From Voxel Field to Fabricated Part

GS-RD Foam Generator · Laser Powder Bed Fusion · Wire Arc Additive Manufacturing · Directed Energy Deposition

The GS-RD foam generator was designed from first principles with fabrication as the output requirement — not visualisation, not simulation. Every geometric parameter has a direct physical consequence at the machine. Voxel size is minimum feature resolution. Threshold is porosity. Minimum wall is printability floor. Connectivity is powder evacuation. The analysis pipeline measures geometry against specification before the build begins.

The system supports two fabrication scales. At fine scale — 3mm tile, 47μm voxel, 188μm median strut — the geometry is sized for laser powder bed fusion and biomedical applications. At large scale — tiles sized to match the resolution of welding-based deposition — the same geometry class is appropriate for structural, architectural, thermal management, and defence applications. The same simulation, the same tiling system, and the same analysis pipeline serve both scales.

> The geometry is scale-invariant. The tile scales with the process. A 50mm tile at wire arc resolution produces the same topological class — stochastic bicontinuous, verified tileability, continuous morphology across joints — as a 3mm tile at laser powder bed resolution. The fabrication process changes. The geometry does not.

Process Scale and Application

Six fabrication processes span the range from bone scaffold to architectural structure, each with a corresponding tile size set by process resolution.

Laser powder bed fusion (metal). 50–100μm minimum feature. 3–6mm tiles. Bone scaffolds, medical implants, fine thermal management geometry. The validated bone ingrowth specification — 68.9% porosity, 469μm median pore, 188μm median strut, 100% connectivity — was measured at this scale.

Laser powder bed fusion (polymer). 80–150μm minimum feature. 4–8mm tiles. Filtration media, acoustic panels, lightweight structural components. The open void network allows direct polymer sintering without support removal in the interior.

Laser hot-wire directed energy deposition. 300–600μm minimum feature. 15–30mm tiles. Aerospace structural components, complex thermal management geometry, defence hardware requiring fine feature control at intermediate scale. Higher deposition rate than LPBF with lower resolution.

Micro-WAAM. 500μm–1mm minimum feature. 25–50mm tiles. Structural panels, heat exchangers, medium-scale architectural components. An emerging process with active research interest for topology-optimised and biomimetic geometries.

Wire arc additive manufacturing. 1–3mm minimum feature. 50–150mm tiles. Large structural components, load-bearing architectural geometry, large heat sinks. High deposition rate, low cost per kilogram, scalable to very large build volumes.

Coarse GMAW deposition. 3–8mm minimum feature. 150–400mm tiles. Architectural facade elements, civil engineering components, large-scale passive thermal structures where pore scale can be centimetre-order.

Part One — Laser Powder Bed Fusion

At fine scale the GS-RD foam geometry maps directly to an LPBF print job. The voxel field becomes a per-layer contour set. Each contour island is hatched and scanned. The geometry statistics from the analysis pipeline inform laser parameter selection before the build begins.

Laser path generation

Hatch pattern

The interior of each contour island is filled with a hatch pattern — parallel scan lines at fixed spacing. For bicontinuous foam each strut cross-section is hatched independently. Hatch distance is typically 60–120μm for metal LPBF. At median strut thickness of 188μm, each strut receives one to three hatch passes depending on hatch spacing — sufficient for full fusion without overmelting adjacent pore space.

Scan strategy

Rotation of the hatch angle between layers reduces anisotropy and improves mechanical properties. Common strategies rotate 67° per layer. For stochastic foam this matters less than for lattices because the geometry itself is near-isotropic — measured anisotropy index 1.02–1.05 across simulation runs. The foam does not have a preferred load direction by design.

Contour scan

A contour pass traces the boundary of each solid region before or after hatching to improve surface finish. For foam struts, the contour pass defines the outer surface that contacts adjacent pore space — critical for surface roughness and osseointegration in biomedical applications. At 47μm voxel resolution the contour is defined at sub-strut precision.

Laser parameters

Power, speed, and spot size are tuned per material. For thin features — struts near minimum wall — reduced power or increased speed prevents overmelting. The simulator output includes strut thickness statistics that directly inform this selection. Median strut of 188μm with minimum wall enforcement at 2 voxels (94μm) defines the lower bound of the printable feature range.

Support structure

Self-supporting geometry

Bicontinuous foam is largely self-supporting. The interconnected solid network provides mutual support across the build volume — each strut is anchored to its neighbours above and below through the continuous solid phase. Overhanging angles above 45° from vertical require support in conventional LPBF, but the foam network rarely produces isolated overhangs of that severity. Support is typically required only at the build plate interface.

Powder removal

The void phase of bicontinuous foam is continuously connected — this is the defining topological property. In LPBF, connected void means unmelted powder can be evacuated after the build through any open face. For scaffold applications complete powder removal is a clinical requirement. The connectivity measurement — 100% in validated runs — confirms the void network is fully connected and evacuation is possible from any face. The open interior export mode eliminates outer face geometry, leaving all six tile faces open for direct powder evacuation.

Thermal management during build

Dense foam volumes have higher surface area per unit volume than solid geometry — SA/V ratio of approximately 6–7 mm^{-1} in validated runs. This increases heat dissipation per unit volume during the build. Thermal gradients and residual stress are lower than in solid sections of equivalent envelope, reducing distortion and warping risk.

In-process monitoring

LPBF systems increasingly use in-situ monitoring — optical, thermal, or acoustic — to detect defects during the build. The geometry statistics produced by the foam analysis pipeline map directly to the signals these systems track.

Per-layer optical images can be compared against the expected slice contour from the slicer. Discrepancies indicate powder spreading failure, laser parameter drift, or geometric error. The voxel field porosity measurement provides a geometric porosity prediction before the build — actual printed porosity measured by Archimedes method or CT scan can be compared against this prediction to validate threshold calibration for a given material and parameter set. Thermal imaging during the build tracks melt pool size, which correlates with feature size. The strut thickness distribution from the analysis pipeline — median 188μm in validated runs — provides a ground truth distribution against which melt pool statistics can be calibrated.

Part Two — Welding-Based Additive Manufacturing

At large scale the same bicontinuous foam geometry is deposited by welding-based additive manufacturing processes — wire arc additive manufacturing, gas metal arc welding deposition, laser hot-wire directed energy deposition, and micro-welding variants. The process resolution determines the minimum tile size. The simulation, tiling, and analysis systems are unchanged. The geometry scales; the computational pipeline does not.

Process variants

Laser hot-wire directed energy deposition

Laser beam with wire feedstock. Minimum feature 300–600μm. Suitable for 15–30mm tiles. Higher resolution than arc-based processes, lower deposition rate. Appropriate for aerospace structural components, complex thermal management geometry, and defence hardware where fine feature control is required at intermediate scale.

Micro-WAAM

Reduced-parameter wire arc deposition targeting minimum features of 500μm–1mm. Suitable for 25–50mm tiles. An emerging process with active research interest in topology-optimised and biomimetic geometries. Appropriate for structural panels, heat exchangers, and medium-scale architectural components.

Wire arc additive manufacturing

Standard wire arc additive manufacturing with minimum feature 1–3mm. Suitable for 50–150mm tiles. High deposition rate, low cost per kilogram deposited, scalable to large build volumes. Appropriate for large structural components, load-bearing architectural geometry, and large heat sinks.

Coarse gas metal arc welding

High-deposition-rate arc welding at larger bead size. Minimum feature 3–8mm. Suitable for 150–400mm tiles. Appropriate for architectural facade elements, civil engineering components, and large-scale thermal management structures where the foam pore scale can be centimetre-order.

Toolpath generation for arc deposition

Layer slicing

The voxel field is sliced at the process layer height — typically 1–3mm for WAAM, 0.3–1mm for laser hot-wire DED. Each layer produces a set of contour islands corresponding to the solid cross-section of the foam at that height. The contour resolution is set by the voxel size of the simulation, not the layer height.

Bead path planning

Each contour island is filled with a deposition bead path. For welding-based processes, the bead width is determined by wire diameter and process parameters — typically 2–8mm for WAAM, 0.5–2mm for laser hot-wire DED. For foam struts near minimum wall, the bead path may be a single central pass rather than a hatched fill. The strut thickness distribution from the analysis pipeline informs whether single-bead or multi-bead passes are required per strut.

Travel speed and wire feed rate

Deposition rate is set by travel speed and wire feed rate. For thin struts, lower wire feed rate and higher travel speed reduce bead cross-section. The minimum wall enforcement at 2 voxels in the simulator defines the thinnest strut the geometry will contain — this is the critical dimension for process parameter selection. At 50mm tile scale with 1mm minimum voxel, minimum wall is 2mm — well within WAAM deposition capability.

Inter-layer dwell and cooling

Welding-based deposition generates significant heat input per layer. Thin strut walls in foam geometry are more susceptible to heat accumulation than solid sections. Inter-layer dwell time allows the deposited material to cool below a critical temperature before the next layer is deposited. The SA/V ratio of the foam — higher than solid geometry — accelerates heat dissipation between layers, reducing required dwell time relative to equivalent solid volumes.

Support and fixturing

Self-supporting at large scale

At WAAM scale, foam struts are 1–8mm in diameter — well above the minimum feature for self-supported deposition. The interconnected solid network is structurally stable during deposition. Support structures are required only at the build plate interface and at any isolated overhang exceeding the material-specific critical angle, typically 45–55° from horizontal for arc processes.

Substrate and transition

WAAM deposition requires a substrate — typically a plate of the same alloy, or a sacrificial base. For large foam components, the substrate may form part of the final assembly — a solid base transitioning to foam infill. This mirrors the clinical bone scaffold concept scaled to structural applications: dense cortical outer layer, bicontinuous foam interior, continuous transition between the two.

Residual stress and post-processing

Welding-based processes produce higher residual stress than LPBF due to larger thermal gradients per layer. The stochastic and near-isotropic nature of the foam geometry distributes stress more uniformly than periodic lattices or solid sections. Post-processing — stress relief annealing or hot isostatic pressing — may be required for high-performance structural applications. The open void network of the foam allows uniform heat penetration during annealing, which is an advantage over closed-cell geometries.

Large-scale application geometry

Architectural and civil

At WAAM scale a single 3×3×3 tile assembly at 50mm tiles produces a 150mm foam block. A 10×2×10 slab produces a 500mm × 100mm × 500mm structural panel with bicontinuous foam morphology. The stochastic interior means no two panels produced from different seeds are identical — a designed variation property that is aesthetically significant in architectural applications and practically significant for diffuse acoustic and thermal performance. The tiling system ensures that panels assemble without visible seams regardless of their internal variation.

Thermal management

Large-scale foam geometry is applicable to heat exchangers, thermal buffers, and passive cooling systems. The SA/V ratio of 6–7 mm^{-1} at fine scale represents the same ratio at any physical dimension — 6–7 m^2/m^3 at metre scale. The continuously connected void phase allows fluid flow in both phases simultaneously — a property specific to bicontinuous topology that open-cell and strut lattice geometries cannot replicate. This makes the geometry uniquely suited to two-phase flow heat exchange applications.

Defence and structural

At intermediate scale — laser hot-wire DED, 15–30mm tiles — the foam geometry is applicable to ballistic absorption panels, lightweight structural infill for aerospace and defence platforms, and multi-functional components combining structural load-bearing with thermal management. The near-isotropic mechanical response, verified connectivity, and scalable pore architecture directly address known limitations of periodic lattice structures in these applications.

In-process monitoring at scale

Real-time monitoring of bead width and height via laser profilometry or structured light provides direct comparison against expected strut dimensions from the analysis pipeline. Drift indicates process parameter shift. Layer-by-layer geometry verification using photogrammetry or structured light scanning checks each deposited layer against the expected slice contour — critical for large builds where geometric accumulation error can cause interference in later layers.

Archimedes density measurement or CT scanning of representative sections confirms printed porosity against the pre-build voxel field prediction of 68–70%. Infrared thermography per layer tracks heat accumulation in strut networks, directly comparable to the strut thickness distribution — thin struts show higher peak temperatures and longer cooling tails.

Pipeline Summary

The pipeline from simulation output to fabricated part follows the same seven stages at both scales. The physical parameters change; the computational structure does not.

1 **Voxel field.** N×N×N binary occupancy grid at physical voxel resolution. Fine scale: N=64, 47μm voxel, 3mm tile. Large scale: N=64, 0.78–2.3mm voxel, 50–150mm tile.

2 **Mesh extraction.** Triangulated surface mesh from voxel face method or marching cubes. Open interior export eliminates boundary faces for seamless assembly and powder evacuation.

3 **Slicing.** Per-layer contours at machine layer thickness. 20–60μm for LPBF. 0.5–3mm for WAAM and DED.

4 **Toolpath.** Hatch and contour scan vectors per layer for LPBF. Single or multi-bead arc or laser path for welding-based deposition.

5 **Support planning.** Base support only at both scales. Foam network is self-supporting. Void phase is fully connected — powder evacuation or fluid flushing possible from any face.

6 **Post-processing.** Powder evacuation and optional HIP for LPBF. Stress relief anneal and machining if required for WAAM and DED.

7 **QC reference.** Porosity 68–70%, median strut at process-appropriate dimension, connectivity 100%, face-match tileability 100%. Geometry statistics from the analysis pipeline serve as the pre-build ground truth against which in-process monitoring is calibrated.

> The foam generator was designed from first principles with fabrication as the output requirement. Every parameter in the pipeline has a physical consequence at the machine. The computational layer that sits above the machine — geometry generation, analysis, and QC reference — is already built. The fabrication path at both scales is a direct mapping from that output.

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