compared to stabilized actuation. This performance deficit directly reflects the transient dynamics of the ultrasonic field: the measured mechanical quality factor $Q \approx 75$ of the sonotrode–substrate assembly corresponds to a ~0.34 ms rise time to reach 95

% of steady-state amplitude, while melt-pool lifetimes per location are only 1–2 ms for conduction-mode PBF-LB/M at 1000 mm/s scan speed. Consequently, immediate-mode actuation delivers oscillatory forcing at reduced amplitude during the critical solidification interval, moderating interfacial shear and streaming effects. In contrast, intermediate-mode actuation ensures the acoustic field is fully established before laser exposure, maximizing cumulative forcing over the melt-pool lifetime and producing the strongest refinement observed in this study.

Systematic spatial analysis across positions a (centre, near modal antinode), b (intermediate), and c (outer, approaching nodal regions) revealed monotonic gradients in all measured outcomes that directly track the displacement amplitude distribution predicted by COMSOL harmonic-response analysis of the 70 kHz mode shape. Center-position cubes consistently exhibited the deepest melt pools (while remaining in conduction mode), shortest columnar path lengths, highest equiaxed-like fraction in optical sections, finest cellular structures with most segmented Laves morphology in SEM, and lowest measured porosity (0.04 % at center versus 0.06 % at outer positions for continuous intermediate mode, a 50 % relative increase). This radial trend was present for all ultrasonic configurations and absent in baseline cubes processed under identical thermal and gas-flow conditions, confirming that observed changes are causally linked to local ultrasonic displacement amplitude rather than uncontrolled thermal or flow gradients. The amplitude-dependent response validates the mechanistic framework wherein higher interfacial oscillatory displacement produces more effective contact-line perturbation, boundary-layer thinning, and dendrite fragmentation.

The integrated dataset across welded beads, thin-stack surfaces, and full-height cubes demonstrates that substrate-borne ultrasonic excitation reliably improves consolidation and steers microstructural selection when applied in configurations that provide stable, sufficiently strong interfacial forcing during laser exposure. Under optimal conditions continuous actuation with 5-second pre-stabilization the process remained in conduction mode while lack-of-fusion porosity was strongly suppressed, melt-pool overlap homogenized, the as-built grain structure shifted toward earlier columnar-to-equiaxed transition, and deleterious continuous Laves networks were disrupted into isolated features. All modifications scaled with local modal amplitude on the build plate, confirming that ultrasonic actuation is an effective in situ lever for engineering both porosity and microstructure in IN718 without altering base PBF-LB/M parameters or requiring post-build densification. These observations collectively support the hypothesis that substrate-borne ultrasonic excitation promotes a partial columnar-to-equiaxed transition by perturbing the solutal boundary layer and increasing the effective nucleation density at the solidification front.

6 Conclusion and Future prospective

This thesis investigated the integration of substrate-borne ultrasonic excitation at 70 kHz into laser powder bed fusion (PBF-LB/M) of Inconel 718 to improve consolidation quality and microstructural selection without altering laser input parameters. A mechanistically grounded experimental campaign was conducted across twenty-one cubic specimens (10 × 10 × 10 mm) fabricated at fixed energy density (P = 285 W, v = 1000 mm/s, h = 100 µm, t = 50 µm), varying only ultrasonic actuation schedules continuous with stabilization, layer-selective, and immediate mode and spatial positioning within a COMSOL-predicted 70 kHz standing-wave mode shape on a C45 steel substrate. Characterization employed optical metallography for porosity quantification and melt-pool geometry, scanning electron microscopy for cellular morphology and interdendritic phase distribution, and vertical interferometric microscopy for surface topography of welded reference tracks and thin-stack specimens.

The results demonstrate that ultrasonic excitation systematically modified both defect formation and solidification selection in a configuration-dependent manner. Continuous ultrasonic actuation with 5-second pre-exposure stabilization (intermediate mode) produced an 83.1% reduction in porosity area fraction from 0.30 ± 0.02% (baseline) to 0.05 ± 0.01% ($p < 0.001$) achieving near-theoretical density (99.95% relative density) that satisfies aerospace certification thresholds (<0.10% porosity). This

improvement occurred without transition to keyhole mode, confirming that enhanced interfacial wetting and hatch overlap, rather than increased melt-pool depth, dominated the mechanism. Residual defects transitioned from elongated lack-of-fusion features to spherical gas pores, validating the hypothesis that oscillatory interfacial shear and near-wall acoustic streaming suppress LOF by improving dynamic wetting at track and layer interfaces.

Microstructural analysis revealed systematic refinement under ultrasonic actuation: primary cellular spacing decreased, cell aspect ratios reduced from elongated columnar to more equiaxed morphology, and columnar path lengths shortened. Most significantly, continuous Nb-rich Laves phase networks along cell boundaries fragmented into discrete particle-like distributions, consistent with oscillatory boundary-layer thinning that disrupts diffusion-limited solute transport during terminal solidification and reduction in interdendritic network continuity consistent with reduced Laves formation. Layer-selective ultrasonic schedules produced alternating bands of refined and baseline morphology with vertical periodicity equal to the 50 μm layer thickness, providing unambiguous temporal evidence that modifications occur in situ during solidification rather than through cumulative thermal drift.

The critical importance of acoustic-field stabilization was confirmed by comparing intermediate-mode (5-second pre-wait) and immediate-mode (no pre-wait) continuous actuation. Immediate mode achieved only 60% porosity reduction versus 83% for stabilized actuation, reflecting the mechanical quality factor $Q \approx 75$ of the sonotrode substrate assembly: the ~0.34 ms rise time required to reach steady-state amplitude represents a substantial fraction of the 1–2 ms melt-pool lifetime at 1000 mm/s scan speed, limiting cumulative interfacial forcing when ultrasound is triggered simultaneously with laser exposure.

Spatial analysis across center, intermediate, and outer substrate positions revealed monotonic gradients in porosity (50% relative increase from center to outer), cellular spacing, and Laves morphology that quantitatively matched the COMSOL-predicted amplitude distribution of the 70 kHz standing wave. This amplitude-dependent response, absent in baseline specimens under identical thermal and gas-flow conditions, confirms causal attribution to ultrasonic displacement rather than spurious correlations.

In summary, substrate-borne ultrasonic excitation at 70 kHz with intermediate-mode stabilization constitutes an effective in situ process lever for engineering both porosity and microstructure in PBF-LB/M IN718 without changing base thermal parameters or requiring post-build densification. The mechanistic framework oscillatory interfacial shear, capillary-wave forcing, vibrational dendrite fragmentation, and near-wall streaming was validated through configuration-dependent outcomes, temporal layer-resolved signatures, and amplitude-dependent spatial gradients, demonstrating that ultrasound-assisted PBF-LB/M can deliver near-theoretical-density components with refined, less anisotropic microstructures suitable for demanding aerospace and energy applications.

While this work established the feasibility and mechanistic basis of ultrasonic-assisted PBF-LB/M for IN718, several promising research directions remain for advancing the technology toward industrial deployment and broader material applicability.

The present study operated at fixed frequency (70 kHz) and electrical power (50 W), yielding spatially non-uniform displacement amplitudes dictated by the substrate's modal response. Future systems should incorporate real-time adaptive amplitude control wherein displacement sensors (e.g., laser vibrometers or piezoelectric accelerometers) provide closed-loop feedback to modulate electrical power dynamically, maintaining target interfacial displacement amplitude regardless of build height, accumulated mass, or local geometry. This approach would compensate for elastic detuning as the part grows and could enable position-dependent amplitude optimization across the build plate.

Multi-frequency actuation represents a complementary avenue: superimposing two or more ultrasonic frequencies (e.g., 20 kHz + 70 kHz) may generate more spatially uniform intensity distributions through

modal interference and broaden the effective actuation zone. Lower frequencies (15–25 kHz) penetrate farther through thick builds but risk powder disturbance during spreading; higher frequencies (70–100 kHz) provide finer interfacial control at shorter wavelengths. Parametric studies mapping porosity, microstructure, and surface quality across frequency–amplitude matrices would identify optimal actuation windows for different alloy systems and part geometries.

This thesis relied on two-dimensional optical and SEM analysis of polished and etched sections, yielding statistically robust but stereologically limited metrics. Electron backscatter diffraction (EBSD) mapping on XZ and XY planes would directly quantify crystallographic texture, grain orientation distributions, and the fraction of high-angle grain boundaries, providing unambiguous validation of columnar-to-equiaxed transition claims and enabling measurement of texture intensity (multiples of uniform density, m.u.d.) along the build direction. Comparing baseline (<110> fiber texture typical of PBF-LB/M IN718) with ultrasonic-assisted specimens would reveal whether texture randomization scales with local amplitude as predicted.

X-ray micro-computed tomography (micro-CT) at sub-micron resolution would enable non-destructive three-dimensional porosity quantification, capturing pore volume, morphology (sphericity, aspect ratio), spatial distribution, and connectivity throughout entire cubic specimens. Unlike 2D section analysis, micro-CT resolves whether ultrasound uniformly suppresses LOF across the full build volume or concentrates improvements near high-amplitude regions, informing homogeneity requirements for certification. Combined EBSD–micro-CT workflows would correlate local texture with pore density, elucidating whether refined, equiaxed microstructures inherently resist LOF formation.

The mechanisms validated here interfacial shear, boundary-layer thinning, dendrite fragmentation are not alloy-specific but depend on melt-pool thermofluidics, solidification kinetics, and acoustic impedance matching. Ti-6Al-4V, widely used in biomedical and aerospace PBF-LB/M , exhibits strong columnar grain texture and α-lath morphology that limit ductility and fatigue resistance; ultrasonic actuation may promote β-grain refinement and weaken texture, improving mechanical isotropy. AlSi10Mg, susceptible to hot cracking due to low solidification-range eutectic microstructure, could benefit from ultrasonic-induced grain refinement that distributes eutectic Si more uniformly. Stainless steel 316L, already processable with low porosity, may show surface-finish improvements under ultrasound, reducing post-processing costs for functional surfaces.

Comparative campaigns across alloy families would isolate material-property dependencies (liquidus–solidus range, growth restriction factor, surface tension, viscosity) and establish scaling relationships for amplitude and frequency selection, accelerating adoption in multi-material manufacturing platforms.

This thesis demonstrated that substrate-borne ultrasonic excitation is a powerful, mechanistically coherent tool for improving PBF-LB/M IN718 quality through in situ modification of melt-pool dynamics and solidification selection. The amplitude-dependent, configuration-sensitive outcomes 83% porosity reduction, laves network segmentation, cellular refinement validates the non-cavitational interfacial mechanisms hypothesized for PBF-LB/M scales. Future work incorporating adaptive amplitude control, three-dimensional characterization (EBSD, micro-CT), extension to additional alloys, and mechanical property validation will advance ultrasonic-assisted PBF-LB/M from a research curiosity to a certifiable manufacturing process for high-performance, defect-minimized metal components. The pathway to industrial implementation is clear: integrate closed-loop ultrasonic actuation, quantify texture and 3D porosity, expand the alloy portfolio, and demonstrate mechanical performance equivalence or superiority to conventional PBF-LB/M.Realizing this vision will enable additive manufacturing to deliver on its promise of geometrically complex, mechanically reliable, near-theoretical-density components for aerospace, energy, and biomedical applications.

7 References

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