

INVESTIGATING DEFORMATION AND RESIDUAL STRESS IN OVERHANG STRUCTURES PRODUCED BY LASER POWDER BED FUSION: AN EXPERIMENTAL AND THERMO-MECHANICAL SIMULATION STUDY

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In laser powder bed fusion (L-PBF), overhang structures are particularly vulnerable to warping and residual stress buildup due to inadequate thermal dissipation and limited mechanical support. While contour scanning is commonly used to improve surface quality, its effects on stress distribution and deformation mechanisms in overhang geometries are not fully understood. This study systematically investigates the impact of contour scanning on overhang components with angles from 45° to 60°, combining experimental tests with coupled thermo-mechanical finite element (FE) simulations. Overhang specimens made of 316L stainless steel were produced using an SLM 125HL system. Experimental results revealed that increasing the overhang angle led to greater deformation, surface defects, and melt-through occurrences. To better understand these behaviors, an FE model incorporating Goldak's double-ellipsoidal heat source and temperature-dependent material properties was developed to simulate the evolution of temperature and stress during contour scanning. Using a reduced-geometry approach—where the model is scaled down in all dimensions to represent three deposited layers (90 μm) over a 1 mm scan length, with volume hatching excluded—the simulation successfully replicates the qualitative deformation patterns and residual stress accumulation observed in the experiments. The simulation further reveals that localized thermal gradients around contour paths induce asymmetric warping at the free ends of overhangs and generate stress concentrations near constrained regions. These insights emphasize the pivotal role of contour scanning in the formation of deformation and residual stresses and provide valuable guidance for optimizing processing parameters to successfully fabricate unsupported overhang features in L-PBF.

Keywords: Laser Powder Bed Fusion (L-PBF); Overhang Structure; Residual Stress; Thermo-Mechanical Coupled Simulation; Contour Scanning Strategy; Warping Deformation.

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1. INTRODUCTION

Laser Powder Bed Fusion (L-PBF) is an advanced additive manufacturing technique widely used to produce metallic components with complex geometries. This process constructs objects layer-by-layer directly from computer-aided design (CAD) data, enabling exceptional design flexibility and high dimensional precision (Oliveira *et al.*, 2020; Volpato *et al.*, 2022; Chowdhury *et al.*, 2022). Nevertheless, the intrinsic characteristics of L-PBF—such as pronounced thermal gradients, rapid solidification rates, and cyclic heating and cooling—induce residual stresses and geometric distortions. These phenomena can detrimentally affect both the geometric fidelity and the functional performance of fabricated components (Xuan *et al.*, 2025; Mohanraj and Sahu, 2025).

Overhang geometries pose significant manufacturing challenges in L-PBF, yet the mechanisms by which process parameters—particularly contour scanning strategies—affect deformation and the formation of residual stresses in these structures remain poorly understood. Section 2 provides a comprehensive review of existing literature on residual stress modeling, experimental analysis of overhang deformation, and the impact of contour scanning, thereby highlighting critical knowledge gaps that motivate the present investigation.

To address these gaps, the present study combines experimental measurements with high-fidelity thermomechanical modeling to systematically examine how contour scanning strategies influence deformation behavior and residual stress evolution in L-PBF-fabricated overhang structures. A range of representative geometries with different overhang angles is analyzed. Furthermore, a layer-by-layer thermomechanical finite element (FE) model is established that incorporates a Goldak double-ellipsoidal heat source and temperature-dependent material properties. The model's predictions of stress and deformation during the contour scanning phase are validated through comparison with experimental data. Through this integrated approach, the specific effects of contour scanning—often obscured in bulk-scale models—can be isolated and systematically linked to the observed deformation and residual stress patterns.

The principal academic contributions of this study are summarized as follows:

- (i) Identification of the influence of overhang angles on warping tendencies during contour scanning;
- (ii) Elucidation of the relationship between thermal asymmetry and deformation mechanisms;
- (iii) Clarification of the predominant role of contour paths in the formation of residual stress “memory effects”;
- (iv) Validation of a high-fidelity thermomechanical model under multi-path scanning conditions.

This research provides theoretical foundations for optimizing build strategies in complex L-PBF structures and offers practical recommendations to improve the dimensional accuracy and structural stability of parts with overhang features.

2. LITERATURE REVIEW

2.1. Residual Stress Modeling in L-PBF

Residual stress prediction in L-PBF has been explored through various numerical techniques. Simplified methods like the inherent strain method (ISM) can effectively capture macroscopic trends in both deformation and residual stress, but their assumption of geometry independence becomes problematic as part complexity increases (Mohammadtaheri *et al.*, 2022). More sophisticated thermo-mechanical FE models provide higher accuracy: the maximum von Mises stress has been observed in the central plane of simple rectangular components (Li *et al.*, 2018), while notable stress asymmetry along the scanning direction has been identified in block geometries and confirmed via XRD measurements (Waqar *et al.*, 2021). However, both investigations were limited to basic geometries lacking overhangs or contour features. A comprehensive review further noted that such simplified geometries do not represent the complex features encountered in practical parts (Luo and Zhao, 2018). Collectively, these findings suggest that the thermomechanical behavior of contour zones in overhang structures—where localized thermal gradients and asymmetric constraints dominate—has not yet been thoroughly modeled. The mechanisms of thermomechanical coupling introduced by contour scanning remain poorly understood.

2.2. Experimental Characterization of Overhang Deformation

Experimental studies have consistently demonstrated that overhang structures are highly susceptible to deformation and surface defects. Among various geometric features, overhangs present pronounced manufacturing difficulties, primarily due to inadequate support beneath the deposited layers (Tao *et al.*, 2024; Pan *et al.*, 2024). During fabrication, overhang regions are constructed directly onto loose powder, which provides only minimal mechanical support and possesses a thermal conductivity substantially lower than that of solidified metal (Feng *et al.*, 2021). This disparity hinders efficient heat dissipation and induces significant thermal asymmetry. The resulting localized heat accumulation destabilizes the melt pool and leads to defects including keyholing, surface irregularities, and warping. Therefore, precise control of thermomechanical deformation and the development of optimized processing strategies are essential to ensure the structural integrity of L-PBF-fabricated overhang parts.

Warping and cracking in overhang regions are fundamentally attributable to the non-uniform accumulation of residual stresses. These stresses compromise geometric accuracy during production and can precipitate structural failure during subsequent processing or under operational conditions (Patterson *et al.*, 2017; Zhang *et al.*, 2018). Nevertheless, previous research has predominantly focused on bulk regions and infill strategies, often overlooking the unique formation mechanisms of overhang features. Achieving a comprehensive understanding of residual stress evolution is therefore imperative for the industrial advancement and reliability of L-PBF technology.

2.3. Contour Scanning Effects

Contour scanning, commonly used to improve surface quality and increase part density, involves applying focused energy to regions near free boundaries. This approach induces pronounced local variations in thermal and stress distributions, particularly within overhang regions that are subject to unique thermal constraints (Ren *et al.*, 2022; Buchenau *et al.*, 2023). In these scenarios, the thermal input from contour paths is likely to dominate the development of localized deformation and residual stress. However, the underlying thermomechanical response mechanisms associated with contour scanning during the fabrication of overhang structures remain insufficiently investigated.

3. EXPERIMENTAL METHODS

3.1. Process Conditions

To explore the geometric formation mechanisms of overhang structures in L-PBF, the present study designed and fabricated a series of overhang specimens with varying overhang angles ($\theta = 45^\circ, 50^\circ, 55^\circ, \text{ and } 60^\circ$). The geometric model of the specimen is depicted in Figure 1. All specimens were produced using an SLM 125HL metal additive

manufacturing system (SLM Solutions, Germany) equipped with a fiber laser operating at 1070 nm. The laser beam features a Gaussian profile with random polarization ($M^2 \approx 1.19$) and is focused through an optical system to achieve a spot diameter of approximately 70 μm . The entire build process was conducted in an argon atmosphere, with the chamber overpressure maintained at 17 mbar to ensure inert processing conditions.

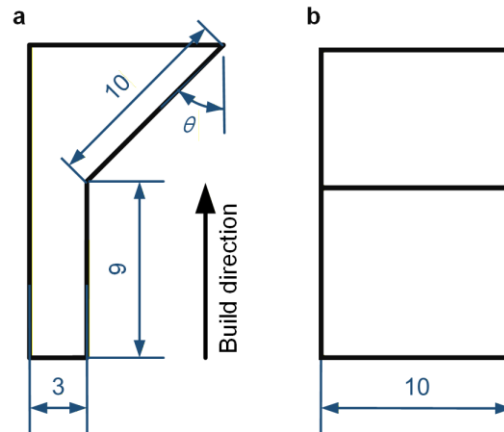


Figure 1. Geometry and dimensions of the specimens: (a) left view; (b) front view. (Units: mm; overhang angles $\theta = 45^\circ, 50^\circ, 55^\circ$, and 60°)

The feedstock material used in this study was 316L stainless steel powder supplied by Avimetal AM Tech Co., Ltd. (China), characterized by a particle size distribution ranging from 15 to 53 μm . The fabrication process adhered to a standardized set of parameters established by the equipment manufacturer (see Table 1) and previously validated for producing high-density parts. When fabricating structures with substantial overhang angles, considerable deformation may occur. Consequently, the process was intentionally interrupted when the overhang region reached approximately 2 mm in height. This controlled termination allowed us to capture intermediate deformation behavior and provided valuable experimental data for understanding the formation mechanisms of overhang structures under extreme conditions.

Table 1. Process parameters and scanning strategies utilized in experimental procedures.

Parameter	Solid region (volume)			Overhang region (down skin)
	Interior hatch	Inner and outer contours	Fill contour	Inner and outer contours
Laser power (W)	200	100	125	100
Scan speed (mm/s)	800	400	500	1000
Hatch spacing (μm)	120	N/A	N/A	N/A
Scan strategy	Stripes, 10mm wide	N/A	N/A	N/A
Hatch rotation angle	33° after each layer	N/A	N/A	N/A
Layer thickness (μm)	30	N/A	N/A	N/A

Note: A support structure with a height of 2 mm was included at the base of each specimen.

3.2. Scanning Path Planning

In the manufacturer's recommended L-PBF scanning strategy, each processing layer comprises three concentric, closed contours arranged from the outermost to the innermost as follows: the outer contour, the inner contour, and the fill contour, as illustrated in Figure 2. The spacing between the outer and inner contours is 90 μm , and the distance between the inner contour and the fill contour is 80 μm .

For each layer, the region extending beyond the previous layer is supported only by loose powder and is therefore particularly sensitive to heat input. This overhang extension requires a reduced energy density and ultimately forms the down-skin surface of the overhang. The width of the extension is determined by the overhang angle θ . During contour scanning, the extension always falls within the contour zone, but the number of contours it covers varies with the overhang angle:

- (i) When $\theta \leq 30^\circ$, the extension is less than one contour width. All contours lie within the solid region and are scanned using the solid (volume) parameters.

- (ii) When $30^\circ < \theta < 60^\circ$, the extension corresponds approximately to one contour width. The outermost contour is scanned using the overhang (down skin) parameters, while the inner contours use the solid (volume) parameters, as illustrated in Figure 2b.
- (iii) When $\theta \geq 60^\circ$, the extension covers approximately two contour widths. Both the outer and inner contours are scanned using the overhang (down skin) parameters, as illustrated in Figure 2a.

The fill contour serves to transition between the contour and hatch regions and is always located within the solid region; therefore, it uses only the solid (volume) parameters regardless of overhang angle.

All contours are scanned in a clockwise direction. The scanning sequence is as follows (refer to Figure 2):

- (i) Outer contour using solid parameters (if applicable, i.e., when $\theta \leq 30^\circ$);
- (ii) Inner contour using solid parameters (if applicable, i.e., when $\theta < 60^\circ$);
- (iii) Fill contour (always uses solid parameters);
- (iv) Outer contour using down-skin parameters (if applicable, i.e., when $\theta > 30^\circ$);
- (v) Inner contour using down-skin parameters (if applicable, i.e., when $\theta \geq 60^\circ$);
- (vi) Hatch (volume).

The process parameters for each contour type are summarized in Table 1.

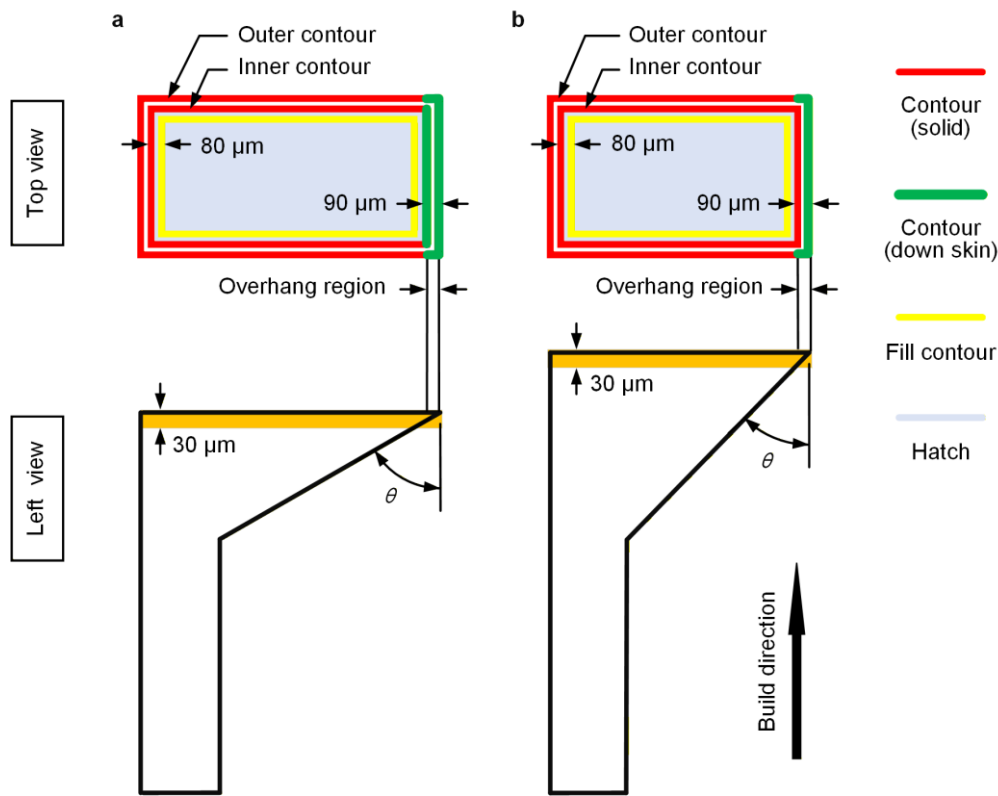


Figure 2. Contour configurations in overhang regions as a function of the overhang angle θ : (a) both the outer and inner contours are processed using the overhang (down skin) configuration when $\theta \geq 60^\circ$; (b) only the outer contour is subjected to the overhang (down skin) configuration when $30^\circ < \theta < 60^\circ$.

3.3. Post-Processing

After printing was complete, wire electrical discharge machining (WEDM) was used to separate the specimens from the substrate. The specimens then underwent mounting. Following this, the lateral surfaces of the specimens were carefully ground using progressively finer sandpaper, reaching up to 2000 grit, to ensure the surface quality met the standards required for subsequent analysis.

Subsequently, high-resolution optical microscopy was employed to acquire cross-sectional images of the specimens. The acquired images were processed utilizing ImageJ software to delineate the outer contours, including the overhang regions. This procedure encompassed several steps: image binarization, contour segmentation using the brush tool, selection of the region of interest using the “wand” tool, and saving the extracted contours as X - Y coordinate data. Finally, Origin software was used to generate line graphs to facilitate a comparative analysis between the actual and designed contours, thereby enabling a comprehensive evaluation of the results.

4. THERMO-MECHANICAL MODELING APPROACH FOR L-PBF FABRICATED OVERHANG STRUCTURES

4.1. Model Development

This study presents a directly coupled thermo-mechanical modeling approach to examine the effects of contour scanning on thermal stress, deformation, and residual stresses in overhang structures produced by L-PBF. The proposed modeling technique simultaneously solves the heat conduction and mechanical equilibrium equations, thereby capturing the bidirectional interactions between the thermal and mechanical fields. This integration enables accurate simulation of the intricate thermo-mechanical phenomena inherent in the manufacturing process. The essential procedural steps involved in the directly coupled thermo-mechanical analysis are illustrated in Figure 3.

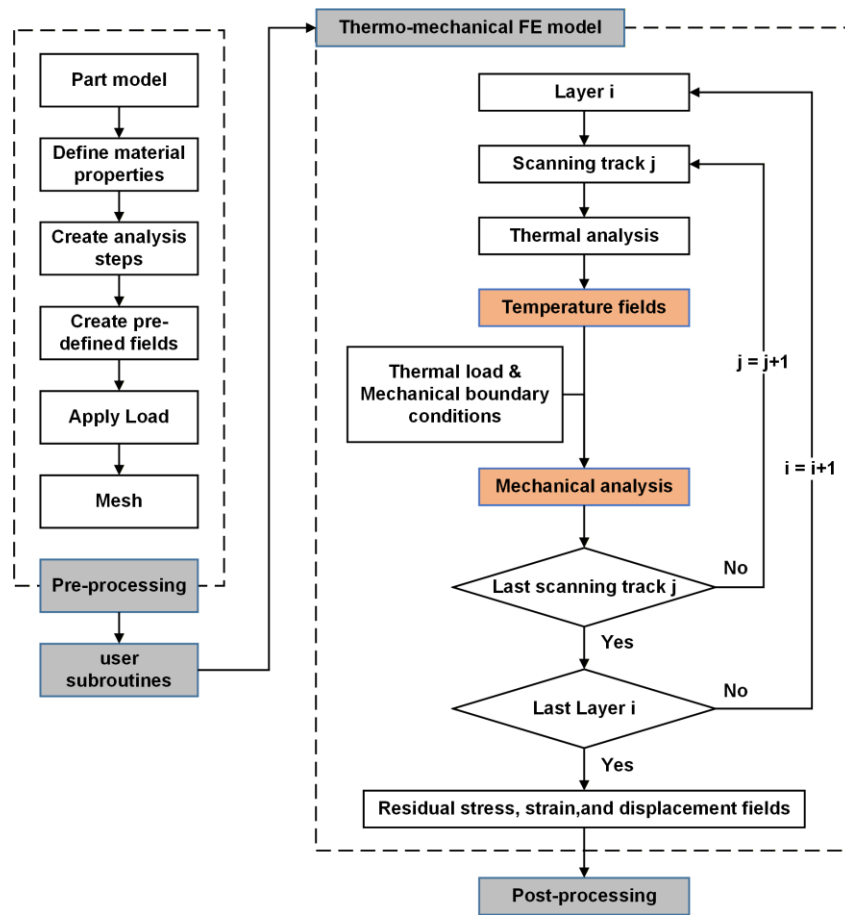


Figure 3. Flowchart depicting the thermo-mechanical simulation using the direct coupling method.

The FE model was constructed using the commercial software ABAQUS, with simulations performed on a high-performance workstation equipped with dual 32-core Intel XEON 8370C CPUs and 128 GB DDR4 RAM. To improve computational efficiency while maintaining predictive accuracy, a reduced geometry methodology was implemented in accordance with the approach described by Gao *et al.* (2024). In this approach, the part geometry is scaled down to preserve the relative proportions of cross-sectional dimensions and maintain the original overhang angle. The modeled domain represents three deposited layers, totaling 90 μm in height, with a scan length of 1 mm—sufficient to ensure a stable melt track along the scanning direction—as shown in Figure 4a. All laser process parameters, including power, scan speed, scan strategy, hatch spacing, and layer thickness, were kept consistent with the experimental conditions. Figure 4b provides detailed information on the model geometry, dimensions, and meshing strategy.

For the temperature-displacement coupling analysis, eight-node coupled thermo-mechanical hexahedral elements (C3D8T) were used. The mesh size was set to 15 μm $\times$ 14.3 μm $\times$ 10 μm in the overhang region and 15 μm $\times$ 15.1 μm $\times$ 10 μm in the solid region, resulting in approximately 22,500 elements in total. A mesh convergence study was conducted, and the results confirmed that the thermal and stress fields are adequately resolved at the adopted resolution. Given that the model focuses on qualitative trends in solid-state heat conduction, the current mesh is considered sufficient.

To ensure accurate boundary-condition modeling, the base of the solid section was fixed in all degrees of freedom, with $U1 = U2 = U3 = UR1 = UR2 = UR3 = 0$. This boundary condition is consistent with the experimental setup, in which the overhang structures were externally constrained only at the bottom of the solid region, with no lateral restraints.

Figure 5a illustrates the distribution of construction and substrate layers within the model, with black contour lines representing substrate layers, red contour lines indicating construction layers, and red dashed lines denoting the areas subjected to laser contouring. For a geometric model featuring an overhang angle of 55° , the contour scanning sequence consists of the inner contour for volume, the fill contour for volume, and the outer contour for the down skin. The adopted scanning strategy is depicted in Figure 5b. In the experimental setup, a layer-by-layer rotation of 33° was employed during solid-region scanning to promote uniformity of deformation and residual stresses across the part. Consequently, this study highlights the significant impact of contour scanning on these aspects. Within the contour-scanning regions, the same scanning sequence and process parameters used in the experimental procedures were implemented, while the solid-region scanning (the hatch for volume) was excluded from the simulation to minimize its impact on the deformation of the overhang structures and to accurately isolate the effects of contour scanning.

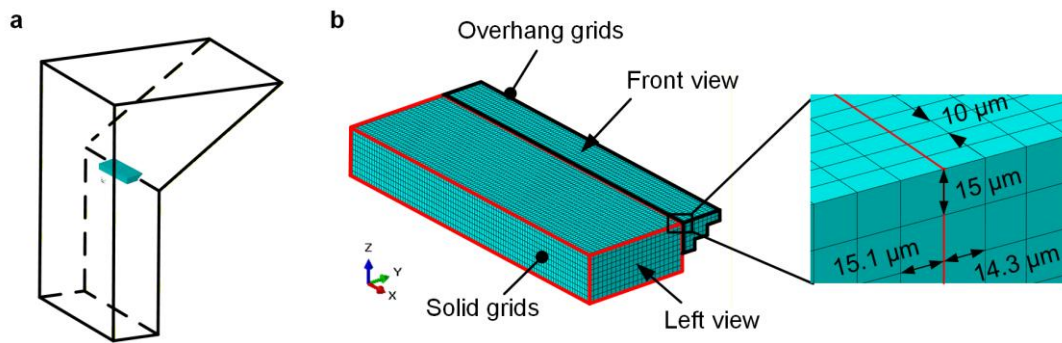


Figure 4. (a) Schematic illustration of the simulation model's positioning within the actual part; (b) geometry and mesh configuration of the FE model, highlighting the mesh sizes for the overhang and solid regions (the right panel presents a magnified view elucidating the specific mesh dimensions).

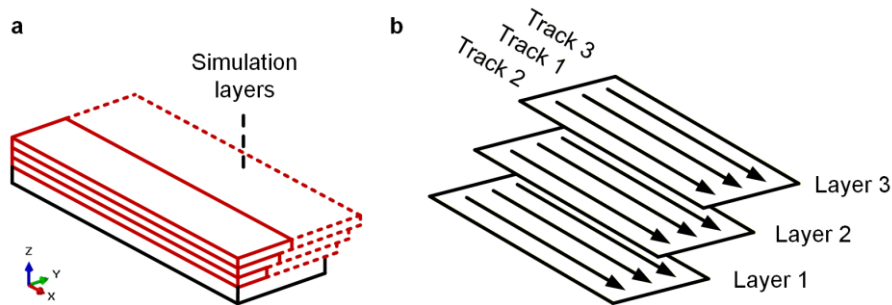


Figure 5. (a) Schematic diagram representing the simulation layers in the model (red dashed lines denote the areas subjected to laser contouring, while the solid red lines indicate the interior regions that remain untouched by laser contouring); (b) contour scanning strategy employed in the process.

The layer-wise nature of the L-PBF process was simulated using the “model change” technique. At the outset of the simulation, the entire geometry was defined with all printing layers initially deactivated. The first layer was activated at the beginning of the simulation, and each subsequent layer was sequentially activated after the preceding layer's laser scan was completed. In the actual L-PBF process, the inter-layer interval is typically set to 30 seconds or longer to ensure adequate cooling. Since our simulations showed consistent results for cooling times beyond 20 seconds, this shorter duration was adopted to improve computational efficiency. Both the initial and ambient temperatures were set to 25°C .

4.2. Heat Source Model

This study utilizes the Goldak double-ellipsoidal heat source model (Gao *et al.*, 2024; Waqar *et al.*, 2021) to accurately represent the laser's thermal energy characteristics. The spatial distribution of energy density was implemented using an ABAQUS user subroutine, DFLUX, written in FORTRAN. Figure 6 illustrates a schematic representation of the Goldak double-ellipsoidal heat source model.

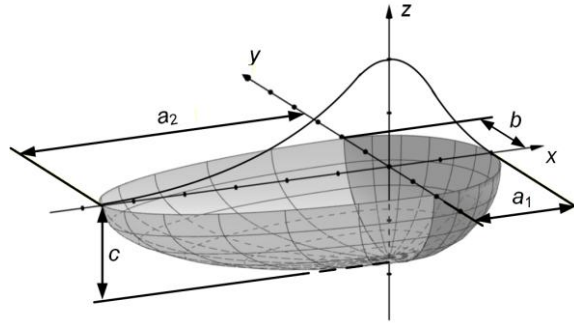


Figure 6. Schematic diagram of the double-ellipsoidal heat source model.

The spatial energy density function of the double-ellipsoidal model is defined as comprising two distinct regions:

(i) Front domain (melt pool formation zone):

$$q_1(x, y, z) = \frac{6\sqrt{3}\eta(f_1 Q)}{a_1 b c \pi \sqrt{\pi}} \exp \left[-3 \left(\frac{x^2}{a_1^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right) \right]. \quad (1)$$

(ii) Rear domain (melt pool solidification zone):

$$q_2(x, y, z) = \frac{6\sqrt{3}\eta(f_2 Q)}{a_2 b c \pi \sqrt{\pi}} \exp \left[-3 \left(\frac{x^2}{a_2^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right) \right]. \quad (2)$$

In equations 1 and 2, η represents the laser absorptivity, and Q denotes the laser power. a_1 and a_2 are the semi-axis lengths of the front and rear halves of the ellipsoid along the scanning direction (x -axis), with the condition $a_1 > a_2$ indicating that the energy is concentrated more in the front half. The parameters b and c correspond to the semi-axis lengths along the transverse (y -axis) and depth (z -axis) directions, respectively, signifying the melt pool width and depth. The coefficients f_1 and f_2 are the energy distribution factors for the front and rear halves of the ellipsoid, respectively, which can be expressed as:

$$f_1 = \frac{2a_1}{a_1 + a_2}, \quad (3)$$

$$f_2 = \frac{2a_2}{a_1 + a_2}. \quad (4)$$

4.3. Thermal Behavior

Assuming the material is isotropic, the thermal equilibrium equation is described by the classical three-dimensional heat conduction equation, which is based on the effective heat capacity method (Mohammadtaheri *et al.*, 2022; Ezekoye, 2016):

$$\rho C_{\text{eff}}(T) \frac{\partial T}{\partial t} = \nabla \cdot [k(T) \nabla T] + Q_{\text{laser}} - Q_{\text{loss}}. \quad (5)$$

In equation 5, ρ denotes the material density, $C_{\text{eff}}(T)$ represents the effective specific heat capacity that accounts for the effects of latent heat during phase change, T is the temperature, k is the thermal conductivity, t is time, Q_{laser} indicates the heat input from the laser, and Q_{loss} refers to the surface heat loss due to convection and radiation.

In the effective heat capacity method, the effective specific heat capacity $C_{\text{eff}}(T)$ is defined as follows:

$$C_{\text{eff}}(T) = \begin{cases} C_p(T), & T < T_s \text{ or } T > T_l \\ C_p(T) + \frac{L}{T_l - T_s}, & T_s \leq T \leq T_l \end{cases}, \quad (6)$$

where T_s and T_l are the solidus temperature (1375°C) and the liquidus temperature (1425°C), respectively, and L is the latent heat (2.7×10^9 J/m³).

At the onset of the laser scanning process (at $t = 0$), the temperature throughout the entire powder bed is uniformly distributed, set to the predetermined ambient temperature:

$$T(x, y, z, t)|_{t=0} = T_0(x, y, z). \quad (7)$$

The surface heat loss for the model, representing heat exchange between the model and its environment, is simplified to account for both convection and radiation. Thus, the surface heat loss during the L-PBF process is given by the following equation:

$$Q_{loss} = h(T - T_0) + \varepsilon\sigma(T^4 - T_0^4). \quad (8)$$

In equation 8, h is the convective heat transfer coefficient ($h = 18 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ (Denlinger and Michaleris, 2016)), ε is the emissivity ($\varepsilon = 0.45$ (Denlinger and Michaleris, 2016)), and σ is the Stefan-Boltzmann constant.

The temperature-dependent data of relevant thermophysical properties, including density ρ , specific heat capacity C_p , and thermal conductivity k , are summarized in Table 2.

Table 2. Temperature-dependent thermophysical properties of materials utilized in simulation analysis (Data from Ref. (Yu *et al.*, 2019)).

Temperature (°C)	Density ($\text{kg} \cdot \text{m}^{-3}$)	Thermal conductivity ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$)	Specific heat capacity ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)
26.85	7954	13.44	498.73
126.85	7910	15.16	512.12
226.85	7864	16.8	525.51
326.85	7818	18.36	538.48
426.85	7771	19.87	551.87
526.85	7723	21.39	565.26
726.85	7624	24.06	591.62
826.85	7574	25.46	605.01
926.85	7523	26.74	618.4
1026.9	7471	28.02	631.78
1126.9	7419	29.32	644.75
1226.9	7365	30.61	658.14
1372	7127	32.41	671.53

4.4. Structural Governing Equations

The total strain tensor $\{\varepsilon\}$ is defined by the following equation (Luo and Zhao, 2018; Irwin and Michaleris, 2016):

$$\{\varepsilon\} = \{\varepsilon^e\} + \{\varepsilon^p\} + \{\varepsilon^{th}\}. \quad (9)$$

In equation 9, ε^e denotes the elastic strain component, ε^p represents the plastic strain resulting from yielding behavior (in accordance with Drucker's postulate of plasticity), and ε^{th} corresponds to the thermal strain induced by the interaction between the coefficient of thermal expansion tensor α and the temperature field gradient $T(x, y, z, t)$.

For isotropic materials, the stress-strain relationships can be further described by the following expressions (Chen *et al.*, 2019):

$$\varepsilon_x = \frac{1}{E} [\sigma_x - \mu(\sigma_y + \sigma_z)] + \int \sigma'_x d\lambda + \alpha_e \Delta T, \quad (10)$$

$$\varepsilon_y = \frac{1}{E} [\sigma_y - \mu(\sigma_x + \sigma_z)] + \int \sigma'_y d\lambda + \alpha_e \Delta T, \quad (11)$$

$$\varepsilon_z = \frac{1}{E} [\sigma_z - \mu(\sigma_x + \sigma_y)] + \int \sigma'_z d\lambda + \alpha_e \Delta T, \quad (12)$$

$$\gamma_{xy} = \frac{\tau_{xy}}{2G} + \int \tau_{xy} d\lambda, \quad (13)$$

$$\gamma_{xz} = \frac{\tau_{xz}}{2G} + \int \tau_{xz} d\lambda, \quad (14)$$

$$\gamma_{yz} = \frac{\tau_{yz}}{2G} + \int \tau_{yz} d\lambda, \quad (15)$$

where E is the elastic modulus, G is the shear modulus, and μ is Poisson's ratio.

The Von Mises yield criterion (Calignano *et al.*, 2018) is employed to determine the equivalent stress. During the L-PBF process, the equivalent stress σ_e is calculated according to equation 16:

$$\sigma_e = \sqrt{\frac{1}{2}[(\sigma_x - \sigma_y)^2 + (\sigma_x - \sigma_z)^2 + (\sigma_y - \sigma_z)^2 + 6(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2)]}. \quad (16)$$

In equation 16, σ_x , σ_y , and σ_z represent the normal stress components in the X , Y , and Z directions, respectively, while τ_{xy} , τ_{yz} , and τ_{zx} correspond to the shear stress components in the XY , YZ , and ZX planes.

The temperature-dependent mechanical properties of the solid phase utilized in the simulation are summarized in Table 3 (Yu *et al.*, 2019). For temperatures above the liquidus, both the yield strength and tangent modulus are assigned negligibly small values to simulate a near-zero stress state, effectively representing the absence of mechanical resistance in the molten phase.

Table 3. Temperature-dependent mechanical properties of the material used in simulation analysis (Data from Ref. (Yu *et al.*, 2019)).

Temperature (°C)	Young's Modulus (GPa)	Poisson's ratio	Yield strength (MPa)	Tangent modulus (MPa)	Coefficient of thermal expansion
26.85	194.7	0.25	228.7	2283	1.48×10^{-5}
126.85	190	0.23	217.4	2023	1.56×10^{-5}
226.85	184.5	0.285	188.8	1765	1.63×10^{-5}
326.85	178.2	0.319	165.2	1531	1.69×10^{-5}
426.85	171	0.322	154.9	1363	1.74×10^{-5}
526.85	161.7	0.305	144.7	1195	1.79×10^{-5}
726.85	141	0.291	124.2	858.6	1.87×10^{-5}
826.85	127.3	0.24	111.1	693.6	1.90×10^{-5}
926.85	112.5	0.24	73.6	558.2	1.93×10^{-5}
1026.9	95	0.24	36	423	1.95×10^{-5}
1126.9	73	0.24	18.4	293.4	1.96×10^{-5}
1226.9	51	0.24	15	265	1.98×10^{-5}
1372	51	0.24	15	265	1.99×10^{-5}

5. RESULTS

5.1. Experimental Results

Figure 7 depicts the variation in the upper surface quality of specimens subjected to different overhang angle conditions. The findings indicate a progressive deterioration in surface quality as the overhang angle increases. At an overhang angle of 45° (refer to Figure 7a), a localized bright region is discernible on the upper surface near the overhang edge, although the affected area is relatively minimal. As the overhang angle is increased, more pronounced alterations in the specimen's surface quality are observed. Specifically, the bright band near the overhang edge becomes noticeably wider.

When the overhang angle reaches 55° (see Figure 7c), the bright region enlarges significantly, accompanied by clear evidence of melt-through. Notably, material loss is evident on the outer side of this bright region, near the overhang edge, causing the specimen's contour to deviate from the intended design and leading to an irregular surface morphology. This phenomenon of melt-through intensifies as the overhang angle increases further. At an overhang angle of 60° (refer to Figure 7d), severe melt-through is apparent along the overhang boundary, demonstrating a distinct trend of progressive deterioration extending from the initial end to the terminal end of the scanning trajectory.

Figures 8 and 9 illustrate the left and right views, respectively, of overhang-structured parts fabricated under varying overhang angles. Each figure includes both the designed contour and the actual contour obtained post-printing. To approximate the outer surface profile of L-PBF-printed overhang parts, reference fitting lines were manually drawn. These lines, guided by visual observation and geometric analysis, serve as a geometric reference for further comparison and analysis.

Two parameters were used to quantify part deformation: horizontal dimensional deviation and angular deviation. The horizontal dimensional deviation is defined as the Euclidean distance between the intersection point of the fitted lines—specifically, the overhang tip of the fabricated part—and the corresponding theoretical overhang tip as determined by the designed contour. In contrast, the angular deviation is characterized as the included angle between the fitted line and the theoretical overhang surface delineated by the designed contour.

The contours of most regions closely align with the intended profiles; however, significant deformation is observed primarily at the tip of the overhang. At this location, the deformation is characterized by an upward displacement on the left side (toward the fixed end of the overhang) and a downward sagging on the right side (adjacent to the free end of the overhang), as illustrated in Figures 8b and c. Notably, the overhang tip exhibits a substantially greater forming height than the design specification, resulting in a relatively slender appearance reminiscent of a thin-walled structure.

The measured horizontal and angular deviations at various overhang angles are illustrated in Figure 10. The results reveal that as the overhang angle increases from 45° to 60° , the horizontal deviation in the left view escalates from 0.459 mm to 1.678 mm, while the angular deviation rises from 6.3° to 19.2° . In contrast, deviations observed in the right view are comparatively smaller; the horizontal deviation increases from 0 mm to 1.005 mm, and the angular deviation increases from 0° to 9.6° . These findings collectively indicate that both horizontal and angular deviations increase with the overhang angle, with the deformation on the left side being significantly more pronounced than on the right. Notably, at an overhang angle of 45° , the contour observed in the right view shows no significant deviation, characterized only by minimal fluctuations in profile.



Figure 7. Surface quality variation of specimens under different overhang angle conditions: (a) 45° ; (b) 50° ; (c) 55° ; (d) 60° .

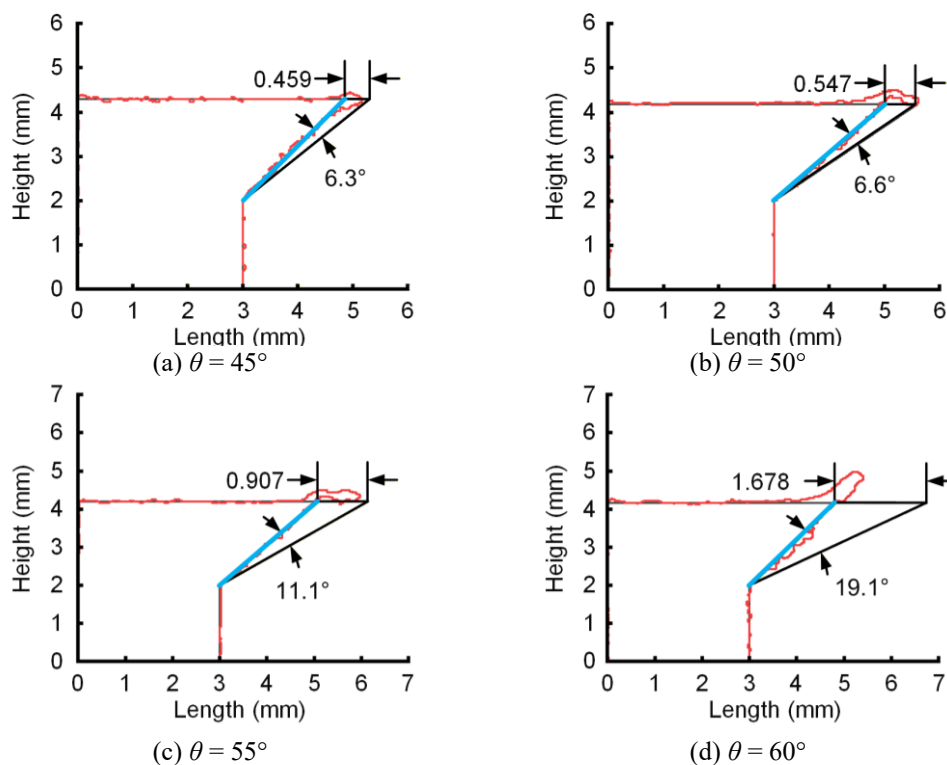


Figure 8. Outer contours of the parts in left view

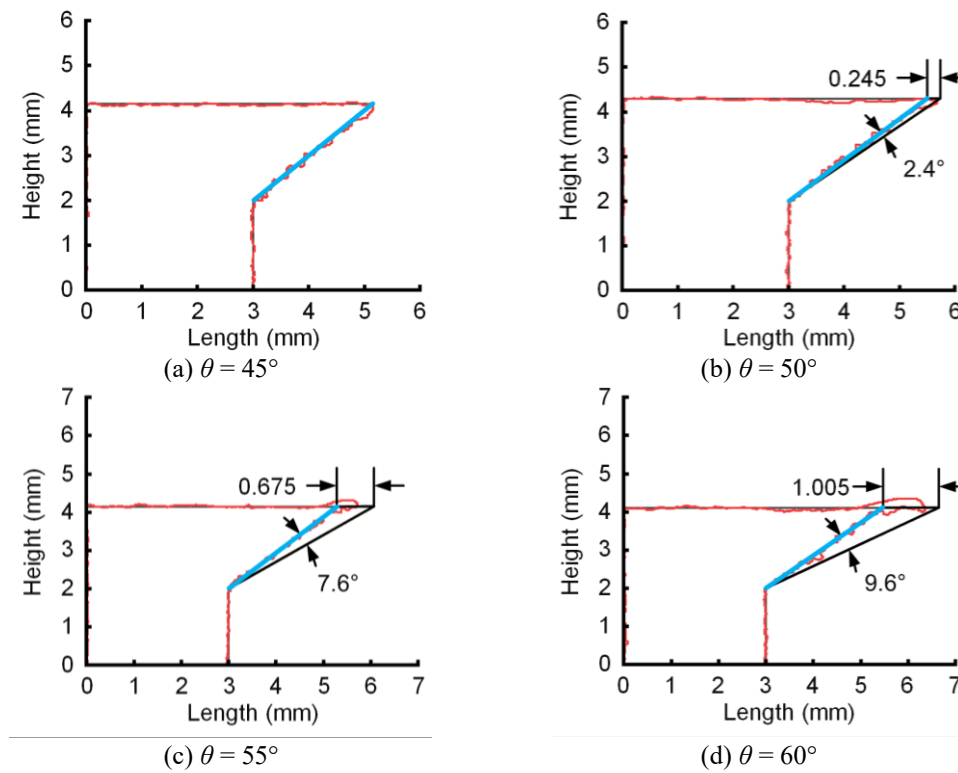


Figure 9. Outer contours of the parts in right view

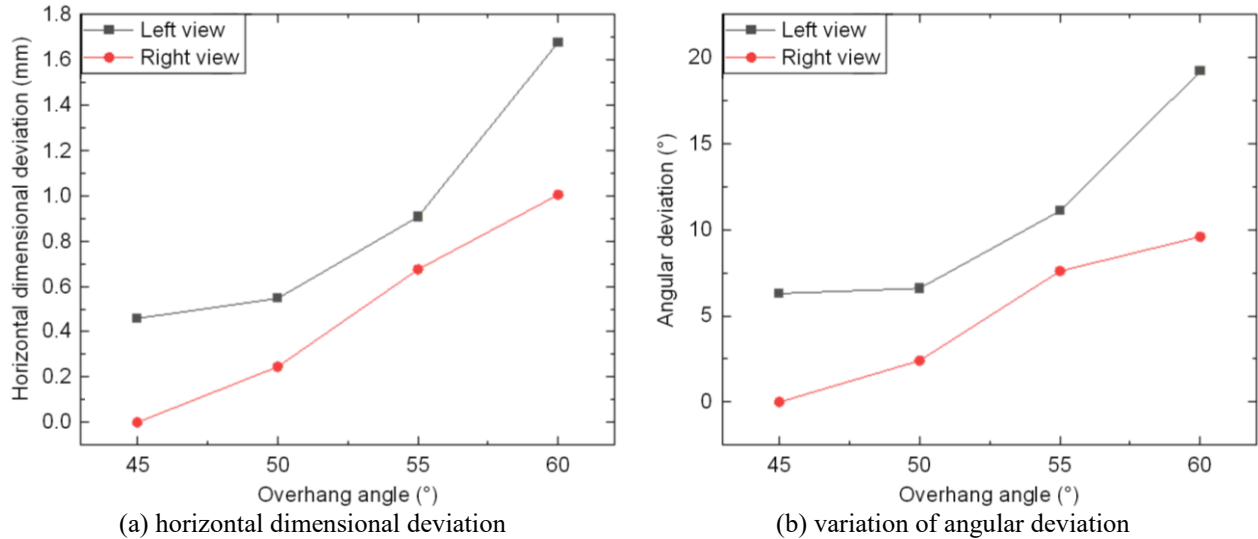


Figure 10. Comparison of deviations between printed and designed profiles as a function of overhang angle

5.2. Simulation Results

5.2.1. Thermal Field Analysis

The presence of a complex thermal gradient is a primary factor in generating high, intricate residual stresses during the L-PBF process. An extensive analysis of the evolution of the temperature gradient during the laser-scanning, heat-conduction, and cooling phases is essential for gaining insight into the mechanisms underlying thermal stress formation. Such understanding enables the development and implementation of effective strategies to reduce residual stress and deformation, thereby enhancing the overall quality of fabricated parts.

Figure 11 illustrates the temperature distribution characteristics of the part during the laser scanning of the third layer and the subsequent cooling phases. Regions where temperatures exceed 1375°C are classified as the melt pool and

are indicated in gray in the figure. For regions with temperatures below this threshold, the temperature spectrum is divided into 12 distinct intervals, each represented by a unique color. The rate of color transition effectively reflects the magnitude of the thermal gradient across the part.

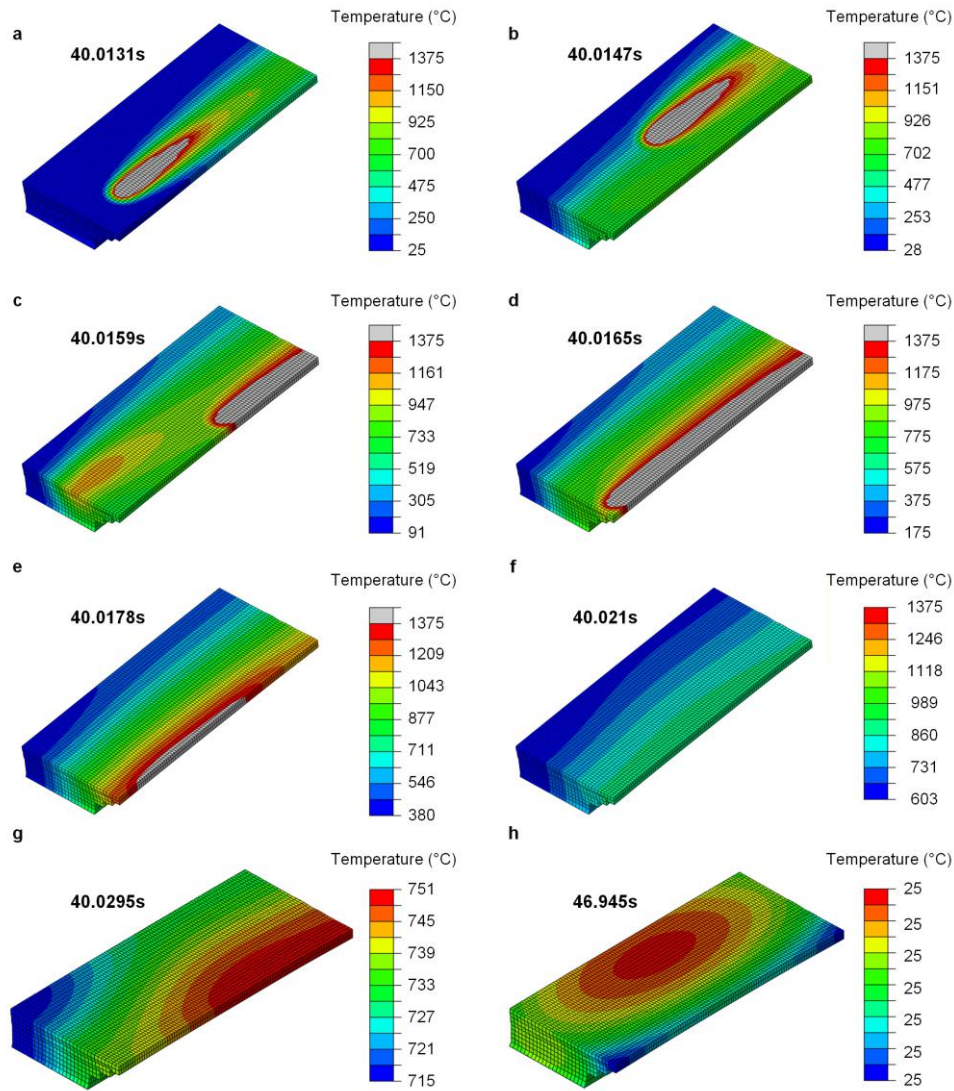


Figure 11. Evolution of temperature distribution during the laser scanning process of the third layer: (a) scan of the first track; (b) scan of the second track; (c, d) scan of the third track; (e-h) cooling phase.

In the scan of the first track (Figure 11a), a laser power of 100 W and a scanning speed of 400 mm/s were employed. The results reveal that the temperature gradient in the melt pool is maximized in the direction of laser motion and minimized in the opposite direction, resulting in a temperature gradient that decreases from the front to the back. This manifests as a thermal field resembling a comet-like trail.

The scan of the second track (Figure 11b) was conducted with a laser power reduced to 125 W and a scanning speed increased to 500 mm/s. In contrast to the first track, this scanning track is positioned further away from the lower surface (down skin) of the overhang. The resulting temperature distribution reflects a combination of the effects from both the first and second tracks. Specifically, on the side distal from the lower overhang surface, the temperature field exhibits a similar comet-tail distribution as observed in the first track. However, on the side proximal to the lower surface of the overhang, thermal accumulation from the first track results in the comet-tail feature being evident only in regions where the temperature exceeds 926 °C.

The scan of the third track (Figures 11c and d) was performed using a laser power of 100 W and a scanning speed of 1000 mm/s. During this phase, the melt pool is elongated and strip-like. Following this scan, the part transitions into the cooling stage (Figures 11e and f).

Throughout the cooling stage, the principal thermal behavior is governed by heat conduction from higher- to lower-temperature regions, as well as by heat exchange between the part and its surroundings. Simulation results indicate that at $t = 40.0178$ s, the minimum temperature within the part reaches 380 °C. At this juncture, a pronounced thermal gradient

is evident, indicating heat diffusion toward the surrounding materials. As the cooling process continues, the thermal gradient progressively diminishes. By $t = 40.021$ s, the peak temperature within the part decreases substantially to approximately 1000 °C, while the minimum temperature increases to 603 °C, resulting in a more homogeneous thermal distribution. By $t = 40.0295$ s, the thermal gradient approaches zero, suggesting an increasingly uniform internal temperature. At this time, the component attains a temperature of approximately 715 °C. Subsequently, it gradually cools toward ambient temperature.

5.2.2. Stress Evolution Analysis

Figure 12 illustrates the temporal evolution of thermal stress in the part during both the laser scanning and cooling stages. The time points selected for the stress distribution in Figure 12 align with those identified for the thermal field in Figure 11.

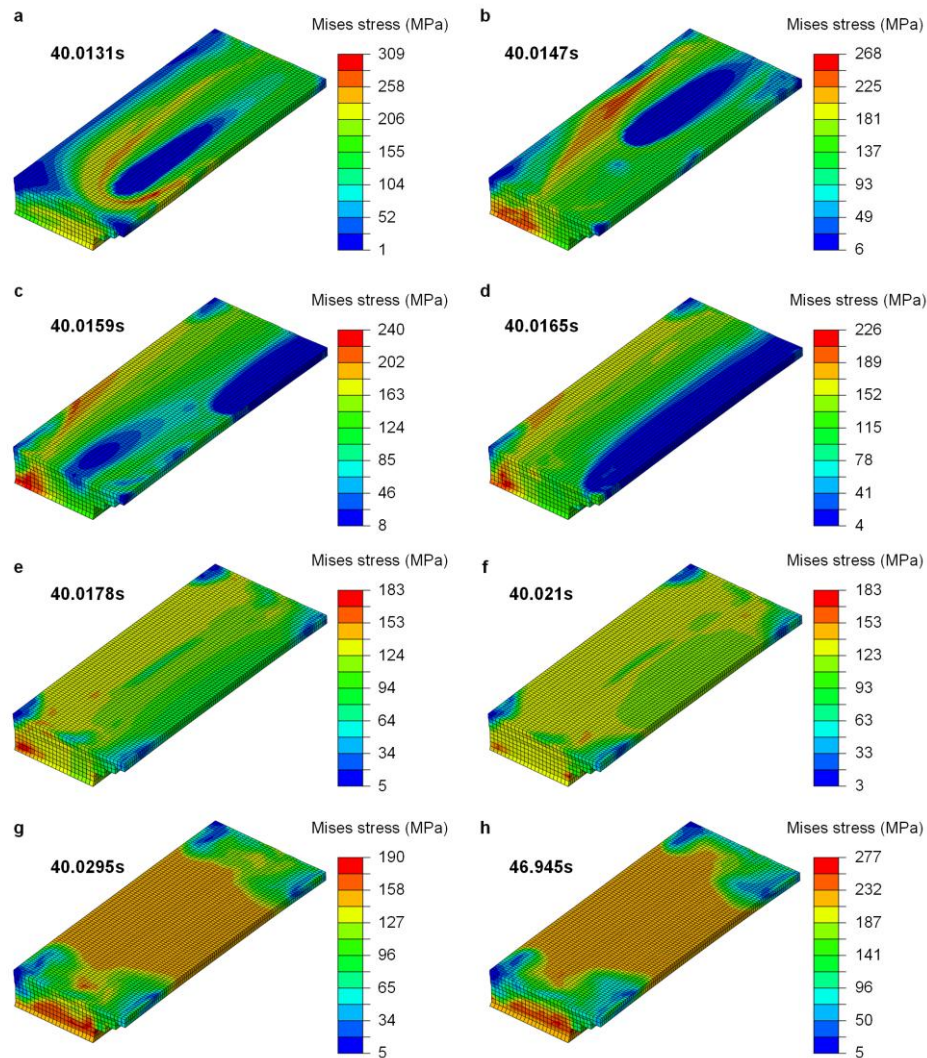


Figure 12. Evolution of stress distribution during the laser scanning process of the third layer: (a) scan of the first track; (b) scan of the second track; (c, d) scan of the third track; (e-h) cooling phase.

In Figure 12a, the stress distribution is examined during the scan of the first track in the third layer. A pronounced stress gradient is observed in regions immediately posterior to the melt pool, closely mirroring the corresponding temperature gradient. Notably, at the interface between the heat-affected zone (HAZ) and the unaffected zone, a band-shaped region of elevated thermal stress exists, with peak stress at this critical interface. This area aligns with the region that displays the steepest temperature gradient.

As illustrated in Figure 12b for the scan of the second track in the third layer, the thermal stress distribution retains residual influences from the scan of the first track. The peak stress region shifts from the front edge of the melt pool to the lateral side of the melt track, farthest from the overhang area. Furthermore, there is a notable decline in the overall

stress level within this high-stress region, decreasing from 309 MPa to 268 MPa. Significantly, during the scan of the third track, the absence of a distinct high-stress region surrounding the HAZ is observed. A comparative analysis of Figures 11c and d indicates that during scanning of the third track, regions in contact with the HAZ consistently exhibit temperatures exceeding 600 °C.

Figures 12e-h depict the evolution of internal stress within the part during the cooling phase. As shown in Figure 12e, in the initial stages of cooling, a clearly defined high-stress region (indicated in yellow) emerges at the end of the part, remote from the overhang. Additionally, a significant stress concentration (shown in red) occurs at the base of this region, with stress levels ranging from 168 MPa to 183 MPa.

Analysis of Figures 11e and f reveals that during the interval from $t = 40.0178$ s to $t = 40.021$ s, the internal temperature gradient decreases gradually, while the minimum temperature increases, suggesting a movement towards a more uniform temperature distribution across the part. This observation is further reinforced by Figures 12e and f, which depict a diminishing red stress-concentration zone and a gradual propagation of the yellow high-stress region towards the overhang.

By $t = 40.0295$ s, the internal temperature gradient approaches insignificance (with a temperature differential of less than 55 °C, as shown in Figure 11g). At this juncture, as represented in Figure 12g, there is a marked increase in the overall stress levels within the part, characterized by the emergence of a substantial high-stress area (143-170 MPa) in the central region, alongside a notable stress concentration (indicated in red) at the bottom near the overhang. In contrast, the four corners of the scanned layer display relatively low stress levels.

In the final cooling phase to ambient temperature (depicted in Figure 12h), the part's overall stress levels increase further. However, the stress distribution tends to stabilize, exhibiting minimal changes beyond this point.

5.2.3. Deformation Evolution Analysis

Figure 13 presents the evolution of displacement along the build direction (Z -axis), viewed from the left side of the model, during the third-layer scanning and subsequent cooling phases. In Figure 13a, at $t = 40.0131$ s, pronounced warping deformation is observed in the overhang regions of both the first and second layers. This deformation primarily results from the combined effects of contour scanning and subsequent thermal cooling, which together cause structural distortion. At this stage, however, the left end of the third layer exhibits minimal deformation. Analysis of temperature and stress distributions indicates that the thermal and mechanical effects generated by scanning the first track of the third layer are not sufficiently transmitted to the component's left end. As a result, this region experiences negligible thermal stress and deformation.

Figure 13b shows the displacement at the left end of the model at $t = 40.147$ s, which coincides with the scanning of the second track in the third layer. Comparative analysis of Figures 11-13 demonstrates that contour scanning in the third layer markedly affects the geometric configuration at the left end of the part. The Z -direction displacement reveals a substantial increase in warping deformation within the overhang regions of the first and second layers. Notably, the warping at the tip of the overhang increases from 0.0026-0.0036 mm to 0.0056-0.0073 mm. Additionally, the spatial extent of the warped region expands further inward from the tip of the overhang.

As shown in Figures 13c and d, scanning the third track in the third layer further intensifies warping deformation at the left end of the part, with the affected area extending even farther from the overhang tip. During the subsequent cooling phase (Figures 13e-h), there is a slight reduction in overall deformation as the temperature decreases; however, the overall distribution of deformation remains largely unchanged.

Figure 14 presents a frontal view of the displacement distribution following the completion of three-layer contour scanning. While the displacement components displayed are not absolute measures of deformation, their spatial variation qualitatively captures the asymmetric warping characteristics inherent in the overhang structure.

Figure 14a illustrates the total displacement distribution. The left side of the part exhibits noticeably greater total displacement than the right side. Furthermore, the first and second layers on the left side exhibit greater displacement than the third layer, indicating that deformation is more pronounced and accumulates in the lower layers. This observation is consistent with the progressive build-up of residual stress characteristic of the layer-by-layer additive manufacturing process.

Figure 14b displays the displacement distribution along the X -direction (scanning direction). Both lateral ends contract toward the center, with the contraction magnitude on the left side (terminal end) exceeding that on the right side (initial end). Moreover, the third layer exhibits less contraction than the first and second layers.

Figure 14c shows the displacement distribution along the Y -direction (transverse direction). The central region of the overhang contracts inward toward the fixed end, and this displacement progressively diminishes toward both lateral sides.

Figure 14d illustrates the displacement distribution along the Z -direction (build direction). The central region of the overhang displays the greatest upward displacement, with this magnitude progressively decreasing toward both lateral ends. Significantly, the left side consistently exhibits higher upward displacement than the right side. This asymmetric displacement pattern aligns with experimental observations, which show that the angular deviation at the terminal end is consistently greater than at the initial end across all examined overhang angles (Figures 8-10).

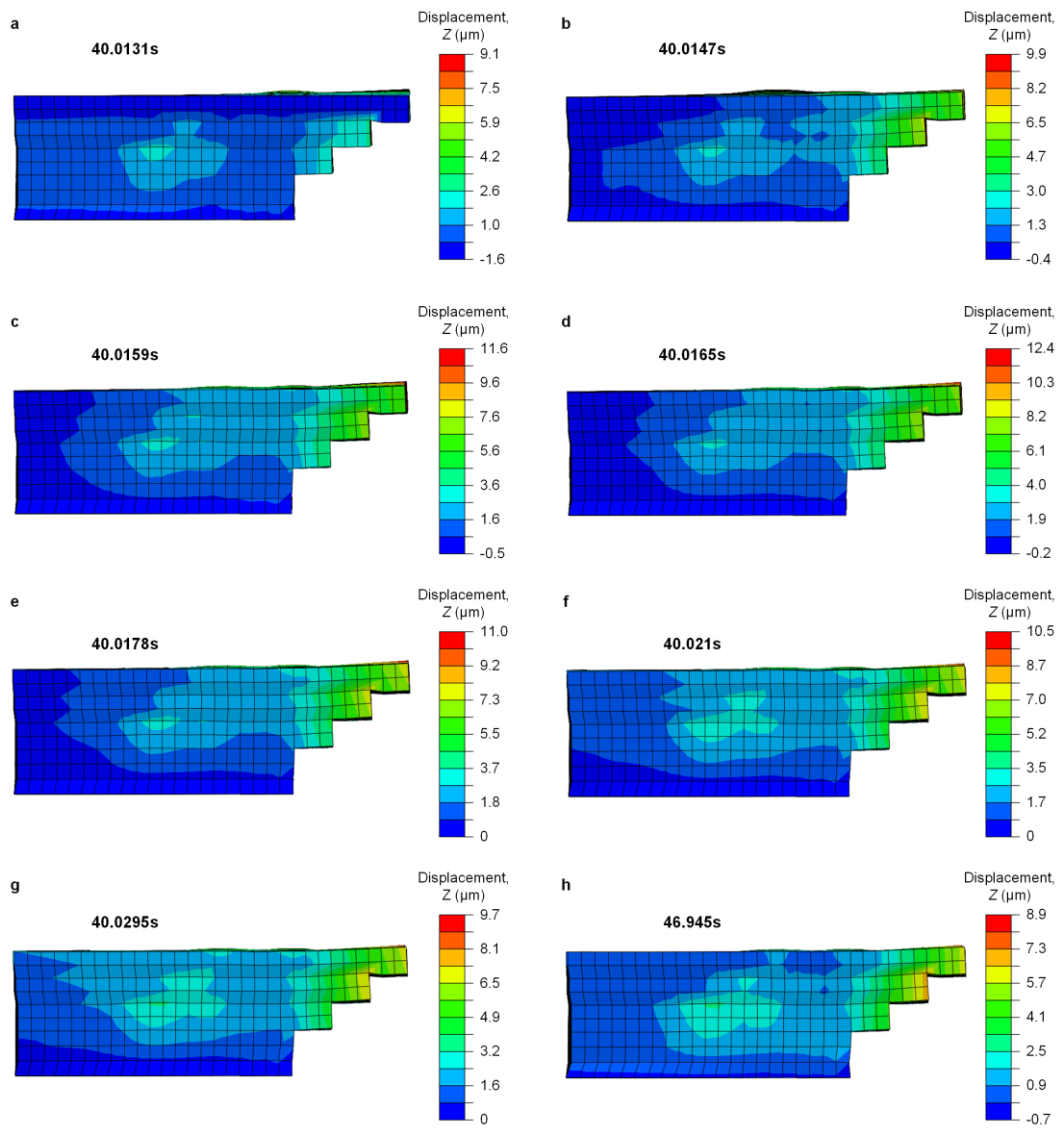


Figure 13. Displacement maps illustrate the evolution of Z-direction displacement on the left side of the part during third-layer contour scanning and subsequent cooling phases.

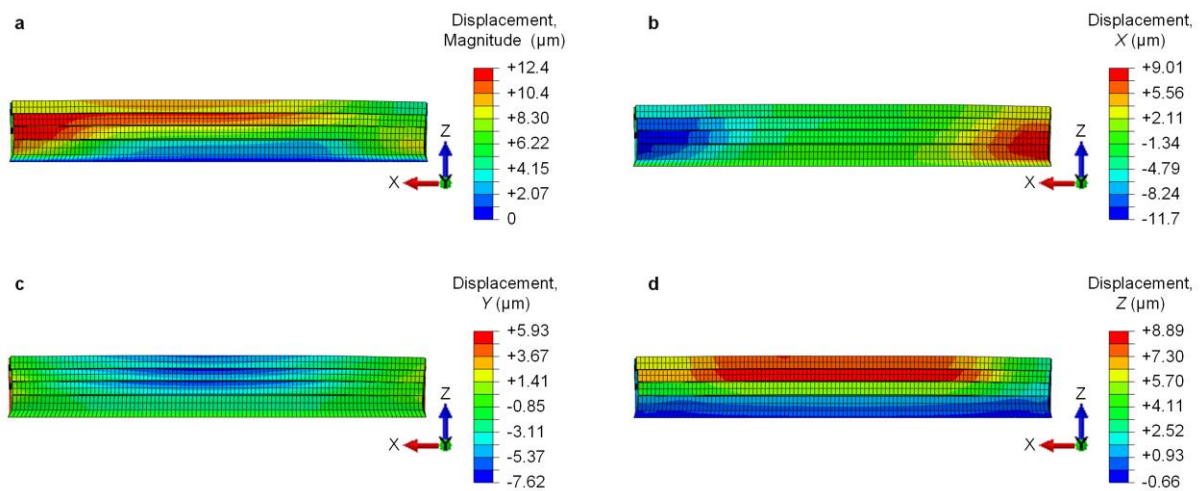


Figure 14. Displacement distribution of the part after three-layer contour scanning (front view): (a) total displacement; (b) displacement along the X-direction (scanning direction); (c) displacement along the Y-direction (transverse direction); (d) displacement along the Z-direction (build direction).

5.2.4. Coupled Analysis of Temperature and Stress Fields at a Representative Node

Figure 15 illustrates the evolution of temperature and stress at a representative node within the part during the three-layer laser scanning process, highlighting the fundamental characteristics of thermo-mechanical coupling and the trend of residual stress accumulation.

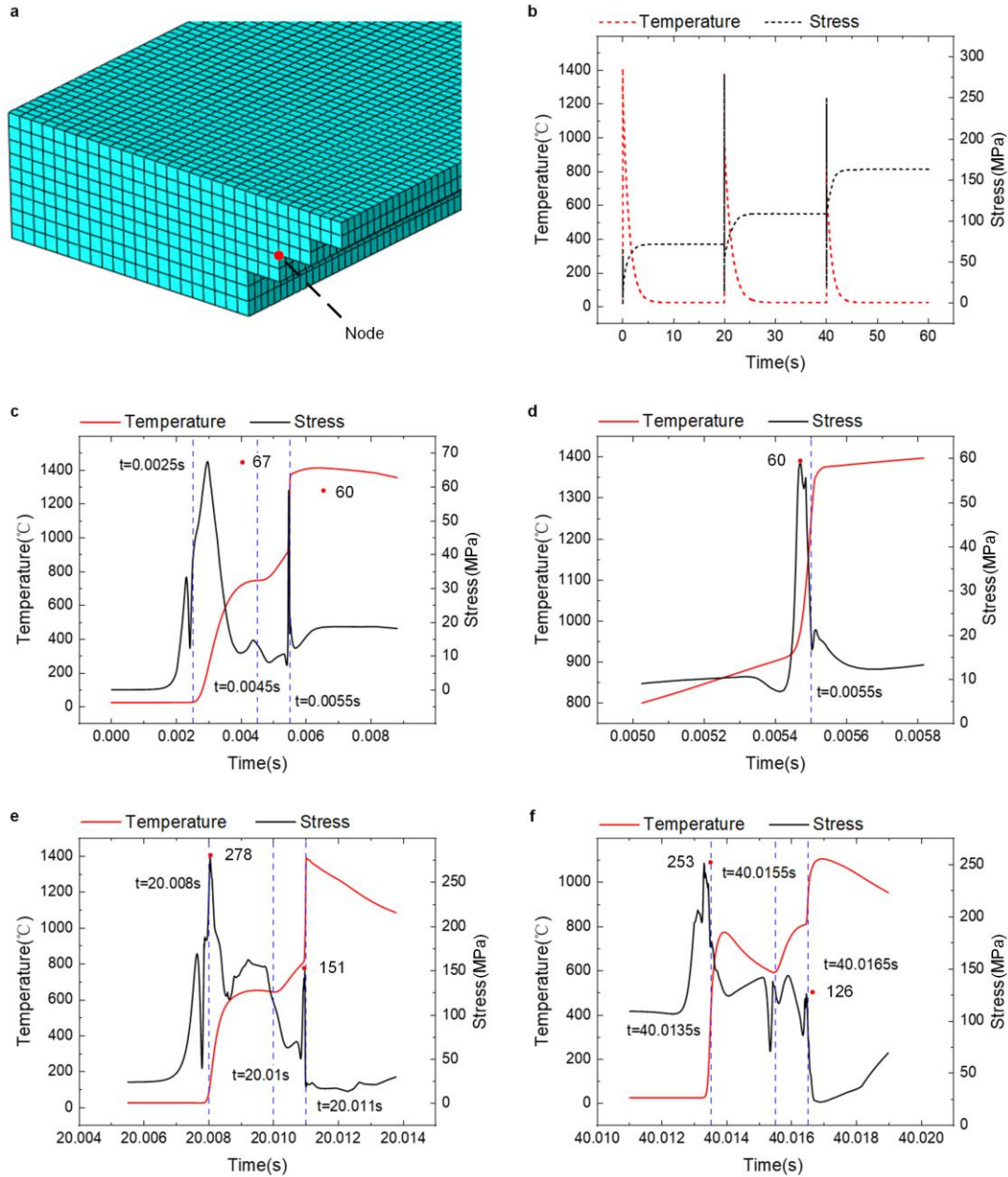


Figure 15. Evolution of temperature and stress at a selected node: (a) location of the selected node within the model; (b) overall evolution of temperature and stress throughout the entire scanning process; (c, d) details of temperature and stress evolution during the scanning of the first layer; (e) details of temperature and stress evolution during the scanning of the second layer; (f) details of temperature and stress evolution during the scanning of the third layer.

Figure 15a depicts the selected node's position within the part, situated in a boundary region subject to substantial influences from both thermal gradients and structural constraints, thus rendering it an appropriate candidate for localized response analysis.

Figure 15b presents the overall evolution curves of temperature and stress at this node throughout the three-layer scanning process. Each layer comprises three parallel scan paths, accompanied by a 20-second cooling interval between layers. This experimental setup effectively captures the implications of thermal history induced by layered scanning and delineates the cumulative pattern of residual stresses within multilayers. Throughout the process, the node experiences

three distinct temperature-stress cycles. During the first-layer scan, the node attains a peak temperature exceeding 1375 °C. However, as scanning progresses to the second and third layers, the maximum temperatures observed at the node gradually decline.

The stress evolution at the studied node during the first-layer scan exhibits characteristic staged behavior: a rapid increase, a brief decline, a subsequent rise, and eventual stabilization. Upon cooling to ambient temperature, the residual stress at this node stabilizes at approximately 72 MPa, slightly exceeding the peak thermal stress developed during heating. This observation suggests that some degree of stress accumulates during layer processing and that thermal stress is not fully relieved. Conversely, during scanning of the second and third layers, although stress follows a similar evolutionary pattern, the peak thermal stresses during heating considerably exceed the corresponding residual stresses upon cooling. This indicates that stress relief mechanisms become increasingly effective as additional layers are implemented. Further analysis reveals that while the residual stresses in the second and third layers are lower than their peak thermal stresses, the final residual stress continues to increase with additional layers, thereby confirming the cumulative effect of residual stress in multilayer laser scanning.

Figure 15c reveals a marked asynchrony between temperature and stress responses during the initial heating phase of the first-layer scan. Specifically, after the first-track scan, the temperature at the node does not increase significantly, suggesting that the laser-induced heat has not been effectively conducted to this region—an evident thermal conduction delay, as corroborated by the temperature distribution shown in Figure 11a. Despite the lag in the temperature response, the stress at the node rapidly accumulates during this interval, peaking at 67 MPa at $t = 0.00297$ s. This implies that local thermal expansion mismatches and structural constraints have already induced significant stress development.

As the scanning of the second and third tracks continues to deliver heat, the node temperature gradually rises. However, prior to $t = 0.00542$ s, the overall stress at the node shows a downward trend with fluctuations, indicating ongoing stress relief or redistribution. Figure 15d provides a detailed analysis for the time interval between $t = 0.0050$ s and $t = 0.0058$ s, highlighting the nuanced response behavior: between $t = 0.00545$ s and $t = 0.0055$ s, the node temperature experiences a sharp increase, while the stress rapidly escalates from $t = 0.00545$ s to $t = 0.00547$ s, reaching a local peak of 60 MPa before subsequently declining.

This phenomenon underscores substantial stress accumulation and release occurring even before heat has fully conducted to the node and the temperature has fully risen, thereby emphasizing a spatiotemporal decoupling mechanism between thermal conduction and stress response. The distinct asynchronous evolution observed during this phase provides critical insights into the transient thermo-mechanical behavior and the mechanisms underlying residual stress formation in multi-track laser scanning processes.

Figure 15e illustrates the instantaneous temperature and stress response of the node during the second-layer scan. The temperature evolution remains largely consistent with that of the first layer, showing a gradual rise across the three scan paths with no notable changes in peak temperature, indicating limited thermal accumulation in the early stages of multilayer scanning. In contrast, the stress response differs significantly from that of the first layer. Specifically, after scanning the first track in the second layer, the node stress rapidly rises to a peak of 278 MPa—substantially surpassing the 67 MPa peak observed in the first layer—indicating the onset of interlayer stress accumulation. Conversely, upon completion of the third-track scan in the second layer, the stress attains only 151 MPa, failing to exhibit the near-equal peak pattern characteristic of the first layer (67 MPa maximum and 60 MPa minimum, with a 7 MPa differential). This shows that the stress distribution during the second-layer scan is significantly reconstructed, leading to increased nonlinearity in the thermo-mechanical response and complex interactions with previous loading conditions.

6. DISCUSSION

This study synthesizes experimental observations with thermo-mechanical coupled simulation analysis to systematically examine the influence of varying overhang angles on the deformation behavior and residual stress development in overhang structures manufactured via the L-PBF process. The primary focus of the simulation is on modeling and analyzing the contour scanning of the parts, which is instrumental in understanding structural responses and the evolution of thermal stresses. The subsequent discussion is organized around several critical themes: geometric deviations, forming quality, the evolution of temperature-stress relationships, and the applicability of the simulation methodologies employed.

6.1. Correlation Between Geometric Deformation Evolution and Overhang Angle

Experimental results demonstrate that increasing the overhang angle significantly increases upward warping of the overhanging part. Both horizontal dimensional deviation and angular deviation consistently increase as the overhang angle grows, highlighting the sensitivity of geometric accuracy to process parameters. Notably, deformation observed from the left view is substantially greater than that from the right, revealing a pronounced asymmetry in the part's thermomechanical response.

This asymmetry primarily results from the clockwise contour-scanning sequence, beginning with the right side (initial end) and then the left side (terminal end). During scanning, thermal energy accumulates on the left side due to heat conducted from previously scanned regions. This accumulation elevates the local temperature, leading to a higher

peak temperature and consequently greater thermal contraction during cooling. As a result, the terminal end experiences greater warping, as consistently observed in both experimental results (Figures 8-10) and simulations (Figures 13 and 14). Although the simulations in this study are limited to contour scanning, the deformation patterns predicted in the overhang region correspond closely with experimental findings, thereby emphasizing the critical influence of the contour scanning strategy on geometric deviations.

6.2. Surface Quality Degradation and Melt-Through Behavior in Overhang Regions

The analysis of surface characteristics reveals that parts with larger overhang angles exhibit a significant expansion of shiny regions on the upper surface within the overhangs and pronounced melt-through, particularly at overhang angles of 55° and 60°. This behavior indicates an inadequate capacity for local heat dissipation, leading to localized overheating of the metal and potential material loss. Despite the simulation's omission of thermal input and vaporization processes during scanning of the interior tracks (volume hatch), the findings on the temperature field's evolution during scanning of the contour tracks highlight the significant impact of contour scanning on boundary heat accumulation. This effect is particularly pronounced in areas around the overhang's free end, where persistent high-temperature bands are more common. Such thermal behavior exacerbates defect development, including melt-through.

6.3. Thermal Stress Response Driven by Temperature Gradient

The thermal stress response induced by temperature gradients is a critical phenomenon in L-PBF processes. Coupled thermo-mechanical simulations of contour scanning reveal that a sharp temperature gradient emerges at the leading edge of the scanning direction during laser application. This sharp transition leads to notable stress concentration in the ensuing heat-affected zone. The spatial distribution of stress shows strong coupling with temporal variations, particularly during the cooling phase. Initial high-stress regions tend to expand toward the free end of the overhang as cooling progresses, ultimately resulting in a stable residual stress distribution. Although the contributions of the volume hatch to the overall thermal field were not included in this analysis, it remains clear that the contour scanning stage plays a predominant role in the evolution of thermal stress within the overhang region.

6.4. Evolution of Interlayer Residual Stresses

This study analyzes the thermo-mechanical evolution at a representative node during multi-path contour scanning, revealing a distinct asynchronous evolution with a four-stage pattern: "heating—accumulation—release—stabilization." The investigation demonstrates that the residual stress at this node increases progressively with the addition of layers. Notably, even within the confines of the contour portions, the thermal input contributes to a multi-layer stress "memory effect." As the number of scanning passes increases, the influence of residual stresses from preceding layers on the current layer's stress response becomes increasingly pronounced. These findings underscore the pivotal role of contour thermal history in the evolution of structural stresses, highlighting its importance for understanding the mechanical behavior of parts produced by L-PBF processes.

6.5. Applicability and Limitations of the Simulation Model

This study employed numerical simulations limited to the contour-scanning phase, deliberately excluding the volume-hatching stage. The computational framework also neglected the powder-to-solid phase transition and melt pool dynamics. These modeling constraints inherently limit the quantitative reliability of the resulting stress and thermal gradient predictions, necessitating careful interpretation of their absolute values.

Despite these simplifications, the qualitative findings—such as the systematic increase in warping with greater overhang angles, the observed asymmetry in deformation along the part, and the sequential buildup of residual stresses across layers—primarily reflect the influence of macroscopic thermal histories and geometric constraints imposed by the contour scanning protocol. These qualitative behaviors are therefore expected to remain robust, irrespective of the modeling limitations. The close correspondence between simulated and experimental deformation patterns provides additional validation for this conclusion. However, it must be acknowledged that the absolute stress values predicted by the simulations are likely underestimated relative to experimental results, owing to the omission of the volume hatching phase, which acts as a substantial additional heat source. To improve the quantitative accuracy of future simulation studies, it will be necessary to implement more comprehensive multiphysics approaches that capture the complex interplay among thermal, mechanical, and phase-transformation phenomena.

7. CONCLUSION

This study employs a dual approach, integrating experimental and numerical simulation methods, to examine the deformation behavior and thermomechanical response mechanisms of typical overhang structures during the L-PBF

process, particularly under varying overhang angles. The primary aim is to assess the influence of the contour scanning process on the structural integrity and residual stress distribution of the resulting parts. The key findings of the research are summarized as follows:

(i) Geometric deviations escalate with overhang angle:

Experimental results show that as the overhang angle increases from 45° to 60°, both horizontal dimensional deviation and angular deviation become markedly more pronounced in the overhang structure. Deformation is primarily concentrated at the free end and is distinctly asymmetric, with greater deformation consistently observed at the terminal end (left side) than at the initial end (right side). This asymmetric behavior is attributed to the scanning sequence, wherein heat accumulation at the terminal end, resulting from earlier scanning of the initial end, leads to elevated local temperatures and intensified thermal contraction during cooling.

(ii) Deterioration of surface quality with increased overhang angle:

At higher overhang angles ($\geq 55^\circ$), the upper surface of the specimens reveals a marked proliferation of shiny bands and melt-through defects. This deterioration can be attributed to localized heat accumulation in the thermal input region, compounded by inadequate support, thereby highlighting the harsh conditions for overhang formation in L-PBF.

(iii) Thermal field dynamics during contour scanning influence stress distribution:

The simulation analysis, focused on the contour scanning phase, elucidates the underlying thermal dynamics. It reveals that the sharp temperature gradient generated at the leading edge of the laser trajectory induces significant thermal stress, leading to potential regions of stress concentration.

(iv) Layer-by-layer accumulation of residual stress:

The evolution curves of residual stress at the representative node indicate layer-by-layer accumulation, with a pronounced influence of the thermal history during contour scanning. During multi-path contour scanning, the stress response is asynchronous and accompanied by a gradual increase in residual stress. It is confirmed that the thermal input of the contour scanning plays a dominant role in stress accumulation.

(v) Simulation provides insight into contour scanning impact mechanisms:

Although the simulation is limited to the contour-scanning stage, it shows qualitative agreement with experimental results for deformation trends, thermal stress distribution, and nodal response patterns. This alignment underscores the significant influence of the contour scanning process on the forming quality of overhang structures.

In conclusion, this research elucidates the critical role of the contour scanning strategy in the evolution of residual stress and deformation behavior in L-PBF parts, thereby providing a theoretical foundation for optimizing scanning paths to enhance forming accuracy.

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