

Build Simulation and Process Parameter Optimization for Additively Manufactured Ti-6Al-4V Lattices for Biomedical Applications [†]

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Abstract

Additive manufacturing (AM) of metallic lattice structures, particularly those made of Ti-6Al-4V, has significant potential for biomedical applications due to their lightweight nature and favorable mechanical properties. However, laser powder bed fusion (LPBF) processes often introduce residual stresses and distortions, which compromise dimensional accuracy and part performance. This study presents a simulation-based approach for optimizing process parameters and post-processing strategies to minimize these issues. Using the Simufact Additive 1.0 ink, 2023 software, voxel sensitivity analysis was conducted to identify an optimal mesh size of 0.35 mm. A Design of Experiments (DoE) approach in MINITAB was applied to optimize key LPBF parameters, including laser power, scanning speed, and scan width. Simulations incorporating stress relief and hot isostatic pressing (HIP) were conducted to assess their impact on residual stresses and distortions. The results show that stress relief effectively reduces maximum distortion by up to 50% in the X direction and 17% in the Z direction for an FCC lattice structure with a 0.75 mm strut thickness. HIP further decreases deflection angles by 77%. The simulation predictions correlate well with the experimental measurements, supporting the use of simulation-driven process optimization to enhance the dimensional stability and mechanical reliability of Ti-6Al-4V lattice structures for biomedical implants.

Keywords: additive manufacturing; simulation; laser powder bed fusion; lattice structure; biomedical application



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1. Introduction

Additive manufacturing (AM), commonly referred to as 3D printing, is a technique that produces three-dimensional objects by depositing materials layer by layer [1]. To create these components, CAD data are required, which the machine uses to divide the file into different layers for assembly throughout the manufacturing process.

After the part is finished, it is removed from the machine. This approach differs from subtractive manufacturing, which involves removing materials using techniques such as machining, turning, milling, drilling, grinding, and cutting [2].

Over the years, AM has gained significant importance. It was originally used primarily for Rapid Prototyping, in which small production batches are more economical, and development timelines are shorter [2].

Recently, it has expanded into various sectors, including healthcare, automotive, aviation, and tailored products, driven by technological progress. Laser powder bed fusion (LPBF) is an advanced additive manufacturing (AM) technique that is transforming metal production, as shown in Figure 1.

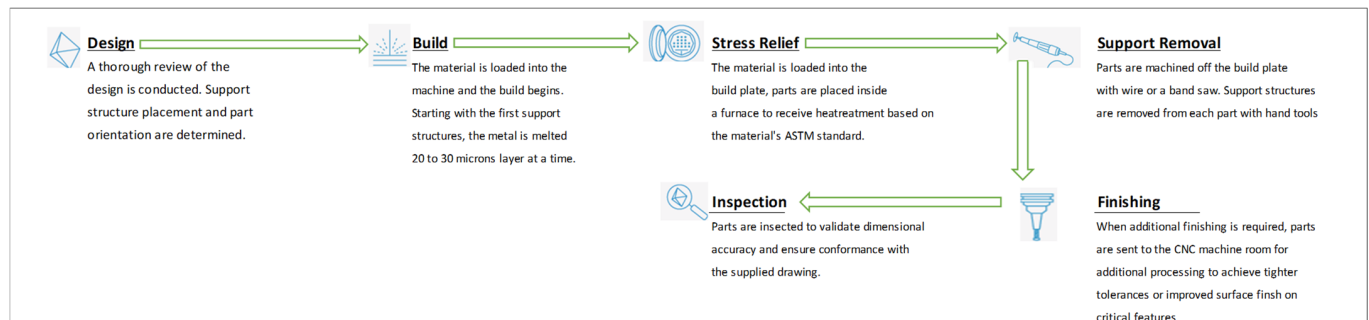


Figure 1. The applied process flow of LPBF printing of metals.

This method uses a laser beam to precisely melt metal powder in a powder bed, focusing on merging specific regions of each layer. After achieving the necessary melting, a new layer of powder is gently spread, enabling the creation of complex and high-quality metal parts [3].

Adopting LPBF can significantly improve manufacturing capabilities and support product development. To produce a top-tier component, multiple process parameters and factors must be considered. Some depend on the specific machine used, whereas others do not. Every parameter must be carefully selected to ensure the production of flawless parts. Studies have indicated that the mechanical properties of the final product can vary significantly depending on the chosen parameters and influencing factors [3]. A summary of the parameters used for LPBF fabrication is as follows:

Laser power refers to the energy exerted each second by the laser onto the powder bed. Hatch spacing indicates the space between the centerlines of two neighboring scanned paths. Scanning speed refers to the rate at which the laser scanner operates throughout the procedure. Layer thickness refers to the elevation of a newly deposited layer on the powder bed following the selective laser melting process. The energy density arises from the interplay of all these factors. Finally, the scan strategy, also known as the hatching strategy, outlines the route taken by the laser beam as it heats the material during layer formation [3]. Figure 2, below, shows the LPBF processing parameters.

Several limitations of the LPBF process involve defects resulting from rapid cooling, such as distortion and residual stress, which are examined in this study. Another limitation of the LPBF method is that the produced parts exhibit uncertain mechanical properties, dimensional precision, and surface finish quality. Surface quality is a crucial technical aspect of additively manufactured components, as it affects the durability, integrity, and functionality of the products [4].

Distortion in additive manufacturing (AM) pertains to the differences between the measurements outlined in the CAD file and those of the completed part [5]. This issue stems from the expansion and contraction of the material caused by heat during the process, along with rapid cooling rates and inconsistent heat conduction across the component.

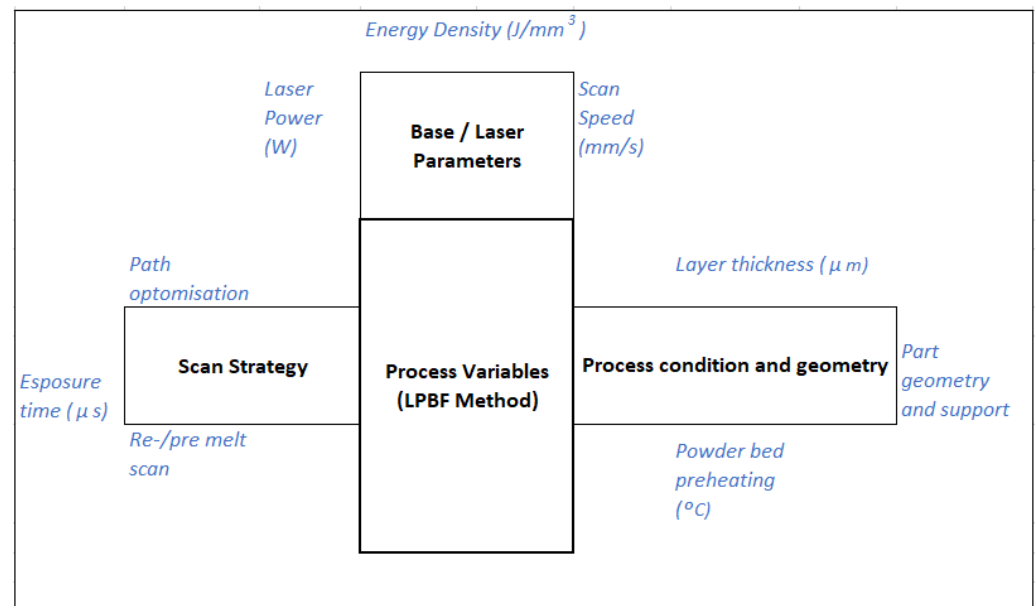


Figure 2. Illustration of LPBF process parameters.

As a heat source delivers energy to a layer, its temperature increases, leading to expansion. During the subsequent rapid cooling, the liquefied substance shrinks and attempts to revert to its shape at a lower temperature.

However, it is limited by the base layer, which hinders restoration. This limitation creates internal stresses, and when these stresses exceed the yield strength of the material, plastic deformation occurs. Consequently, this procedure may cause distortion and residual stresses in the component [6].

Residual stresses refer to the stresses that persist in a material at equilibrium, even without any external forces applied [7,8]. These stresses may arise after manufacturing, heating, or various processes that result in uneven plastic deformation. Residual stresses, which are frequently unintentionally introduced during manufacturing, are crucial factors in material design and analysis.

Various studies have investigated the effects of process parameters on residual stress. It has been noted that processing parameters may influence the residual stress more significantly than the material properties [9]. A significant interaction exists between the scan speed and power; although greater power generally leads to more residual stress, a faster scanning speed often produces less. This is associated with energy density, as low power and high speed result in a lower energy density, thereby decreasing the residual stress. The layer thickness notably influences the residual stress, where thicker layers create a larger temperature disparity between layers, resulting in diminished residual stress. Earlier research has confirmed that a greater thickness leads to a greater temperature difference between layers, resulting in reduced residual stress. Previous studies have confirmed that thicker layers decrease residual stresses [10,11].

Residual stresses resulting from large temperature variations and swift cooling lead to deformation of parts during the LPBF process. Elevated residual stresses arise from print quality problems, such as part deformation and fractures, caused by rapid cooling and elevated temperatures. Figure 3 demonstrates the formation of residual stresses in AM, as described by the cantilever and bridge curvature methods (BCM). Figure 3, below, illustrates the residual stress as a function of scanning strategy (a), measurement of rotation angle (b)–(d) [8].

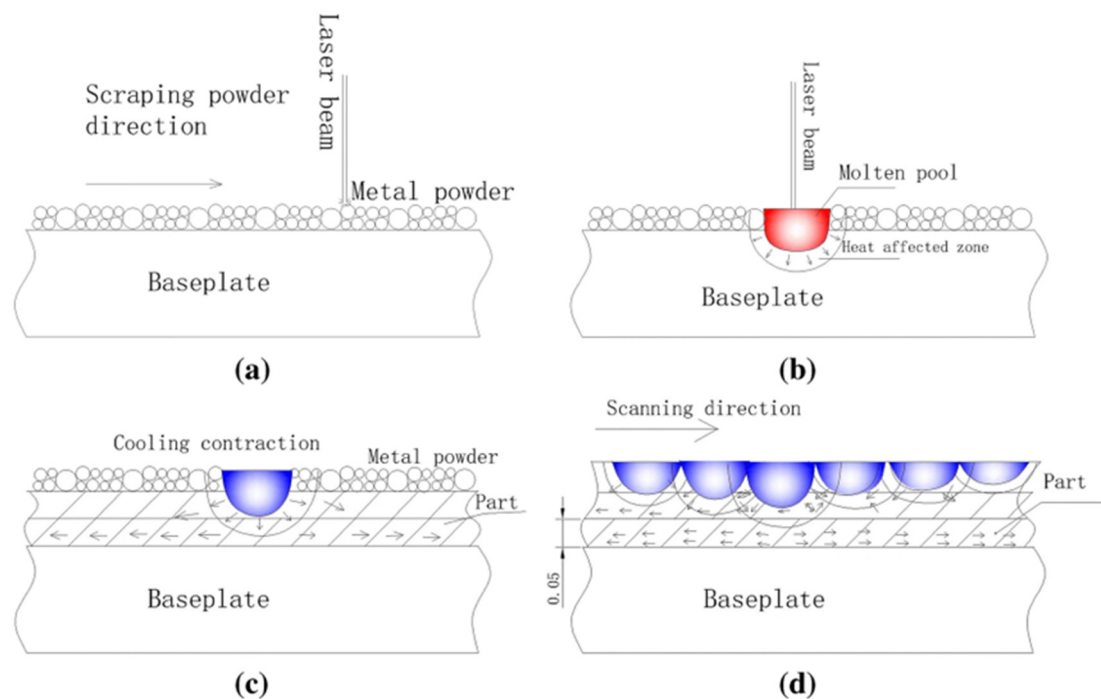


Figure 3. The evolution process of cyclic thermal stress in SLM. (a) Powder spreading. (b) Melting pool formation. (c) Solidification contraction. (d) Cyclic cooling. Reprinted from [12].

Post-Processing techniques.

The surface quality of manufactured components poses a major challenge in the metal AM process. Achieving the desired surface quality requires post-processing.

Mechanical techniques such as laser polishing, magnetic field-assisted finishing, grinding, polishing, and other methods have been employed with additively manufactured metallic components to enhance surface quality and control surface integrity characteristics. Excluding grinding and mechanical polishing, research indicates that most of these procedures fail to meet the surface criteria [9]. Thermal post-processing in additive manufacturing uses heat treatments, like stress relieving and hot isostatic pressing (HIP), to improve the mechanical properties of 3D printed parts by altering their microstructure, relieving residual stresses, and increasing density. These processes optimize a part's performance and durability by controlling its microstructure and reducing defects like porosity and internal stresses generated during the printing process [10]. Figure 4 below illustrates the mechanical and thermal post-processing techniques.

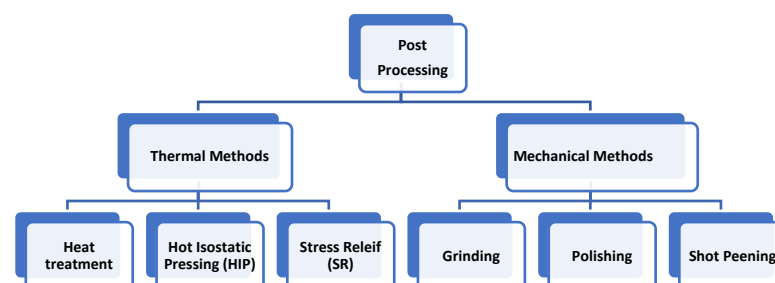


Figure 4. Classification of different post-processing operations after printing metallic parts.

Post-processing treatment in additive manufacturing includes Figure 5:

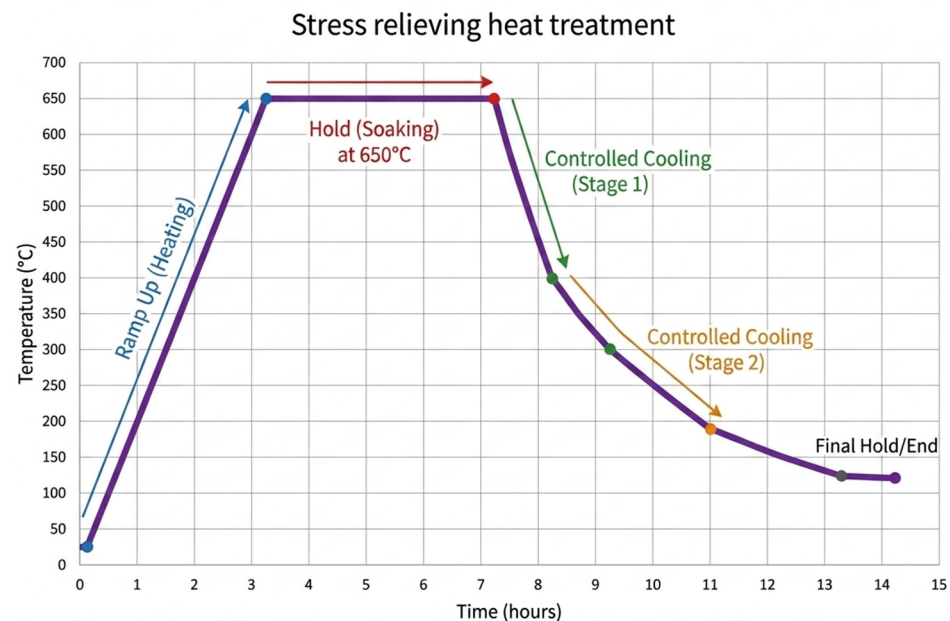


Figure 5. This figure represents the stress relief cycle.

Thermal Post-processing—Stress-relieving heat treatment (SR) and hot isostatic pressing (HIP).

Stress-relieving heat treatment is considered an important step for parts produced by LPBF technology due to the significant internal stresses caused by thermal effects during the process. The stress relief is performed according to ASTM F3301 or SAE [2], typically inside a vacuum furnace at a specified temperature and duration. Afterwards, the specimen is slowly cooled to room temperature in the furnace to prevent oxidation and reduce the formation of new residual stresses. In the stress relief process, parts are gradually heated to a target temperature of 650 °C (see Figure 5), with thicker sections reaching this temperature at the same rate as thinner ones. The parts are then immersed to ensure thermal equilibrium has been established. Following this, they are gradually cooled to ensure uniform cooling of both thick and thin sections, which helps prevent the development of new residual stresses. Stress relief treatments can be applied to nearly all Ti-alloys without compromising their strength and ductility. These treatments help decrease undesirable internal residual stresses that often result from cold working and forming processes. However, residual stresses can never be completely eliminated but only reduced to a level equivalent to the alloy's normal yield strength at the stress relief temperature.

Hot isostatic pressing (HIP) is carried out in compliance with ASTM F3301 [13]. The specimen is placed under an inert atmosphere, not less than 100 ± 5 MPa and 920 °C, and held at a chosen temperature within ± 10 °C for 120 ± 30 min, subsequently being cooled down under an inert atmosphere to below 425 °C, Figure 6. Hot isostatic pressing improves quality and performance in AM parts production. HIP has been used as a method to consolidate metal powders and metal matrix composites to produce fully dense components, to eliminate porosity in sintered products, to produce metal-clad parts through diffusion bonding, and to eliminate defects in castings. HIP, as illustrated in Figure 6, is a process that is used to consolidate metal powder or eliminate defects in solids such as pores, voids, and internal cracks, and then the material is densified to 100% of the theoretical density. When previously densified parts having surface-connected porosity need to be fully densified, the HIP cycle must be done in gas-tight capsules made from sheet metal or glass. The process includes high Isostatic gas pressure, meaning that the pressure acts on all surfaces of the components in all directions, leading to densification. The mechanism

for densification during HIP is plastic deformation, creep, and diffusion. Initially, plastic deformation is the dominant driving mechanism since the applied external pressure is higher than the yield stress of the material at the HIP temperature, thus making the voids in the material collapse. After the initial plastic deformation, creep and diffusion contribute to densification [4].

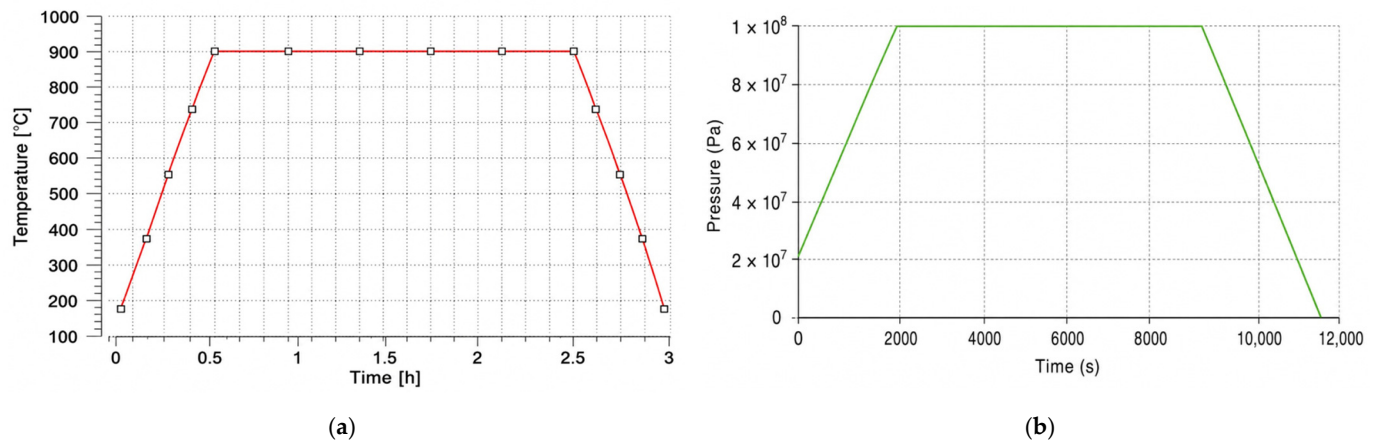


Figure 6. This figure represents the hot isostatic pressure (HIP), (a) Temperature vs. time (b) Pressure vs. Time.

These mechanisms not only collapse and close the pores but also totally eliminate them to create a material free of defects. Three main parameters in a HIP cycle determine the densification. These are temperature, pressure, and hold time. HIP temperatures are often in the range of 70 to 90% of the solidus temperature of the material being processed, and the pressure used is usually in the range of 100–200 MPa, mostly with argon as the pressure medium. The holding time is dependent on the thickness of the components being processed, since there is a longer temperature delay in the core of the large parts, depending on the thermal conductivity of the material [11].

Purpose of lattice structures.

Lattice structures in medical implants, like hip implants offer many benefits that enhance performance [14]. These designs lower the bulk elastic modulus, reducing the gap between titanium alloys and natural bone, aiding integration. They promote high permeability, allowing nutrients and oxygen to flow, supporting cell viability and tissue growth. Lattice structures also improve elasticity, accommodating natural bone movement and stresses, which enhances tissue growth and bone ingrowth. After healing, the implant mimics natural bone. Surface finish impacts osseointegration, ensuring a good fit and secure bonding with bone, increasing implant success and lifespan [6].

The paper presents a comprehensive study on the simulation-based optimization of selected LPBF process parameters and post-processing strategies for Ti-6Al-4V lattice structures in biomedical applications. The research addresses a relevant gap in additive manufacturing (AM) by focusing on residual stresses and distortions. The use of the Simufact Additive software and MINITAB®17 for Design of Experiments (DoE) is explored, and the results align with empirical observations.

The study addresses critical challenges in AM, such as residual stresses and distortions, which are pivotal for biomedical applications. The combination of voxel sensitivity analysis, DoE, and post-processing simulations (stress relief, HIP) is covered. The correlation between the simulation and experimental data validates the approach, particularly the reduction in distortion (50% in X-direction, 77% with HIP). The findings are directly applicable to improving the dimensional stability of Ti-6Al-4V implants.

Lattice structures designed for laser powder bed fusion (LPBF) affect and reduce stress shielding—the phenomenon where an implant carries more load than the surrounding bone, causing bone resorption—by mimicking the porous nature and low elastic modulus of human bone. By utilizing tailored, interconnected porosity, these structures prevent the “rigid shield” effect of solid implants. Here is how lattice structures affect and mitigate stress shielding in metallic printed parts:

1. Tailoring elastic modulus to match bone.
2. Reduced Stiffness: Solid titanium (Ti6Al4V) has a much higher Young’s modulus (approx. 110 GPa) compared to cortical bone (10–30 GPa), leading to stress shielding. Lattice structures designed with relative densities of 0.1–0.5 can significantly reduce the effective elastic modulus, matching it closer to bone.
3. Topology Effects: The choice of unit cell significantly impacts stiffness. Triply Periodic Minimal Surface (TPMS) structures, such as the gyroid, are highly efficient in providing necessary strength while maintaining a lower modulus, reducing the rigidity that causes stress shielding.
4. Porosity Control: Higher porosity in the lattice structure directly results in a lower stiffness, which reduces the load-carrying capacity of the implant and transfers more stress to the surrounding tissue.

Mechanisms for Reducing Stress Shielding:

1. Bone Ingrowth: The interconnected pores allowed by LPBF facilitate long-term osseointegration (bone in-growth), strengthening the bond between the implant and bone.
2. Lowered Residual Stress: By allowing for better stress redistribution during the manufacturing process, the final implant behaves more elastically, reducing the unnatural stiffening effect on surrounding tissue.

Simulation of the AM process.

As it has been seen before, there are too many variables in the process and interactions between parameters that make it difficult to understand. In these cases, the finite element method (FEM) simulation approach can be useful to explore the final properties and the behavior of the process with different parameters without investing money in experiments, as shown in Figure 7. Even though 3D printing is a new process, there are some equations that intend to simulate the whole process and its mechanical behavior [15–17].

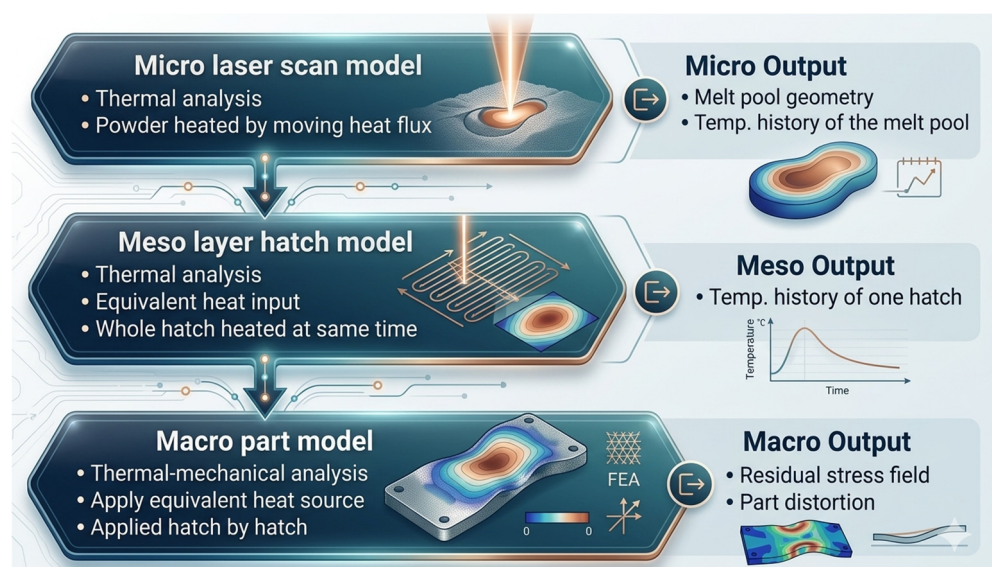


Figure 7. Schematic representation of different level of simulation scales.

Depending on the physical considerations and their timescale, three types of simulations can be found:

Microscale simulation models focus on heat absorption and material interactions, capturing phase changes within a domain comparable to the layer thickness, typically ranging from 1×10^{-6} to 1×10^{-2} m per element. These micromodels offer insights into the thermal cycles and microstructure variations around the melted and solidified layers.

Macroscale simulation models use a fixed layer size and thermal cycle to compute residual stresses and distortions in the manufactured part. Phase changes and feedstock details are not considered. Instead, the final properties are determined based on the thermal cycle and history. These simulations account for powder deposition and clamping conditions as boundary conditions.

Mesoscale simulations aim to describe the material's composition and mechanical properties. The information gained from mesoscale simulations is used in conjunction with data from macroscale and microscale simulations to provide a more comprehensive understanding of the material's behavior and performance.

2. Materials and Methods

2.1. Materials

2.1.1. Ti-6Al-4V Alloy

The material that will be used is a titanium alloy, Ti-6Al-4V, which is a high-specific-strength alpha-beta titanium alloy with exceptional corrosion resistance. The material model used: elastic-plastic with temperature-dependent properties of Ti-6Al-4V (from MatWeb/ASM) [18]. Thermal properties: conductivity, specific heat, and expansion coefficients applied in Simufact Additive. It is one of the most widely used titanium alloys, and it is used in a variety of applications that require low density and strong corrosion resistance, such as aerospace and biomechanical applications. Typically, this titanium alloy is heat-treated to vary the amounts of the alpha and beta phases in the microstructure, which results in different mechanical properties.

Titanium and its alloys are highly valued metals by the additive manufacturing sector due to their high strength, low density, excellent corrosion resistance, high biocompatibility, and good formability (ability to undergo deformation without damage) [10]. Ti-6Al-4V is one of the weakly stabilized $\alpha\beta$ alloys; The phase transformation in Ti-6Al-4V strongly depends on the temperature and cooling rates [19] as presented in Figure 8.

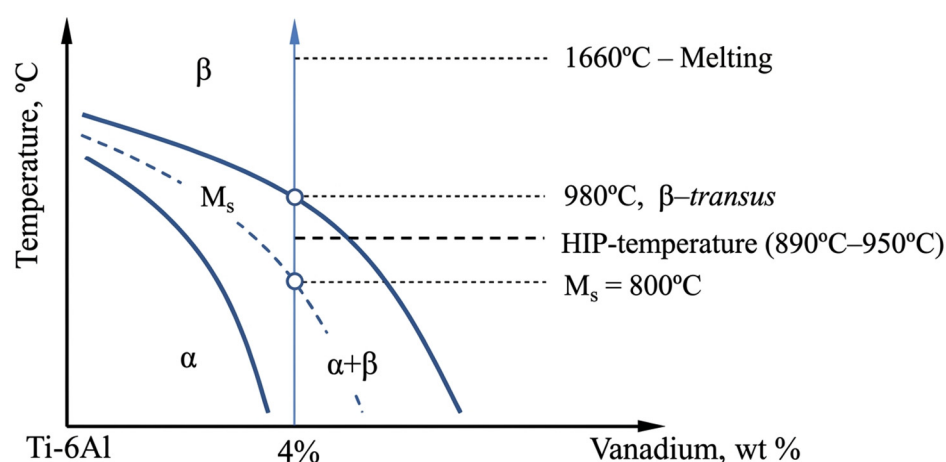


Figure 8. Schematic pseudo-binary phase diagram of the Ti-6Al-4V. Reprinted from Ref. [19].

Figure 9a shows the morphology of powder particles as spherical or subspherical; Figure 9b shows the particle size distribution of the powder, with diameters ranging from

6 μm to 44 μm [15]. The response to heat treatments of this alloy is directly related to the amount of β -phase after quenching and to its instability; it has good room-temperature properties thanks to its relatively high aluminum content. This alloy has different microstructures depending on the path of thermal or thermo-mechanical treatment. This gives Ti-6Al-4V a large variety of mechanical properties.

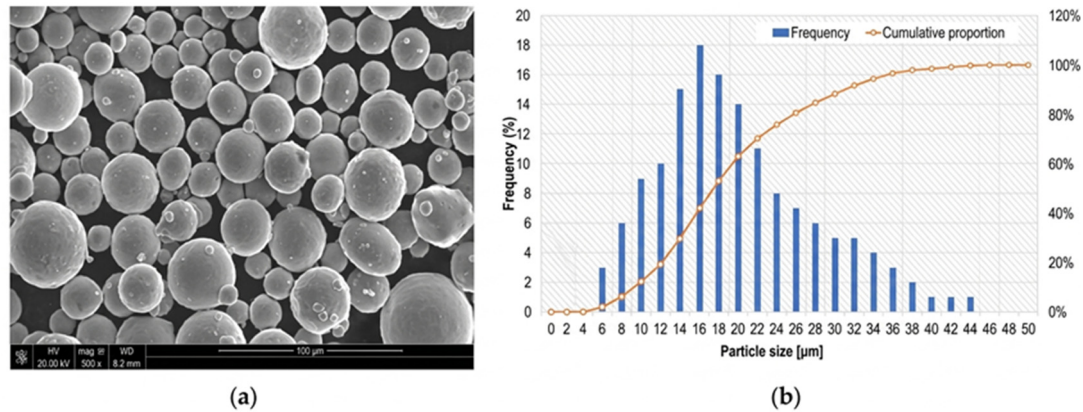


Figure 9. The powder information: (a) the microscopic morphology and (b) particle size distribution diagram of the Ti6Al4V [18].

Ti-6Al-4V alloy is the most commercially used titanium alloy, accounting for over 50% of global titanium alloy usage [13].

The chemical composition of the powder is shown in Table 1 below.

Table 1. The chemical composition of the powder.

Element	Al	V	Fe	C	H	O	N	Ti
Content	6.18	3.82	0.16	0.0075	0.0027	0.069	0.012	Bal.

2.1.2. Specimen Geometry

The study aims to simulate LPBF using the titanium alloy Ti6Al4V, employing available resources such as the E1 SolidWorks 2023 CAD software, Minitab analysis tools, and the Simufact Additive Software.

For using the BCM, a bridge-like part must be built on a base plate and later cut off. After removal from the base plate, the part can curl up through an angle as illustrated in Figure 10.

The single cube with dimensions 15 mm $\times$ 15 mm $\times$ 15 mm, was created in SolidWorks, meshed, and then used to create the lattice structure in nTopology. Simple Cube geometry was used to create lattice structures for additive manufacturing, and the LPBF process was selected. An FCC, BCC, and diamond unit cells were chosen because they are relatively well-known and simple structures. They are also self-supporting structures, which simplifies the printing process. The strut thickness was varied from 0.5, 0.75, and 1.0 mm. The lattice designs were created on the nTopology CAD software.

The curvature method is a technique in which deflection (curl-up angle) stemming from residual stress is measured for a bridge-like, thin plate or cantilever structure (Figure 11). A specially shaped part is built on a base plate and later cut off. After removal from the base plate, the part can curl up through an angle that can be measured [20,21]. Simulations are then used to calculate the actual residual stress corresponding to this measured curl-up angle. A major weakness of methods that rely on distortion and localized strain measurement to calculate residual stress is that the stress relaxation does not necessarily

release all the stress from the component. As a result, the calculated stress is not necessarily representative of the actual state of stress in the part. Therefore, methods that can profile the residual stress for the greater part of the volume are preferred [15,22].

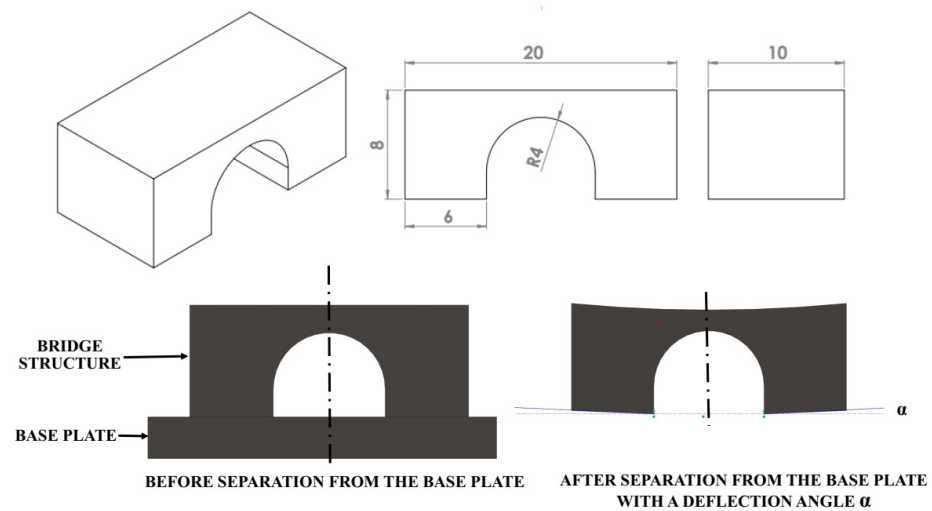


Figure 10. Illustration of the deflection angle after separation the specimen of Bridge structure from the base plate after printing.

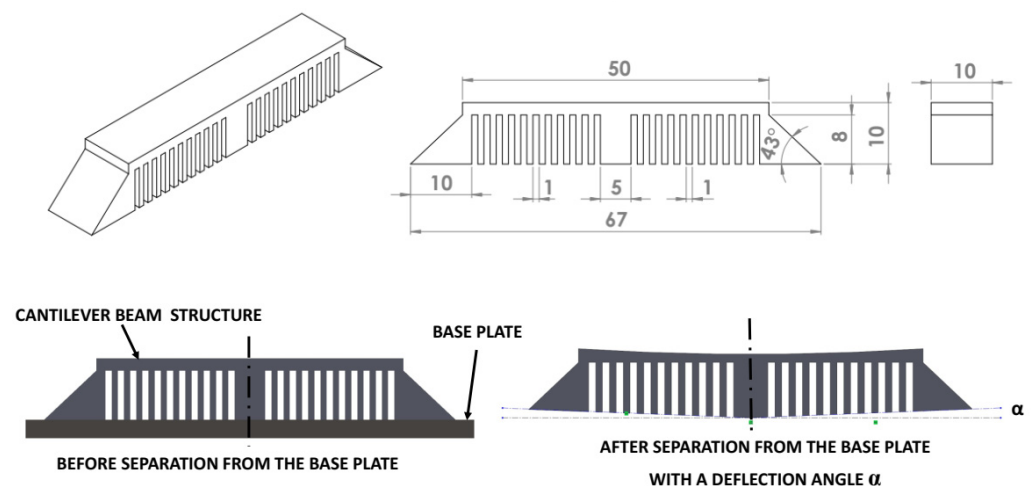


Figure 11. Illustration of the deflection angle after separation the specimen of cantilever beam structure from the base plate after printing.

2.2. Methodology

2.2.1. Method

The primary steps of the study are shown in Figure 12. It begins with a voxel mesh study to determine the optimal voxel size, which will be used in the subsequent optimization of printing parameters. The goal is to investigate the optimal combination of process parameters to minimize the maximum values of distortion and residual stresses using numerical simulation. A full factorial experimental design was established to identify the most significant parameters and find the optimal setting of those printing parameters that can achieve the intended objective function, exploring all parameter combinations considering three factors, each with three levels, resulting in a total of ($3^3 = 27$ Combinations).

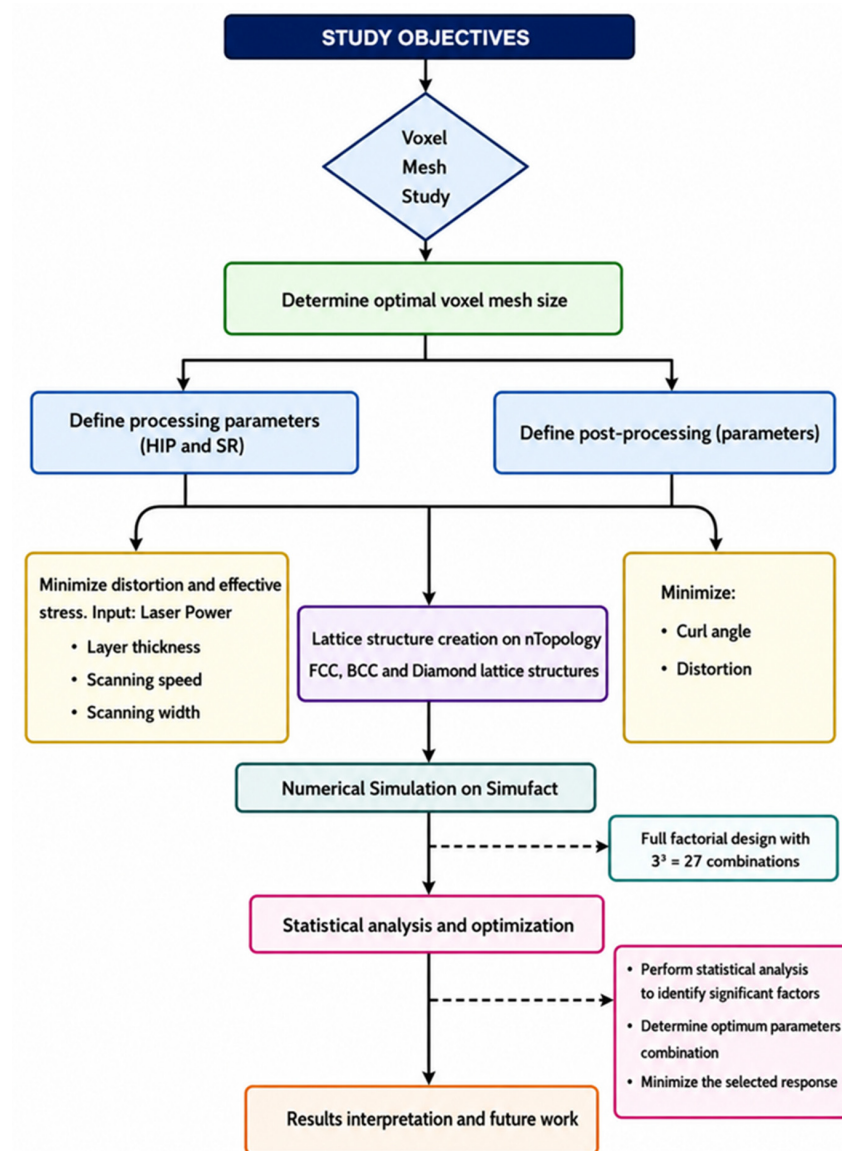


Figure 12. Methodology flow diagram.

Therefore, laser power, scan speed, layer thickness, and scan width, which are presented in Figure 12, were chosen as the input variables, as shown in Table 2, with the maximum values of effective stress, total distortion, Z distortion, and angle being the output. The selected ranges for these parameters were defined to ensure stable melting and high-quality fabrication, as supported by previous studies [16].

Table 2. Input variables of the LPBF process parameter optimization.

Factor	Levels		
	(−1)	(0)	(+1)
LP: Laser Power (W)	160	240	320
SS: Scanning Speed (mm/s)	800	950	1100
SW: Scan Width (μm)	60	90	120

- Laser power: Determines the energy delivered to the powder bed, while insufficient power leads to incomplete melting and excessive power causes overheating or vaporization.

- Scan Speed: Controls the laser exposure time along the melt track. Low speeds cause excessive heat accumulation, whereas high speeds result in poor fusion.
- Layer Thickness: Affects the bonding between layers and overall part density. Thinner layers promote higher density and better surface finish, but increase build time.

2.2.2. Voxel Sensitivity Study

In performing a sensitivity study, the simulation software Simufact Additive was used. The type of simulation used was a thermomechanical macroscale simulation, which takes a lot of time depending on the voxel size. Small voxel size means more elements and therefore more precision, but more calculation time. Because of this, a voxel size was chosen between 0.2 and 0.55 mm and compared these results with distortion and effective stress. The geometry used in this study was the bridge, and the varied processing parameters were laser power, scanning speed, and scanning width. From Figure 13 it can be deduced that the voxel size stabilizes at 0.35 mm. As a result, the 0.35 mm voxel size was chosen and used for the simulation across the study for better repeatability and predictions of the results.

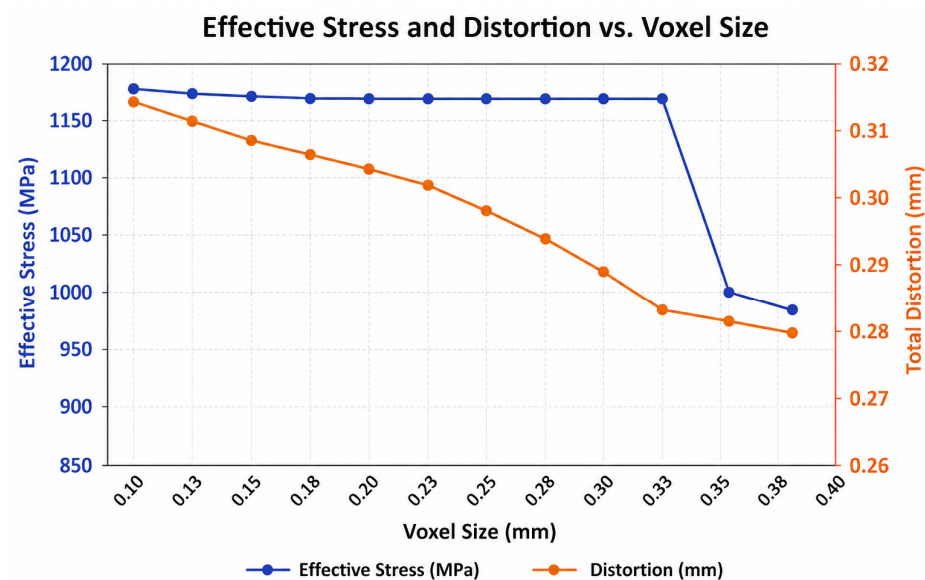


Figure 13. Effective stress and distortion at different voxel sizes.

2.2.3. Processing Parameter Simulation

The 27-run Design of Experiments (DoE) shown in Table 2 follows a full factorial design with center points for three factors, each at three levels. Each combination of factor levels appears exactly once in the design.

The following parameters were employed as inputs for our process:

Scanning path: Meander strategy with 67° rotation between layers.

Boundary conditions: Fixed bottom surface to mimic baseplate clamping, and convection cooling applied to free surfaces.

Assumptions: Isotropic material behavior, no cracking considered, and layer-wise activation with inherent strain calibration.

These additions will help readers better understand the simulation's scientific basis.

2.2.4. Post-Processing Simulation

The optimized processing parameters were then used as inputs for the simulation of post-processing procedures. The bridge curvature geometry was incorporated into this simulation. Post-processing strategies from the literature [18], such as stress relief (Figure 5)

and hot isostatic pressing (HIP) (Figure 6), were employed in the study. The sequence of applications is as follows: simulate as-built, simulate as-built and then SR, simulate as-built and then HIP, simulate as-built and then HIP + SR, and finally simulate as-built and then SR + HIP. Table 3 below.

Table 3. Post-processing strategies.

Post-Processing Strategy	Description
Stress relief (SR)	Initial heating was performed at a rate of 200 °C per hour, followed by a holding temperature of 650 °C for 4 h. Afterward, the sample was furnace-cooled [18]
Hot Isostatic Pressure (HIP)	Heating the furnace to 920 °C, while applying a pressure of 100 MPa for 2 h [18]
SR and HIP	SR and HIP as above
HIP, then SR	HIP and SR as above.

Thermal treatments, such as stress relief annealing and hot isostatic pressing (HIP), are among the most common bulk post-treatments. Different combinations of post-processing treatments are used to release thermally induced residual stresses, which also further consolidate the material by closing processing-induced pores; homogenizing; and optimizing the phase state, morphology, and texture of structural elements, consequently improving the mechanical performance of as-built parts.

2.2.5. Lattice Structure Simulation

Lattice Structure Creation

The three-step approach discussed above involving processing parameters, post-processing, and validation with complex geometries will be explored here, whereby we optimize the additive manufacturing parameters and subsequently use these parameters to create parts with lattice structures. After optimizing the processing and post-processing parameters, we simulated the parts containing lattice structures. Figure 14 below illustrates the beam thickness.

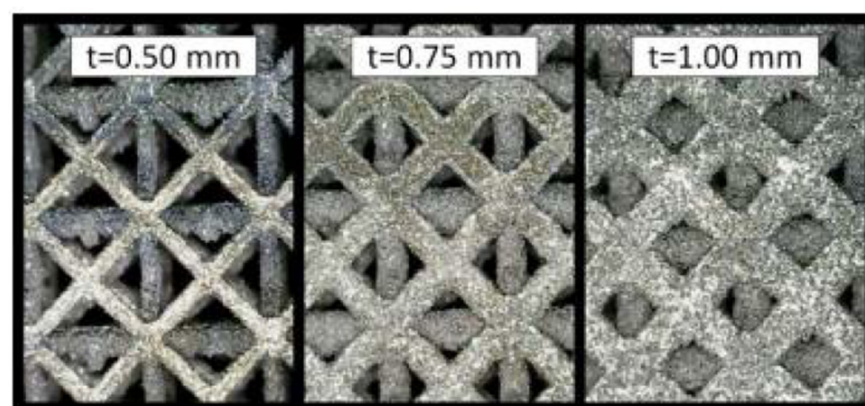


Figure 14. Illustration of lattice design comparison. Reprinted with permission from Ref. [14]. Copyright 2022 Mabrouk M.

The lattice structures created are FCC, BCC, and diamond unit cells. The cell size is 3 mm in all directions (Figures 15–17). These parameters were applied to three different beam thicknesses: 0.5 mm, 0.75 mm, and 1.00 mm.

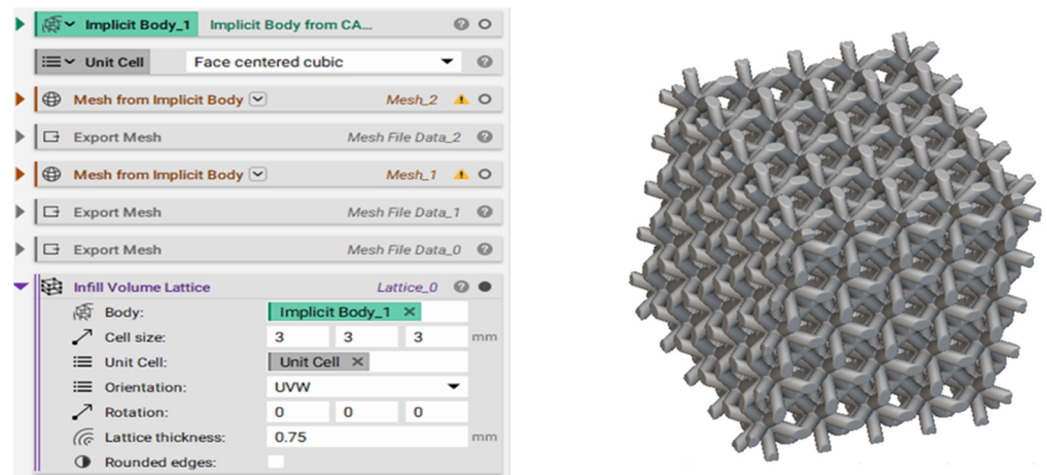


Figure 15. Illustration of the configuration of the FCC lattice structure unit cell, 0.75 mm.

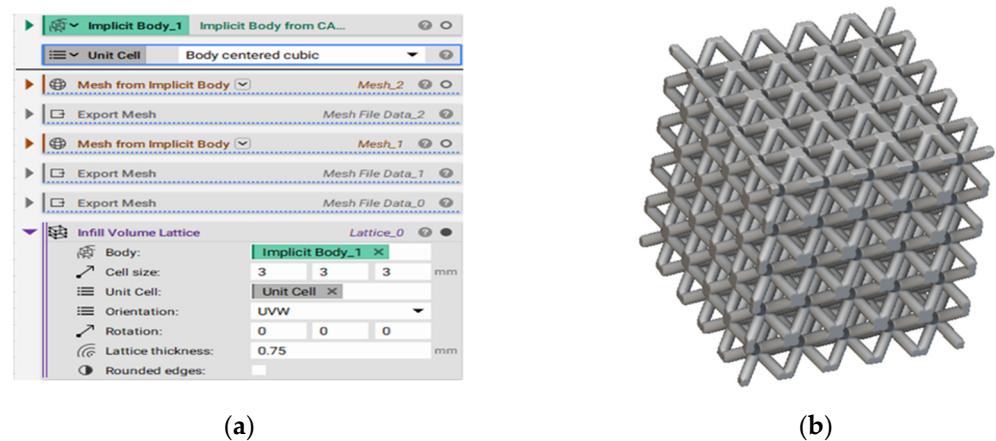


Figure 16. Illustration of the configuration of the BCC lattice structure unit cell, 0.75 mm: (a) nTopology—notebook for BCC and (b) 3D 0.75 mm lattice (not meshed).

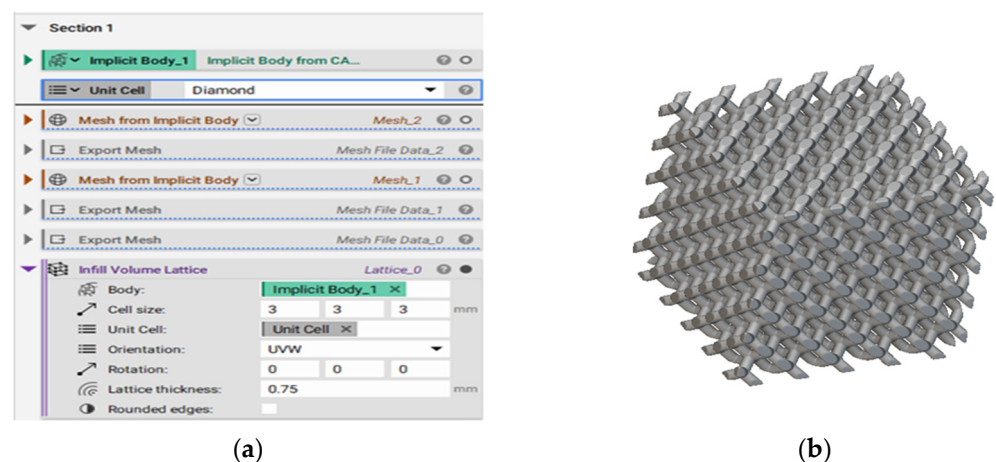


Figure 17. Illustration of the configuration of the diamond lattice structure unit cell, 0.75 mm: (a) nTopology—notebook for diamond and (b) 3D 0.75 mm lattice (not meshed).

Meshing and Exporting the Models

The software from nTopology version 5.15 uses a unique export method, unlike the standard one. For that, you need to make the finite element mesh see mesh figures for all selected lattices in Figure 18a–c.

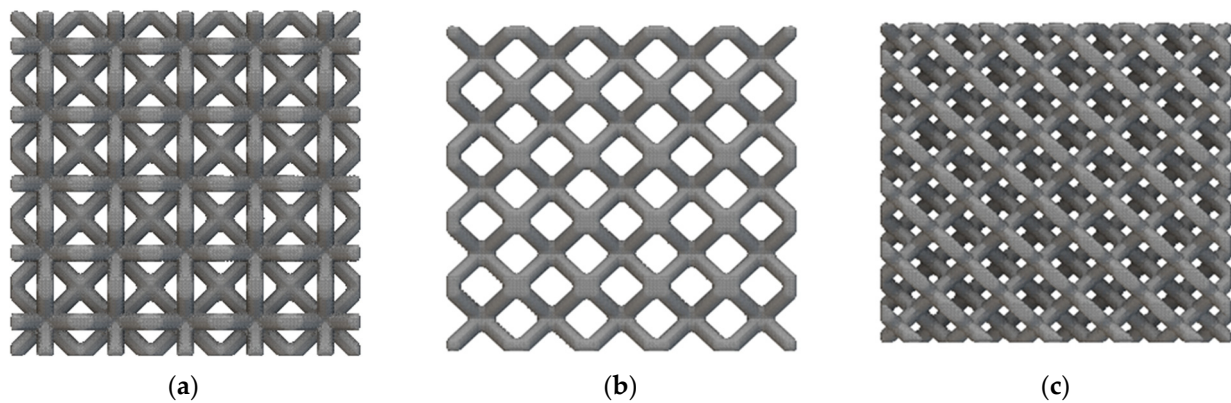


Figure 18. Illustration of mesh results for different unit cells: (a) FCC mesh; (b) BCC mesh; (c) diamond mesh.

Model Exportation to Simufact Additive 1.0 Ink, 2023, Figure 19

In nTopology, we save the meshed file, which will be exported to Simufact for simulation.

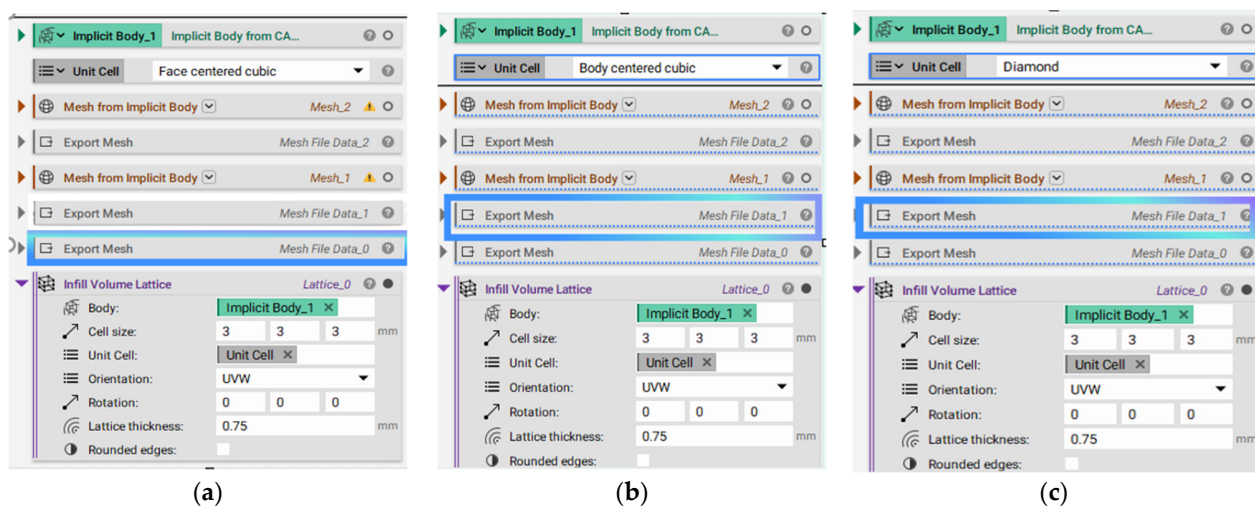


Figure 19. Illustration of nTopology exportation: (a) FCC mesh export; (b) BCC mesh export; (c) diamond mesh export.

Simulation Settings in Simufact Additive 1.0 Ink, 2023

1. Material properties: Ti6Al4V.
2. The lattice thickness will be 0.75 mm and 1.00 mm.
3. Unit cells will be varied as follows: FCC, BCC, and diamond.
4. Post-processing will be stress relief.

Simufact Additive is a powerful and scalable process simulation environment for the first-time-right optimization of metal additive manufacturing processes. Simufact Additive is developed for the analysis of laser powder bed fusion (L-PBF) processes, which are also known as selective laser melting (SLM). Simufact Additive covers the main manufacturing process chain, including Figure 20:

1. Building.
2. Cutting and removal of the support structures and plate.
3. Heat treatment/stress relief and hot isostatic pressing (HIP) processes.

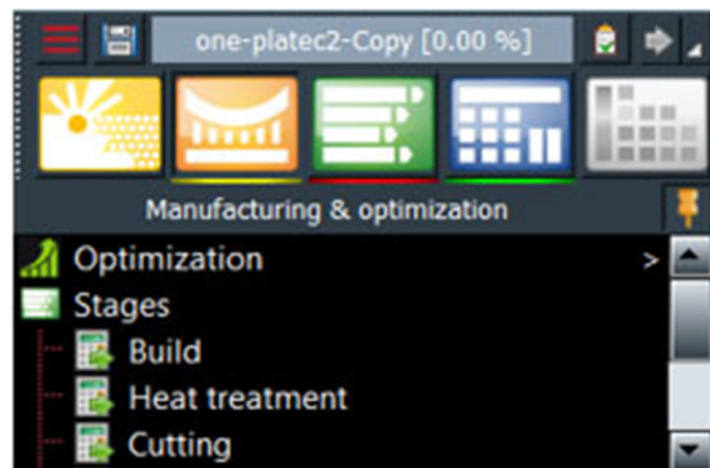


Figure 20. Illustration of Simufact manufacturing and optimization.

Simufact Additive helps you produce 3D printed parts right-first-time by:

1. Optimizing build-up orientation based on distortion, cost, build time, support volume, etc.
2. Optimizing part geometry to minimize distortions.
3. Minimizing residual stresses.

3. Results and Discussion

3.1. Results

3.1.1. LPBF Processing Parameters

Below, we illustrate the relationship between different LPBF processing parameters. Figure 21 shows the main effect plot from Minitab for maximum total distortion “MaxTD” with scanning width (SW), scanning speed (SS), and laser power (LP), along with a Pareto chart of the standard effects at a confidence level of 95%, $\alpha = 0.05$.

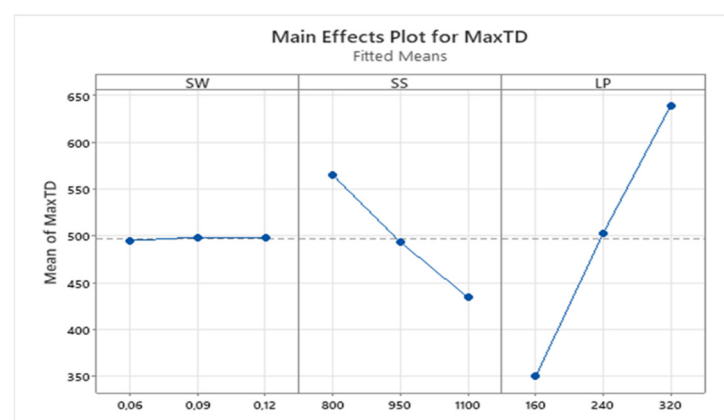


Figure 21. The figure above shows the main effects plot for total distortion (MaxTD) in μm .

From the above results, Figure 21, it can be seen that there is no interaction between the parameters with fitted means.

Regression Equation in Uncoded Units:

$$\text{Max_TD} = 353 + 958 \text{ SW} - 0.667 \text{ SS} + 3.395 \text{ LP} - 1936 \text{ SW} \times \text{SW} - 0.581 \text{ SW} \times \text{SS}. \quad (1)$$

The maximum distortion is expected to occur in the Z direction. From the graph below, it was found that laser power and scanning speed have a direct relationship in

reducing the maximum distortion, with lower laser power and scan speed resulting in the least distortion.

Regression Equation in Uncoded Units for Z direction—build direction:

$$\text{Max_ZD} = 346 + 970 \text{ SW} - 0.649 \text{ SS} + 3.334 \text{ LP} - 1960 \text{ SW} \times \text{SW} - 0.588 \text{ SW} \times \text{SS} \quad (2)$$

Scanning speed and laser power have the strongest effect on distortion: higher power increases energy input, raising residual stress; higher speed reduces energy density, lowering distortion.

Scan width showed minimal influence on distortion in our range (0.06–0.12 mm), as seen in the Pareto chart (Figure 22).

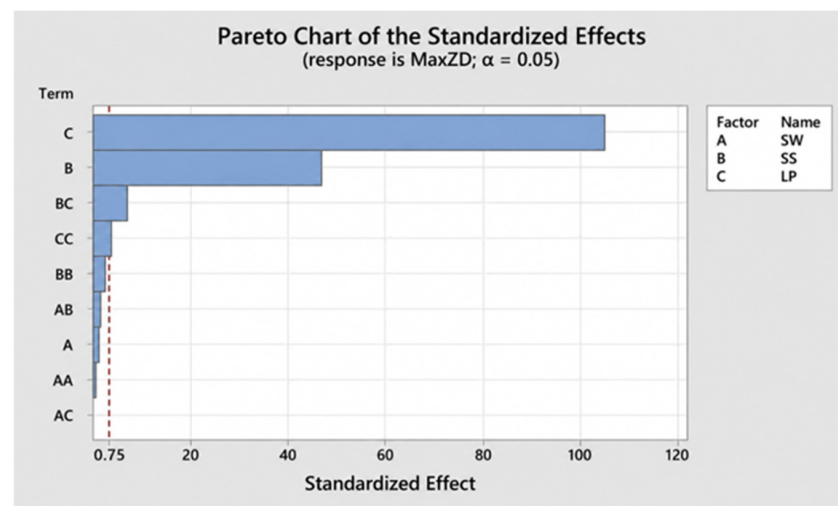


Figure 22. Pareto chart of the standardized effects (response is maximum Z direction distortion, Alpha = 0.05).

The interaction term ($\text{SW} \times \text{SS}$) indicates that at wider scan widths, speed effects are amplified.

3.1.2. Post-Processing Parameters

This section illustrates the Z-direction distortion, maximum distortion, and principal stress results, Figures 23–25. The as-built results are compared with the post-processing strategies of stress relief and hot isostatic pressing.

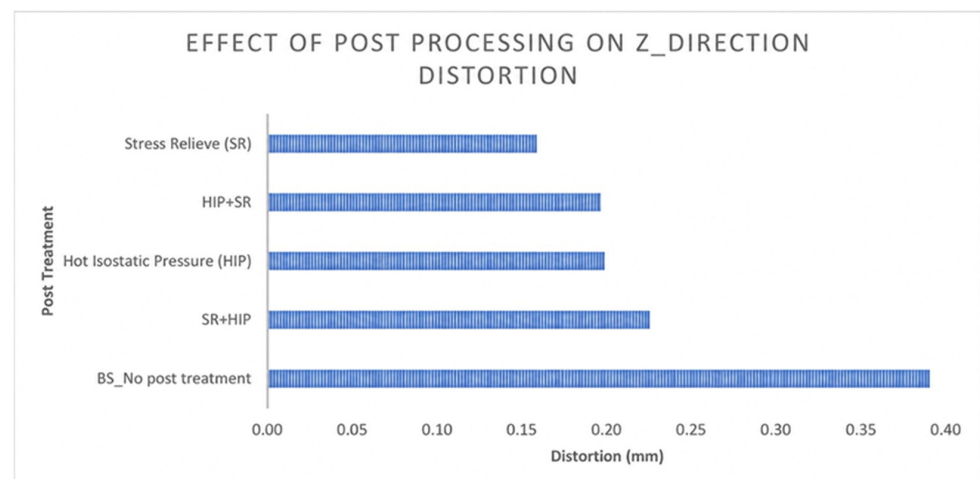


Figure 23. Z-direction distortion after post-processing.

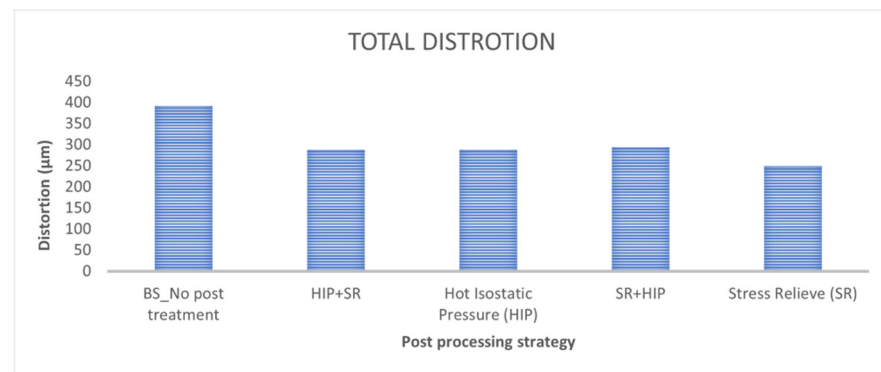


Figure 24. Results of total distortion after post-processing.

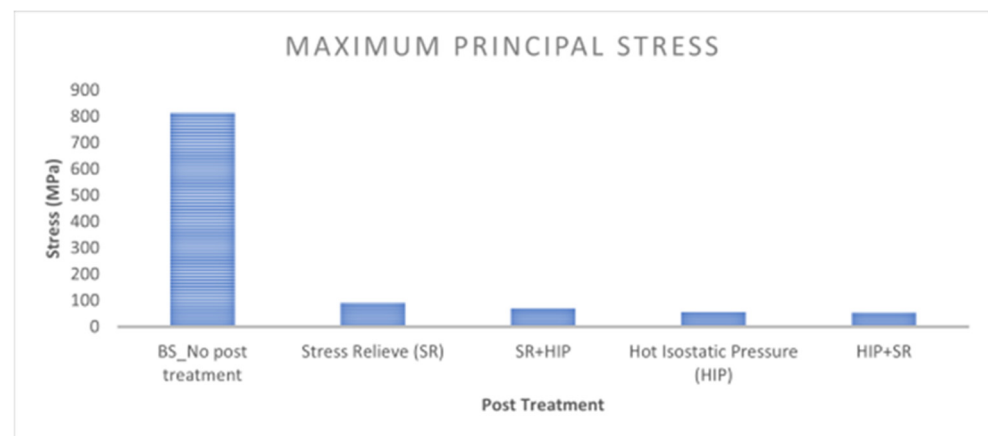


Figure 25. Results of total principal stress after post-processing.

3.1.3. Lattice Simulation

One of the typical lattice structures used in biomedical applications is the face-centered cubic (FCC), body-centered cubic (BCC), and diamond unit cells, available in sizes of 0.75 mm and 1.00 mm. These structurally different lattice structures were chosen to validate the processing parameters and post-processing parameters using these more complex structures. Figures 26–28, below shows the configuration of the 3D view in its constituent cell design.

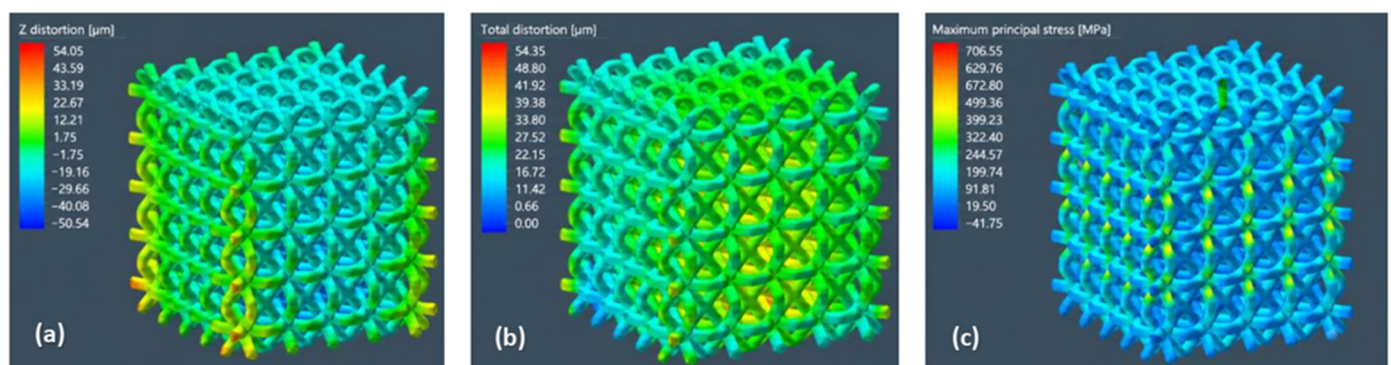


Figure 26. Schematic figure illustration of FCC lattice structure extracted: (a) Z distortion; (b) total distortion; (c) principal stress.

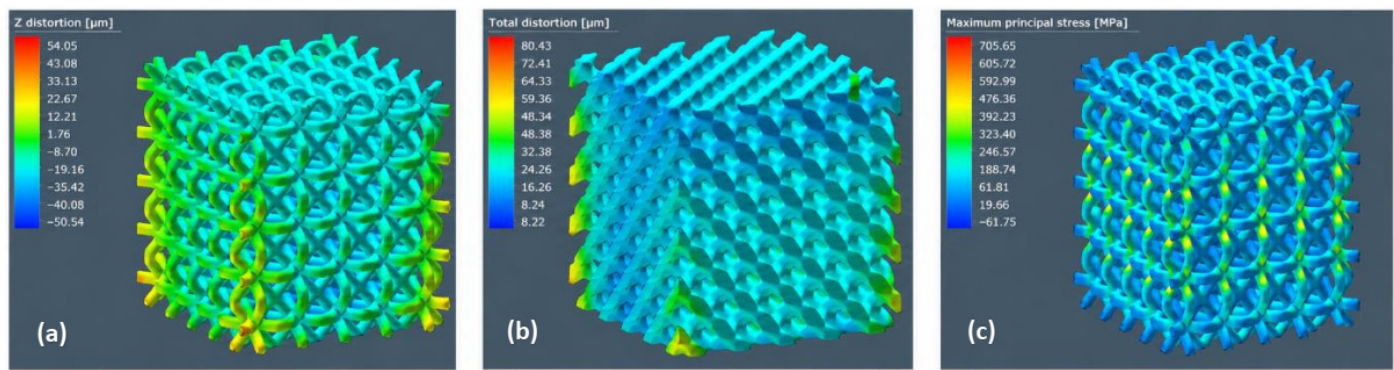


Figure 27. Schematic figure illustration of BCC lattice structure extracted: (a) Z distortion; (b) total distortion; (c) principal stress.

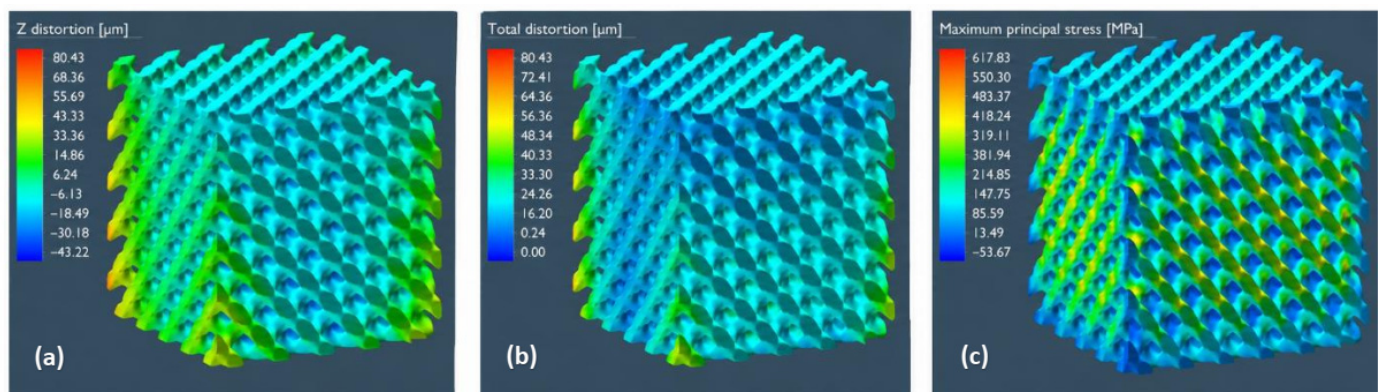


Figure 28. Schematic figure illustration of diamond lattice structure extracted: (a) Z distortion; (b) total distortion; (c) principal stress.

Note—Simufact (additive, welding, or forming) color scales for distortion analysis are used to visualize the magnitude of displacement (deformation) on a part, typically showing how much the geometry has deviated from its nominal CAD shape.

Here is the breakdown of the color scales:

- Red (Maximum): Indicates the highest level of distortion or displacement on the component. These are areas with significant deviation, often occurring at corners, edges, or areas with high thermal gradients.
- Yellow/Green (Moderate): Represents intermediate levels of distortion.
- Blue (Minimum): Indicates the lowest amount of deviation or displacement.

FCC, BCC, and diamond lattices were chosen for their self-supporting nature and differing strut arrangements, which influence heat accumulation and distortion.

Thicker struts (1.0 mm) show lower distortion due to higher stiffness and more uniform cooling.

The choice of lattice affects the surface area-to-volume ratio, thereby altering thermal gradients and residual stress distributions. The Table 4, below compares the mechanical properties obtained from simulation with those from experimental work [8].

The samples generated during the experimental work [8] were readied for both destructive (tensile testing) and non-destructive testing by Pressure-Influenced Powder (PIP). Table 5 above indicates that porosity affects the local compressive behavior and hardness of the LPBF samples, leading to significant uncertainty in yield stress, which varies from 990 to 1163 MPa. This was ascribed to the existence of pores in regions examined with decreased yield stress.

Table 4. Summary of lattice simulation for FCC, BCC, and diamond.

Unit Cell	Condition	Thickness (mm)	Max TD (μm)	X Distortion (μm)	Y Distortion (μm)	Z Distortion (μm)	Principal Stress (MPa)
FCC	As build	0.75	281.28	222.49	22.52	238.01	706.55
	Stress-relieved	0.75	235.55	111.28	52.48	385.68	174.83
	Stress-relieved	1.00	210.46	46.78	45.95	205.48	80.4
BCC	Stress-relieved	0.75	235.55	111.28	52.58	248.13	617.63
	Stress-relieved	1.00	228.44	72.78	50.59	1385.68	174.83
Diamond	Stress-relieved	0.75	228.44	72.78	50.59	223.56	617.63
	Stress-relieved	1.00	228.44	72.78	50.59	248.13	176.01

Table 5. Mechanical properties comparison for experimental work [8] with simulation results.

	PIP	Simufact
Yield Stress:	1163 MPa	Yield Stress
UTS:	1178 MPa	UTS: 975 MPa

4. Discussion

Enhancing processing parameters required examining elements such as scanning speed, width, and laser power in LPBF through Minitab, employing a sophisticated tool to discover ideal ranges. The goal was to reduce residual stresses and deformations after printing, with stress distribution showing tensile at the top/bottom and compressive in the Z direction. Simulation, particularly for stress relief, lowered maximum deformation and residual stresses assessed by the BCM approach [23].

Distortions in the X and Z directions were smaller than in the Y direction; a 0.75 mm FCC lattice's stress relief process reduced X distortion by 50%. EBDS analysis [24] indicates that heating at 650 °C for 4 h further alleviates internal stresses. Decreases of 17% in Z-stress and 16% in Z distortion were noted for the identical lattice. The results correlate closely between simulations and experiments, exhibiting comparable processing parameters—although some differed in the simulation.

The printed samples utilized laser power ranging from 100 W to 200 W, with the simulations suggesting an ideal value of 187 W. Each study type employed a layer thickness of 0.03 mm. An evaluation of distortion relative to scanning speed, width, and laser power indicates that increased laser power and scanning speed reduce distortion, while scanning width has a negligible impact. Each of the three parameters affects the curling angle, with the scanning width being the most important.

This study investigates how different combinations of stress relief and hot isostatic pressing stages affect distortion and residual stresses in the titanium alloy produced by LPBF. The primary results indicate that both effective and principal stresses are influenced by post-processing conditions, using as-built components as control references. While the literature thoroughly explores thermal and thermochemical treatments of titanium,

this study particularly focuses on the quantitative alterations in stress state resulting from these treatments.

The key observation is that the suggested post-processing techniques led to diminished distortions and reduced residual stresses in the material. Nevertheless, the voxel mesh analysis was lacking, as the effects of internal parameters needed calibration using empirical data. Depending on these findings, upcoming simulations will utilize a 0.35 mm voxel mesh guided by the existing simulation results.

The connection between residual stress and distortion is such that when residual stresses are tensile, the resulting distortions are compressive, and the reverse is true. This pattern is relevant to the distributions of both maximum and minimum values. Maximum distortion rises at reduced efficiency, whereas the minimum distortion grows when the scanning speed decreases. Efficiency, scanning rates, and beam width significantly influence the upper distribution limit. The accuracy of geometry and distortion in the printed samples is evaluated through the use of computer tomography (CT) scans.

The samples are scanned axially to minimize distortion and maintain uniform measurement conditions. The assessment concentrates on the highest deviation from the perfect form in the Z direction. Residual stresses are determined using X-ray diffraction. The area being irradiated is 1 mm², utilizing a collimator with a diameter of 1 mm for every measurement. Residual stresses are evaluated in both axial (aligned with the samples) and radial (perpendicular to the sample axis) orientations. The assessment adheres to ISO EN 15305:2008 [22] taking into account normal and tangential parts. Residual stresses are problematic as they encourage crack formation and shorten fatigue life. Reducing tensile residual stresses results in improved fatigue performance.

The influence of the parameters on the maximum distortion can be explained as follows: an increase in scanning speed and a wider scanning beam both lead to higher maximum distortion. Efficiency also factors in, as reduced efficiency results in increased maximum distortion. These connections suggest that modifying scan speed, beam width, and efficiency can directly affect the distortion results.

Earlier studies show that the simulation demonstrated compressive residual stress in the central area, whereas the upper and lower zones displayed tensile stress. The distribution of residual stress, evaluated by the observed angle of deflection and distortion in the simulation, was significantly greater in the Z direction than in the X and Y directions. This was likewise demonstrated to be true in the literature. The yield from tensile testing is approximately 878 MPa, in line with the specification. The yield stress obtained from the Simufact simulation falls within a range of 1174.1 MPa for the identical sample of FCC lattice structure with a strut thickness of 0.75 mm. The yield stress from the simulation and PIP aligns with the yield stress obtained from tensile testing (destructive testing) [16]. There is a relationship in decreasing internal stresses, minimizing porosity, and distortion among the methods applied in the simulation, compared to the findings from the experimental work performed. Importantly, there were no inconsistencies between the produced samples and the simulated outcomes; these small deviations are attributed to simulation assumptions (e.g., uniform powder properties or simplified support modeling) and experimental variability (e.g., local porosity or machine vibrations). In summary, the results from both the experimental research and simulation studies show that the values align closely with empirical observations, following a residual stress pattern that matches the earlier scientific literature.

The main stress was also analyzed in relation to scanning speed (SS), laser power (LP), and scanning width (SW), revealing that the principal stress is inversely related to itself. Principal stress, which includes the maximum and minimum principal stresses on a plane, is essential for understanding the behavior of materials under load, especially for brittle

materials. It helps identify potential failure areas and guides the assessment of material durability and deformation, making it important in fields like structural engineering, geomechanics, and materials science.

The Z displacement and deflection angle in the bridge cantilever method (BCM) simulation, following stress relief and hot isostatic pressure (HIP) post-processing, revealed that stress relief lowers the deflection by 30%, while HIP decreases the angle by 77%. Stress relief (650 °C, 4 h) allows dislocation rearrangement and stress relaxation via thermal recovery. HIP (920 °C, 100 MPa) closes pores via plastic deformation and diffusion, reducing stress concentrators and homogenizing residual stress. Combined treatments (HIP + SR or SR + HIP) further stabilize microstructure and minimize retained stresses. The simulated distortion (BCM angle) matches the experimental trends because both reflect stress relaxation after cutting from the baseplate.

The deflection angle measures the amount of residual stresses in the component following production. When the section is removed from the base plate, the bridge bends due to internal tensions. The surface at the base of the bridge's pillar shifts from its usual alignment and creates a curved angle, reflecting thermal stresses. The line that establishes the curling angle α° and the curling process is specified. Bending is caused solely by residual stresses in the X direction at the upper part.

5. Conclusions

Build simulation and optimization of LPBF processing and post-processing parameters helps to predict the formation of defects like irregular surfaces, distortions, and residual stresses. Build simulation also leads to more reliable manufacturing of complex designs like lattice structures, especially for biomedical applications. In this study, the effect of optimizing processing and post-processing parameters was investigated using the bridge curvature method. The results were validated by simulating more complex lattice structures. The total distortions, Z-direction distortions, and principal stresses were observed in as-built parts and stress-relieved parts, and found to be reduced with the application of stress-relieved post-processing strategies. The simulated results matched the parameters used in the experimental work, where layer thickness and beam width were kept constant, while scan width, scan speed, and laser power were varied. The results from destructive tensile testing indicate that the yield stress is slightly lower than the yield stress predicted by simulations and the Pressure-Influenced Powder (PIP) yield stress.

According to the results, the following conclusion can be drawn:

- (1) The processing parameters like scanning speed (SS) and laser power (LP) have a direct correlation in reducing the total distortion, Z direction distortion, and residual stresses as measured by principal stresses and normal stress. The scanning width was found not to affect the reduction in these defects.
- (2) The post-processing strategies of stress relief (SR) and hot isostatic pressing (HIP), and the combination of these strategies, have proven to reduce the internal stresses caused by rapid cooling and the presence of pores.
- (3) Build simulation helps to understand the local thermal conditions for better comparison between lattice structures and solid processing.
- (4) Build simulation allows for more reliable manufacturing of lattice structures used for biomedical applications.

In future work, research will focus on expanding from this work by expanding other processing parameters, which were kept constant, e.g., layer thickness, scanning strategy, etc. The LPBF process defects, such as residual stresses, porosity, and distortions, will be explored further to gain a deeper understanding of their impact on the produced parts' physical and mechanical performance.

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Conflicts of Interest: Author Anton Du Plessis was employed by the company Math2Market North America Inc. All authors declare no conflict of interest.

Abbreviations

AM—Additive Manufacturing, LPBF—Laser Power Bed Fusion, HIP—Hot Iso-static Pressing, SR—Stress Relieving, DoE—Design of Experiments, FCC—Face-centered Cubic, BCC—Body-centered Cubic, BCM—Bridge Curvature Method, CT—Computer tomography, PIP—Pressure-Influenced Powder.

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