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Effects of Z-axis Increment on Forming Quality and Microstructure Evolution of Inconel 625 fabricated by Laser Directed Energy Deposition

During the layer-by-layer stacking of laser directed energy deposition (LDED), interlayer thermal accumulation significantly alters convective flow patterns and actual layer dimensions, making the Z-axis increment (ΔZ) a critical factor for thermal-fluid stability. To elucidate this transient mechanism, this study investigates the thermo-fluidic and solidification behaviors of Inconel 625 alloy under varying ΔZ during fundamental double-layer deposition. A transient 3D model coupling heat transfer and fluid flow was developed using the Volume of Fluid (VOF) method and validated experimentally. Results reveal that an excessive ΔZ amplifies positive laser defocusing and temperature gradients, triggering intense Marangoni convection that destabilizes the melt pool free surface and increases porosity. Conversely, an optimized insufficient ΔZ of 1.10 mm mitigates the layer height loss induced by thermal accumulation, maintaining a stable laminar flow and continuous thermal input. Furthermore, ΔZ strongly dictates the local cooling rate and solidification morphology. An increase in ΔZ elevates the cooling rate, refining the primary dendrite arm spacing (λ) and enhancing local microhardness. Based on the rapid solidification thermal history, a modified Kurz-Fisher model, $\lambda = 45.72(G \cdot R)^{-0.28}$, was established. The characteristic exponent $n = 0.28$ quantitatively captures the unique solute trapping and intense interfacial thermal constraints inherent to the LDED process. This work elucidates the cross-scale relationship among thermo-fluid flow, layer-height mismatch, and microstructural evolution, providing a mechanistic basis for adaptive Z-axis control in LDED of Inconel 625.

Keywords: Laser directed energy deposition; Inconel 625; Z-axis increment; Forming Quality; Microstructure evolution.

1. INTRODUCTION

Laser Directed Energy Deposition technology (LDED) has demonstrated immense application potential in the manufacturing and repair of high-performance complex components, such as aero-engine turbine disks and gas turbine blades, owing to its narrow heat-affected zone, high metallurgical bonding strength, and exceptional geometric flexibility [1-3]. Inconel 625, a nickel-based superalloy, is one of the primary materials utilized in LDED technology due to its outstanding mechanical properties and corrosion resistance in high-temperature environments [4-7]. In practical layer-by-layer LDED, the programmed Z-axis increment must remain coordinated with the actual layer-height growth. A mismatch between them can alter the laser defocusing condition and interlayer remelting behavior, thereby affecting geometric accuracy and forming stability during the manufacturing and repair of Inconel 625 components. However, the LDED process involves highly complex

laser-powder-thermal interactions; the molten pool is microscopically small and exists for a fleeting duration, making it exceedingly difficult to observe its internal thermo-fluidic behaviors in real-time solely through experimental means, which poses a significant challenge for the precise regulation of process parameters [8,9]. Given the complexity of the rapid melting and solidification process, numerical simulation has emerged as a crucial tool for quantitatively evaluating molten pool evolution behaviors, as well as predicting and improving the solidification characteristics of deposited coatings [10,11].

Recently, research has been conducted extensively on the evolution of temperature and flow fields during the LDED process using numerical simulation techniques. Yong et al [12] accurately predicted the cross-sectional size evolution of the molten pool by combining vision detection with finite element simulation, confirming the effectiveness of numerical simulation in optimizing process parameters. Mo et al [13] further focused on the forming process of layer-by-layer thin-walled parts, deeply analyzing layer-by-layer stacking process characteristics and revealing the mechanisms by which residual heat from thermal accumulation affects the evolution of transient stress fields at different loca-

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tions. For layer-by-layer stacking, existing research predominantly concentrates on the influence of in-plane parameters such as laser power, scanning speed, and scanning path on forming quality. Jin et al [14] investigated flow field evolution in multi-track cladding based on multiphase flow theory, discovering that thermal accumulation becomes pronounced as cladding progresses, and the Marangoni flow on the overlapping side weakens with an increasing overlap ratio, thereby affecting the flatness of the cladding layer. Hao et al [15] established an inclined cladding model to study molten pool flow and final cladding morphology under various scanning paths on inclined substrates. They found that under inclined postures, overlapping claddings scanned in positive and negative y-directions were unlevel, whereas the cladding morphology produced by positive x-direction scanning with negative y-direction overlapping was the most stable. Although these studies have significantly advanced the understanding of thermal evolution and molten-pool behavior in LDED, their emphasis has mainly been placed on single-track geometry, multi-track overlap, scanning strategy, or thermal-stress accumulation. Comparatively limited attention has been paid to the vertical geometric matching between the programmed deposition-head displacement and the actual layer-height evolution during layer-by-layer stacking. In particular, the mechanism by which this mismatch changes the laser defocusing condition and subsequently affects molten-pool thermo-fluidic stability and interlayer forming quality remains insufficiently understood [16,17].

In conventional process planning, ΔZ is often prescribed as a fixed value based on the theoretical or experimentally measured height of an isolated single track, without explicitly accounting for the variation in actual layer height caused by interlayer thermal accumulation [18]. However, during actual deposition, interlayer thermal accumulation causes the molten pool volume to expand and convective melt flow to intensify, resulting in the actual layer height deviating from the prescribed increment. If ΔZ fails to compensate for this deviation, the resulting geometric mismatch directly alters the laser defocusing distance. This induces severe fluctuations in the effective heat input, which subsequently triggers thermo-fluidic instability, lack of interlayer fusion, and increased porosity [19,20]. Furthermore, variations in interlayer thermal cycling significantly impact the temperature gradient (G) and solidification rate (R) at the solid-liquid interface, ultimately dictating the growth morphology of microscopic dendrites [21,22]. Ferreira et al [23] investigated the microstructural anisotropy of Inconel 625 deposits, highlighting that the transient thermal history is the key factor influencing grain growth. Research by Gao et al [24] demonstrated that the G/R ratio at the trailing edge of the molten pool decreases significantly as thermal accumulation intensifies, which is the primary cause of the columnar-to-equiaxed transition. These studies demonstrate the strong dependence of solidification morphology on the local thermal history and solidification parameters. However, the cited studies mainly establish relationships between thermal conditions and microstructural evolution, whereas the role of a directly controllable

geometric process parameter, such as the Z-axis increment, has received comparatively less attention. More importantly, the coupling pathway from ΔZ mismatch to laser defocusing, molten-pool thermo-fluidic behavior, local solidification conditions, and finally dendritic evolution has not yet been quantitatively clarified during the initial transition from single-layer to layer-by-layer deposition [25,26].

In light of this, focusing on the Inconel 625 alloy, this study employs a combination of numerical simulation and experimental validation to establish a transient thermo-fluidic coupling model of the molten pool driven by surface tension, gravity, and buoyancy. Building upon the fundamental parameters determined via single-track experiments, the study primarily investigates the underlying mechanisms by which ΔZ mismatch alters the convective flow, temperature field distribution, and free surface stability of the molten pool during fundamental double-layer deposition. Concurrently, a microstructural prediction model is established based on rapid solidification theory to quantitatively reveal the regulatory effects of ΔZ on the primary dendrite arm spacing. The scientific merit of this work lies in establishing a quantitative cross-scale relationship among Z-axis mismatch, laser defocusing, molten-pool thermo-fluidic behavior, local solidification conditions, and dendritic evolution during the transition from single-layer to layer-by-layer deposition. From an engineering perspective, the study provides a physics-based criterion for selecting the Z-axis increment according to the actual layer-height evolution rather than simply adopting the isolated single-track height. The results can further support the development of adaptive Z-axis compensation and closed-loop height control strategies for the stable manufacturing and repair of Inconel 625 components by LDED.

2. EXPERIMENTAL AND NUMERICAL METHODS

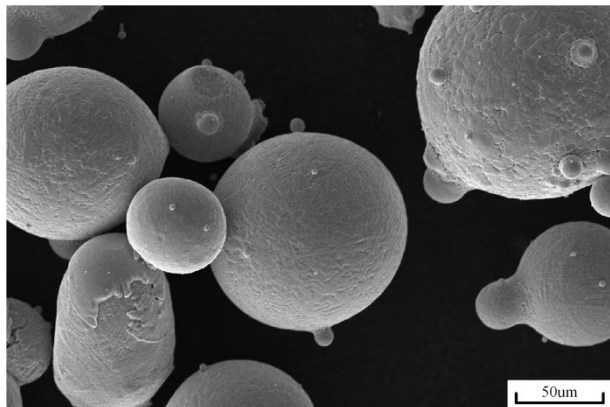
2.1 Experimental Materials and Setup

Spherical Inconel 625 (In625) powder was selected as the deposition material, and 45 steel with dimensions of 100 mm × 100 mm × 10 mm was used as the experimental substrate. Prior to deposition, the surface of the 45 steel plate was polished with sandpaper and wiped with alcohol to remove impurities. The deposition material was a nickel-based Inconel 625 superalloy powder produced by Jiangsu Xuzhou Vilari Company. The specific chemical compositions of both the Inconel 625 powder and the 45 steel substrate are detailed in Table 1. As illustrated in Fig. 1, the powder particles exhibit a predominantly spherical morphology with smooth surfaces, which is conducive to ensuring optimal flowability during the deposition process.

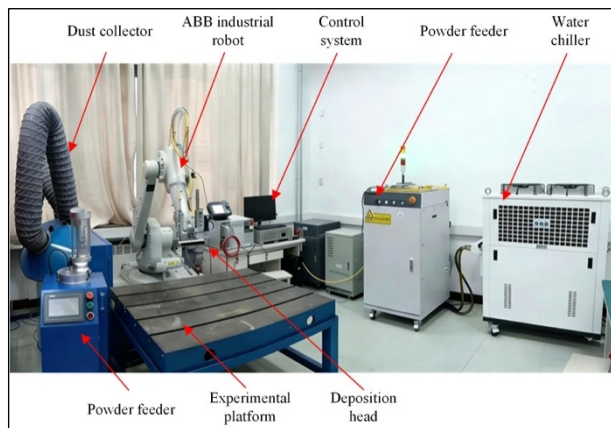
As shown in Fig. 2, the laser directed energy deposition system used in the experiment primarily consists of an ABB IRB1600 robot, a Raycus RLF-C3300 laser, an HW-05SF powder feeder, a Siemens S7-1200 PLC control system, and a CWFL-4000 dual-temperature dual-pump water chiller. The working water temperature of the chiller was kept constant at 25 °C.

Table 1. Chemical compositions of the Inconel 625 powder and 45 steel substrate (wt. %)

Material	Element	Ni	Cr	Mo	Nb	Fe	Si	Al	Ti	Mn	C
Inconel 625	Mass fraction	Bal.	21,5	9	3,65	4	0,5	0,4	0,4	0,5	-
45 steel	Mass fraction	0,3	-	-	-	Bal.	0,25	-	-	0,6	0,5

**Figure 1. Microscopic surface morphology of the spherical Inconel 625 powder**

After the deposition experiments, samples with dimensions of 15 mm × 15 mm × 10 mm were sectioned using wire electrical discharge machining. The cross-sections of the samples were sequentially ground using 400-, 800-, 1200-, 1500-, and 2000-grit sandpaper, and then polished to a mirror finish. Subsequently, the samples were etched using an aqua regia solution; after etching, they were wiped with alcohol and blown dry. For the characterization of cross-sectional morphology and dimensions, a DSX1000 digital microscope with a large depth of field was used for 3D scanning imaging of the deposition profile, and ImageJ software was employed to measure geometric dimensions such as height, width, depth, and contact angle of the deposition track.

**Figure 2. Laser Directed Energy Deposition experimental setup**

The macroscopic morphology and microstructural features of the deposited layers were thoroughly observed using an optical microscope and a Tescan 250 field-emission scanning electron microscope, respectively.

2.2 Numerical Simulation Framework

2.2.1 Simplifications and Assumptions

As schematically illustrated in Fig. 3, during the laser directed energy deposition process, heat transfer outside

the molten pool and the influence of the initial environment are involved, alongside internal energy transfer, heat and mass transfer, and solid-liquid phase transitions. Considering all these factors in the numerical simulation would result in massive computational loads and low efficiency. Therefore, to establish a stable and unified mathematical model for convection-diffusion and solid-liquid phase transitions, certain simplifications and assumptions were made for the deposition process:

(1) The laser energy distribution follows a Gaussian profile.

(2) The molten pool is treated as an incompressible Newtonian fluid with a laminar flow regime.

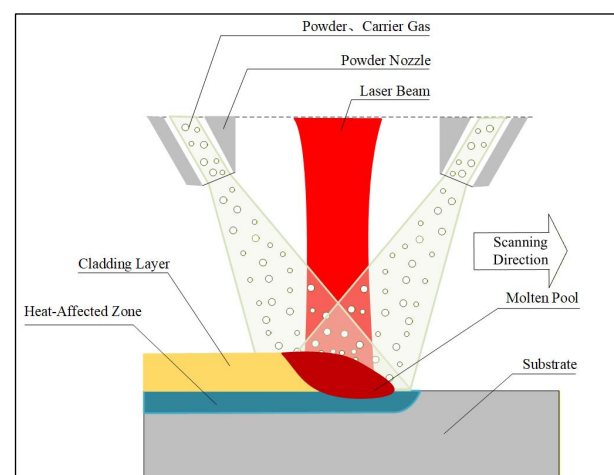
(3) The powder particles exhibit a Gaussian distribution.

(4) The effect of the shielding gas on the molten pool is ignored, and the mass and heat losses due to molten pool evaporation are neglected.

(5) The solid phase region, liquid phase region, and solid-liquid mushy zone are defined as continuous media; the solid-liquid mushy zone is assumed to be in thermal equilibrium and stationary.

2.2.2 Geometric Model

The overall dimensions of the computational domain are 20 mm × 20 mm × 10 mm (X × Y × Z). The thickness of the lower substrate is 3 mm, and the upper air domain is 7 mm thick. A larger air domain thickness facilitates subsequent computational analyses of layer-by-layer and multi-track stacking. Hexahedral meshing was performed using GAMBIT software, as illustrated in Fig. 4. To prevent numerical dissipation of the gas-liquid free interface in regions with sudden mesh transitions and to ensure the precision of dynamic molten pool tracking, a uniform high-resolution mesh was adopted in the forming area. The top plane of the model was defined as a pressure outlet boundary, while the remaining faces were set as wall boundaries.

**Figure 3. Schematic diagram of the laser directed energy deposition process**

The mesh consists of 303,408 elements and 317,900 nodes. The Pressure-Implicit with Splitting of Operators (PISO) scheme was employed for pressure-velocity coupling, utilizing a transient solution approach.

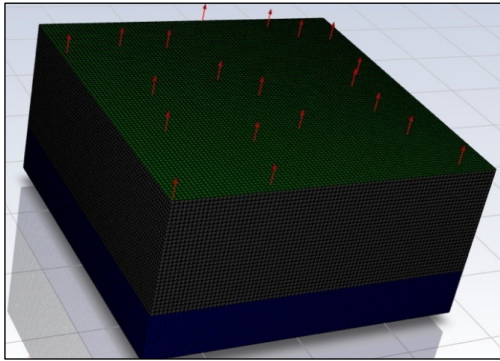


Figure 4. 3D mesh model of the computational domain

2.2.3 Moving Laser Heat Source Model

In the numerical simulation, a moving laser acts as the energy input source. Its heat source formulation and associated parameters must align as closely as possible with actual experimental conditions, particularly considering the spatial distribution characteristics of the energy density. The energy density of an actual laser beam typically exhibits a peak in the central region, attenuating gradually towards the periphery. Consequently, this study adopts a custom Gaussian distribution model to describe the volumetric laser heat source. Its mathematical model is expressed as Equation (1)[27]:

$$HS_n = \frac{P_n}{V_c \int_1^n \exp\left(-\frac{3r_n^2}{r^2}\right)} \exp\left(-\frac{3r_n^2}{r^2}\right) \quad (1)$$

2.2.4 Initial Conditions and Energy Boundaries

The initial environmental and substrate temperatures of the model are both set to $T_1=300$ K, and the initial flow velocity across the entire domain is zero. The boundary conditions are illustrated in Fig. 5: pressure outlets are set on the top and side surfaces of the computational domain to simulate an open environment; heat conduction and thermal radiation boundaries are applied to the bottom of the substrate; at the gas-liquid free interface, heat conduction, thermal radiation, and convective heat transfer are comprehensively considered.

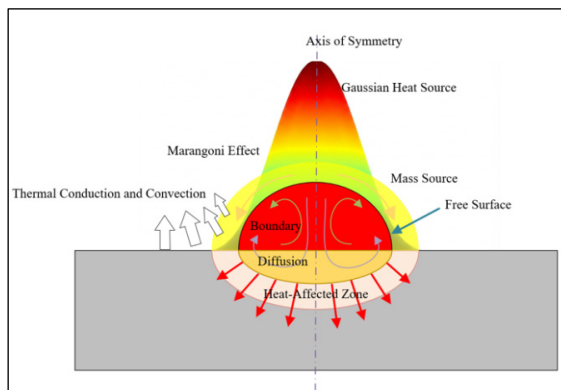


Figure 5. Boundary conditions for numerical simulation of laser directed energy deposition

To track the free liquid surface of the molten pool, the Volume of Fluid (VOF) method is utilized to accurately trace the dynamic evolution of the surface, and a gravity source term is incorporated into the momentum equation.

2.2.5 Material Properties

The thermophysical properties of Inconel 625 are shown in Fig. 6 [28].

3. Results and Discussion

The height, width, and penetration depth of the deposition track are fundamental geometric parameters for evaluating forming quality, while the contact angle, dilution rate, and aspect ratio can more comprehensively characterize the morphological features of the deposition track [29].

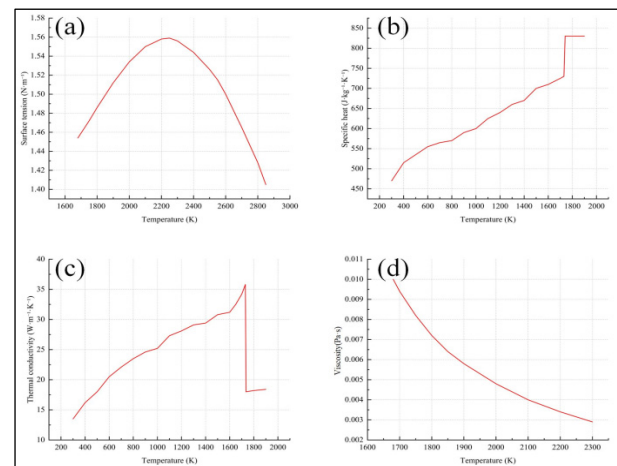


Figure 6. Thermophysical properties of In625: (a) surface tension; (b) specific heat; (c) thermal conductivity; (d) viscosity

Given that the aspect ratio and dilution rate directly determine the quality of interlayer metallurgical bonding in subsequent multi-track overlapping, this study focuses on these two key characteristic parameters as evaluation indicators to quantitatively assess the computational accuracy of the numerical model. Fig.7 illustrates the cross-sectional morphological features of the deposition track and the definition of its geometric size parameters.

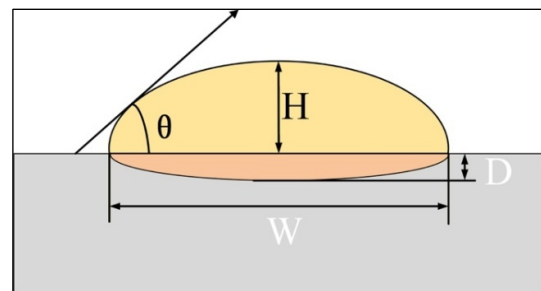


Figure 7. Schematic of the cross-sectional dimensions of a single deposition track

3.1 Optimization of Single-Track Deposition Process

To reveal the influence laws of key process parameters on the macroscopic morphology and dimensions of the

deposited layer, a 3D numerical model of single-track deposition was established, and an orthogonal experiment involving laser power (P), scanning speed (V_s), and powder feed rate (V_g) was designed. The specific parameters are listed in Table 2.

To eliminate the interference of unsteady processes during the start-stop stages on the forming quality, the experimental deposition time was set to 5 s. In the numerical simulation, to balance computational accuracy and efficiency, the deposition time was set to 1.5 s. As can be seen from Fig. 8, morphological transition zones exist at both the start and end of the simulated deposition track; therefore, the cross-section at the midpoint of the simulation time was selected for analysis to accurately characterize the steady-state morphological features of the deposited layer.

Corresponding to the 16 sets of orthogonal experimental parameters in Table 2, Fig 9 displays a comparison of the single-track cross-sectional morphologies obtained via simulation and experiment under various process conditions. The subplot labels (a) to (p) in the figure correspond to the orthogonal experiment numbers. To quantitatively evaluate the simulation accuracy, the parameters annotated on the right side of the figures are defined as follows: δ_H is the relative error of the simulated deposition height compared to the experimentally measured value, δ_W is the relative error of the simulated deposition width compared to the experimentally measured value, and A is the aspect ratio of the simulated deposition layer. As observed from the figures, the numerical model exhibits good prediction accuracy over a wide range of parameters. The maximum relative errors between the simulated values and the experimentally measured deposition layer height and width are controlled within 4.17% and 8.84%, respectively.

Table 2. Process parameters of the orthogonal experiments

No.	Laser power P/W	Scanning speed $V_s/mm \cdot s^{-1}$	Powder feed rate $V_g/g \cdot min^{-1}$
a	1000	6	10.8
b	1000	8	13.5
c	1000	10	16.2
d	1000	12	18.9
e	1250	6	13.5
f	1250	8	10.8
g	1250	10	18.9
h	1250	12	16.2
i	1500	6	16.2
j	1500	8	18.9
k	1500	10	10.8
l	1500	12	13.5
m	1750	6	18.9
n	1750	8	16.2
o	1750	10	13.5
p	1750	12	10.8

The errors primarily originate from the model's simplified assumption regarding powder utilization efficiency and the micro-perturbations of the shielding gas flow on the molten pool surface during actual processing.

Regarding the powder feed rate, although increasing the powder feed rate can increase the cladding layer height, the laser shielding and scattering effects

produced by an excessively high concentration of powder flow will significantly attenuate the effective energy reaching the substrate.

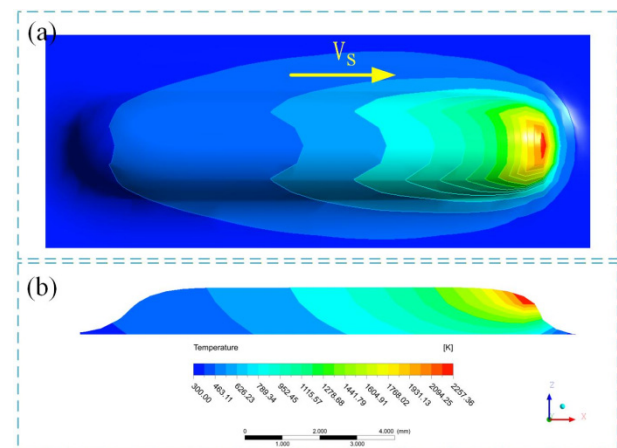


Figure 8. Numerical simulation of a single-track deposition: a) Top view; b) Side view

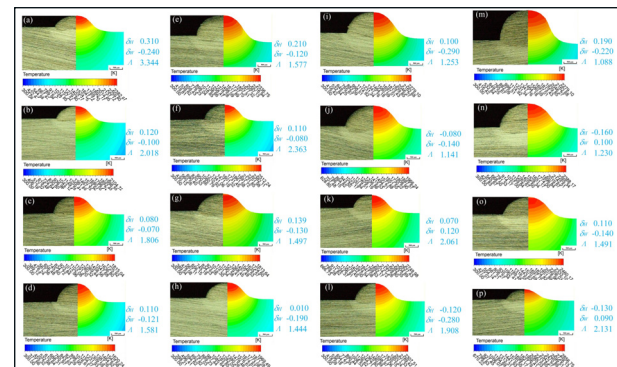


Figure 9. Comparison of the experimental and simulated cross-sectional morphologies of single-track depositions under various process parameters

The range analysis results show that the powder feed rate of 13.5 g/min corresponds to the optimal comprehensive indicators for forming quality, indicating that this rate ensures deposition efficiency while effectively circumventing energy attenuation caused by excessive powder. In summary, although the parameter combination $P=1500$ W, $V_s=8$ mm/s, $V_g=13.5$ g/min was not directly included in the orthogonal experimental design table, based on the mean value inference of each factor level, this combination is the theoretical optimal process parameter. Consequently, this study used it as the benchmark process parameter for the subsequent double-layer deposition experiments for validation. The results demonstrated that under this parameter, the macroscopic profile of the single-track deposited layer was continuous and full, with good metallurgical bonding and no visible macroscopic cracks. The excellent macroscopic geometric features and forming stability provide a reliable fundamental quality guarantee for the subsequent exploration of layer-by-layer stacking processes.

3.2 Optimization of Z-axis Increment in Double-Layer Stacking

During the layer-by-layer stacking process, the Z-axis increment directly determines the laser defocusing amount and the interlayer remelting depth, acting as a

core parameter affecting forming stability. Existing research often adopts a simplified strategy, setting the Z-axis increment directly to the average height of a single-track deposited layer. Based on the previous simulation and experimental results, the average height of a single-track deposited layer is approximately 1.40 mm. Therefore, using the single-track average deposition height as a benchmark, this study established three sets of gradient parameters 1.10 mm, 1.40 mm, and 1.70 mm to conduct numerical simulations and experimental validations of double-layer stacking. As illustrated in Fig.10, these parameters correspond to three typical deposition states: insufficient increment, equivalent increment, and excessive increment, respectively. The design of these parameter gradients aims to systematically elucidate the evolution laws of how ΔZ mismatch affects the thermo-fluidic behavior of the molten pool and forming quality. With 1.40 mm as the theoretical reference point, the 1.10 mm insufficient increment condition explores the geometric compensation mechanism for the flow effect caused by thermal accumulation; simultaneously, the 1.70 mm excessive increment condition is introduced to investigate the triggering mechanism of flow field instability and defect evolution caused by energy attenuation when positive laser defocusing is significantly amplified, thereby comprehensively evaluating the model's predictive capability under different thermophysical boundary conditions.

Although the single-track cladding layer height ΔH is approximately 1.40 mm, the selection of the Z-axis increment ΔZ exerts a decisive influence on forming stability. When ΔZ is set to 1.40 mm, Fig.10(b) shows that the forming process does not reach a steady state; instead, geometric discontinuity and morphological instability emerge. This is because, during the layer-by-layer stacking process, the molten pool undergoes a flowing effect driven by gravity and surface tension, inevitably causing the actual effective height increase of the deposited layer to be less than the single-track height on an isolated substrate. In this case, setting ΔZ equal to the theoretical cladding height causes the actual deposition height growth to lag behind the nozzle's lifting speed, inducing a cumulative positive drift in the laser defocusing amount and weakening the interlayer remelting capability.

When ΔZ is further increased to 1.70 mm, Fig.10(c) exhibits an even more severe morphological deterioration. Because the increment is far greater than the actual layer height increment, the degree of laser defocusing rapidly intensifies with the increasing number of layers, leading to a sharp drop in the effective spot power density acting on the molten pool surface. The significant deficiency in energy input restricts the spreading and wetting ability of the molten pool on the previous deposited layer. Although complete macroscopic structural collapse has not yet occurred in the double-layer deposition, compared to the full transition at $\Delta Z = 1.10$ mm, the wetting angles on both sides show a tendency to increase. As the number of deposited layers further increases, this restricted spreading caused by defocusing will continuously accumulate, ultimately increasing the risk of morphological instability in layer-

by-layer stacking. In contrast, when the process parameter ΔZ is set to 1.10 mm, Fig.10(a) displays a full and uniformly transitioned cross-sectional morphology. This value conforms to the mass conservation and geometric compensation criteria for layer-by-layers-tacking; the moderate insufficient increment strategy effectively compensates for the height loss caused by melt flow, ensuring that the laser energy can penetrate to the top of the previous layer, maintaining a constant remelting depth and thermal input boundary conditions, thereby achieving high-quality forming control.

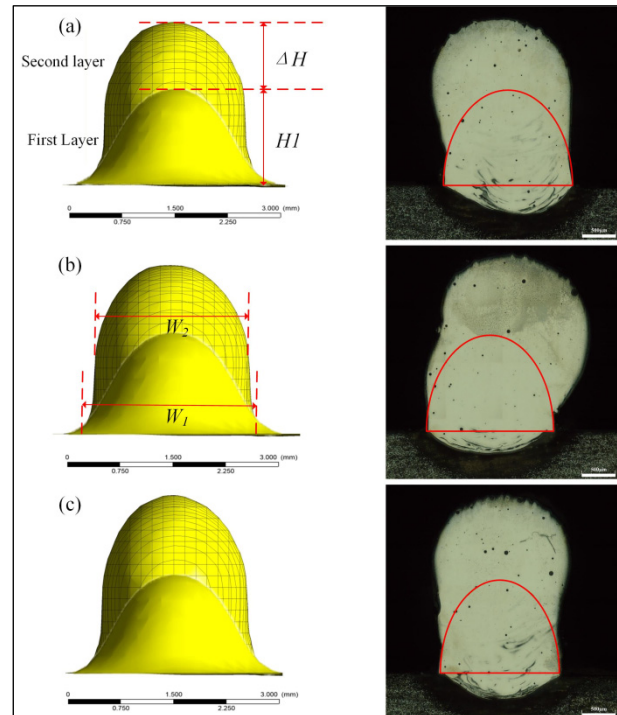


Figure 10. Cross-sectional macroscopic morphologies of double-layer depositions under varying Z-axis increments (ΔZ): (a) 1.10 mm; (b) 1.40 mm; (c) 1.70 mm

To quantitatively verify the accuracy of the aforementioned thermo-fluidic field evolution and morphological analysis, this study extracted the dimensions of the deposition tracks under different Z-axis increments, as shown in Table 3. To facilitate the evaluation of the model's prediction accuracy, the experimental measurements and their corresponding numerical simulation results under the Z-axis increments of 1.10 mm, 1.40 mm, and 1.70 mm are grouped and labeled as a1/a2, b1/b2, and c1/c2 in the table, respectively. The data indicate that the geometric dimensions from the numerical simulation highly match the experimental results. More importantly, when the increment ΔZ is set to 1.10 mm, the actual double-layer deposition height increment ΔH is approximately 1.05~1.08 mm, achieving an accurate match with the set increment height; whereas when ΔZ is set to 1.40 mm and 1.70 mm, the actual layer height increments ΔH are only 1.12~1.14 mm and 1.21~1.23 mm, respectively, far below the theoretical increment heights. This data discrepancy quantitatively corroborates the previous conclusion: if the increment fails to adapt to the reduction in actual layer height caused by thermal accumulation, it will inevitably lead to severe positive laser defocusing and thermo-fluidic field mismatch.

Table 3. Experimental and simulated dimensions of the deposition tracks under different Z-axis increments

No.	$\Delta Z/\text{mm}$	H_1/mm	W_1/mm	$\Delta H/\text{mm}$	W_2/mm
a1	1.10	1.40	2.08	1.08	1.92
a2	1.10	1.40	1.90	1.05	1.96
b1	1.40	1.40	2.19	1.14	2.09
b2	1.40	1.40	1.88	1.12	2.07
c1	1.70	1.40	2.19	1.21	2.05
c2	1.70	1.40	1.83	1.23	1.96

To reveal the thermophysical causes of the morphological differences, Fig. 11(a) shows the molten pool temperature field contours under different Z-axis increments. Simulation results indicate that as ΔZ increases, the peak temperature of the molten pool exhibits a decreasing trend, specifically dropping from 2832.73 K to 2643.67 K. Combined with the quantitative analysis of the simulated temperature distribution curves under different Z-axis increments in Fig. 11(b), it can be seen that within the $0 < \Delta Z < 1.4$ mm range corresponding to the first deposition layer region, the temperature curve under the $\Delta Z = 1.1$ mm condition is noticeably higher than the other two groups. This is because when $\Delta Z = 1.1$ mm, the molten pool is closest to the high-temperature region of the previous layer, resulting in high interlayer heat conduction efficiency; the residual heat from the underlying layer provides a significant thermal insulation effect for the current molten pool, effectively mitigating drastic changes in the temperature gradient and helping to maintain the continuity of interlayer heat input. Furthermore, the thermal accumulation effect during the layer-by-layer stacking process reduces the melt viscosity and exacerbates its lateral spreading, causing the actual deposited layer height to gradually decrease as the number of layers increases. In this state, ΔZ becomes the dominant factor determining the forming quality. If ΔZ fails to adapt to the reduction in actual layer height, the accumulation of layer height mismatch will cause the positive laser defocusing amount to continuously increase. The consequent enlargement of the spot area and significant drop in effective power density will result in insufficient surface heat input to maintain the steady-state evolution of the molten pool; at this point, even if the residual temperature of the bottom layer is high, it cannot compensate for the lack of local heat input, thereby triggering morphological instability. Therefore, an appropriate insufficient increment is essentially an effective process compensation for the loss of layer height and laser defocusing behavior caused by thermal accumulation.

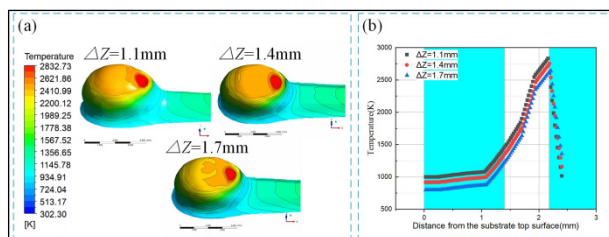


Figure 11. Temperature field simulation under different Z-axis increments (a); and the corresponding temperature distribution curves (b)

The flow mode and convection intensity within the molten pool are crucial in determining the porosity and microstructure. As shown in Fig.12, the flow field

morphologies under different ΔZ vary significantly. When $\Delta Z = 1.1$ mm, thanks to the uniform temperature distribution, the surface tension gradient of the molten pool is small, the Marangoni convection effect is weak, and the melt exhibits a stable laminar flow with an average velocity of approximately 0.30 m/s. This stable flow regime avoids severe liquid surface fluctuations caused by strong convection, facilitating the maintenance of geometric stability at the free surface of the molten pool [30]. However, it is worth noting that, as shown in the metallographic cross-sections in Fig. 10, a certain number of porosity defects exist inside the deposited layers under all three aforementioned ΔZ parameters. This indicates that although a moderate insufficient increment strategy can effectively control the macroscopic forming profile of layer-by-layer-stacking and the stability of the thermal-accumulation flow field between layers, it does not fundamentally eliminate the microscopic porosity issues caused by the oxygen carried by the powder itself or the entrainment of shielding gas. Subsequent multi-dimensional and multi-physics synergistic optimization research is still required, integrating parameters such as laser power, powder feeding system, and environmental atmosphere. Conversely, when ΔZ is increased to 1.70 mm, the larger defocusing amount leads to a decrease in the spot energy density and an increase in the temperature gradient on the molten pool surface, inducing intense Marangoni convection with a maximum flow velocity reaching 0.4 m/s. Although strong convection helps homogenize solutes, excessively high flow velocities easily entrain shielding gas and form vortices in the middle and rear of the molten pool, exacerbating fluctuations on the forming surface.

Comprehensively analyzing the morphological features, thermal field evolution, and flow field stability, $\Delta Z = 1.1$ mm is determined to be the optimal Z-axis increment for layer-by-layer stacking of the In625 alloy. While effectively regulating interlayer thermal accumulation, this parameter maintains a stable laminar flow and avoids molten pool surface fluctuations triggered by intense Marangoni convection, thereby ensuring precise control over the macroscopic morphology and dimensions of the deposited layer. It should be pointed out that the double-layer deposition in this study primarily reveals the universal mechanism of layer height reduction caused by thermal accumulation during the initial stage of layer-by-layer stacking and the ΔZ compensation.

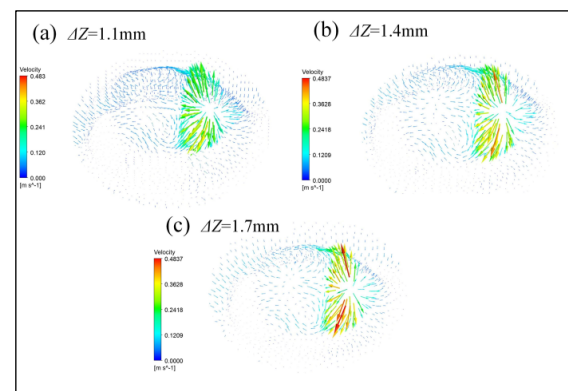


Figure 12. Flow field simulation under different Z-axis increments: a) 1.10mm; b) 1.40mm; c) 1.70mm

When depositing the third layer and beyond, gradually approaching a thermal steady state, the intensifying thermal accumulation will make the loss of single-layer height increment even more pronounced. Therefore, the fixed insufficient increment of 1.10 mm determined in this paper is more suitable as a process reference for the initial stage of stacking. In the actual forming of components with a high number of layers, to maintain continuous matching between energy and geometry, the increment ΔZ should evolve towards a dynamically decreasing adaptive compensation strategy, which also points the way for the closed-loop process control of subsequent layer-by-layer stacking.

3.3 Effect of Z-axis Increment on Primary Dendrite Arm Spacing

Based on the determination of the optimal Z-axis increment, its regulatory mechanism on micro-solidification behavior was further explored. Selecting the overlapping region of the double-layer deposition as the characteristic study object, the temperature gradient G and solidification rate R were extracted at equal intervals from point c at the bottom of the molten pool to point a at the top, as illustrated in Fig. 13, to analyze their evolution laws along the deposition height.

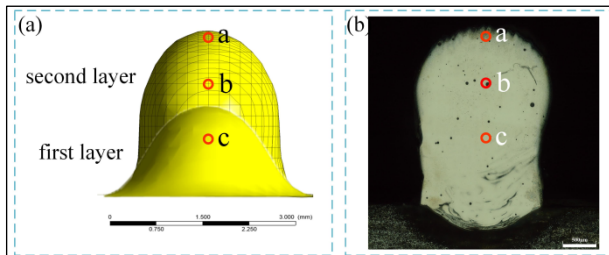


Figure 13. Schematic of data extraction locations in the overlapping zone of double-layer deposition: a) simulation result; b) experimental result

Fig. 14 illustrates the distribution trends of solidification parameters within the overlap zone when $\Delta Z = 1.1$ mm. As shown in Fig. 14(a), the temperature gradient G reaches its maximum value of 1339.62 K/mm at the bottom of the molten pool and gradually decreases to 601.22 K/mm as the height increases; conversely, the solidification rate R exhibits an opposite trend, climbing rapidly from 0.162 mm/s at the bottom to 3.681 mm/s at the top. This occurs because the bottom of the molten pool is immediately adjacent to the substrate, where heat conduction dominates dissipation, resulting in a high temperature gradient and a low growth rate. Fig. 14(b) further reveals the evolution laws of the cooling rate ($G \times R$) and the morphology parameter (G/R). Under their combined effect, $G \times R$ surges from 217.02 K/s at the bottom to 2213.09 K/s at the top, and this massive disparity in cooling rates directly causes the differentiation in dendrite coarseness across different regions. Concurrently, the parameter G/R , which dictates crystal growth morphology, significantly decreases with height. The extremely high G/R value at the bottom is conducive to maintaining interface stability, thereby promoting the continuous growth of directional columnar crystals; meanwhile, the lower G/R value at the top

indicates increased undercooling, escalating the tendency for the microstructure to undergo a columnar-to-equiaxed transition [31].

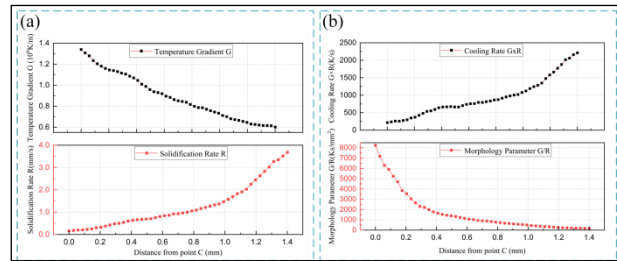


Figure 14. Distribution characteristics of solidification parameters along deposition height in the overlap zone: a) temperature gradient G and solidification rate R ; b) cooling rate $G \times R$ and morphology factor G/R

Fig. 15 compares the effect of different Z-axis increments on the distribution of solidification parameters along the molten pool height. As ΔZ increases from 1.1 mm to 1.7 mm, interlayer thermal interaction weakens, and the preheating and thermal insulation effect of the previous deposited layer on the current molten pool decays, causing the thermal boundary conditions of the molten pool to more closely approximate those of a cold substrate. This leads to enhanced heat dissipation efficiency at the same height, significantly increasing the cooling rate. Taking the middle region b of the molten pool as an example, when $\Delta Z = 1.7$ mm, its average cooling rate increases by approximately 123% compared to when $\Delta Z = 1.1$ mm. In terms of morphological control, the increase in ΔZ causes the magnitude of the increase in the temperature gradient G to outpace the change in the solidification rate R , leading to an elevated G/R value in the corresponding region. This implies that a larger Z-axis increment not only refines the grains but also enhances the directional growth capability of columnar crystals to a certain extent, suppressing the formation of stray grains.

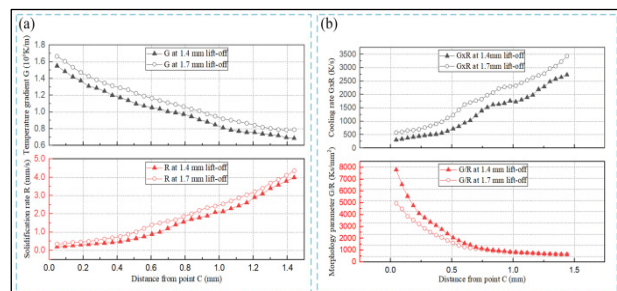


Figure 15. Comparison of solidification parameters distribution along melt pool height under different Z-axis increment: a) Temperature gradient G and solidification rate R ; b) Cooling rate $G \times R$ and morphology parameter G/R

The microstructural morphologies shown in Fig. 16 and the measurement results of the primary dendrite arm spacing (λ) listed in Table 4 validate the accuracy of the aforementioned simulation analysis. From the top to the bottom of the molten pool, λ gradually coarsens with the decreasing cooling rate. Within the same region, as ΔZ increases, the cooling rate elevates, undercooling increases, and the nucleation rate rises significantly, thereby restricting the lateral growth of dendrites and resulting in a reduced primary dendrite arm spacing [32].

Table 4. Cooling rate, primary dendrite arm spacing, and microhardness in different regions under varying Z-axis increments

Sampling area	$\Delta Z=1.1\text{mm}$			$\Delta Z=1.4\text{mm}$			$\Delta Z=1.7\text{mm}$		
No.	Cooling rate K/s	$\lambda/\mu\text{m}$	Hardness HV	Cooling rate K/s	$\lambda/\mu\text{m}$	Hardness HV	Cooling rate K/s	$\lambda/\mu\text{m}$	Hardness HV
Region a	2113.09	5.29	272	2735.54	5.03	276	3435.48	4.62	283
Region b	794.18	7.10	258	1210.41	6.22	265	1773.14	5.77	269
Region c	217.02	10.17	245	310.55	9.14	251	583.19	7.53	256

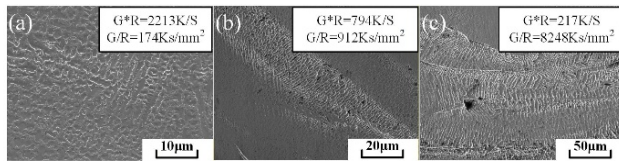


Figure 16. SEM micrographs showing the microstructural evolution in the overlap zone at $\Delta Z= 1.1\text{mm}$: a) top region; b) middle region; c) bottom region

To achieve quantitative prediction from process parameters to microstructures, this study introduces the classical Kurz-Fisher (K-F) dendrite growth model. The original K-F model comprehensively considers the effects of the solute diffusion coefficient D , the solute partition coefficient k , and interfacial energy, and can accurately describe the evolution law of primary dendrite arm spacing λ under low-speed cooling conditions typical of traditional metal casting [33]. The K-F model is expressed as:

$$\lambda = 4.3 \left(\frac{D\Gamma\Delta T_0}{k} \right)^{\frac{1}{4}} G^{-\frac{1}{2}} R^{-\frac{1}{4}} \quad (2)$$

where Γ is the Gibbs-Thomson coefficient, and ΔT_0 is the crystallization temperature range. However, the LDED process is characterized by an extremely high temperature gradient and rapid solidification, during which the solute trapping effect is pronounced, making the traditional low-speed growth model difficult to apply directly. Under these non-equilibrium solidification conditions, the cooling rate emerges as the core variable controlling the dendrite scale, exhibiting a significant negative exponential correlation with the primary dendrite arm spacing. Therefore, the K-F model can be simplified into the following power-law function:

$$\lambda = A(G \cdot R)^{-n} \quad (3)$$

By performing non-linear regression fitting using the experimental data and the simulated cooling rates ($G \times R$) from Table 4, a modified predictive model suitable for LDED forming of In625 alloy was obtained:

$$\lambda = 45.72(G \cdot R)^{-0.28} \quad (4)$$

The fitting results demonstrate a correlation coefficient $R^2 > 0.95$, confirming the accuracy of the modified model. The characteristic exponent $n = 0.28$ in this modified model deviates somewhat from the characteristic values of 0.33 or 0.5 for diffusion-controlled growth in classical solidification theory. This reflects the unique synergistic effect of solute trapping and strong interfacial thermal constraints under the rapid solidification conditions of the laser directed energy deposition process. The extremely high temperature gradient on the order of 106 K/m at the bottom of the

molten pool during the LDED process acts as a strong constraint and stabilizer on the solid-liquid interface morphology, partially suppressing the lateral branching and coarsening behaviors of dendrites induced by thermal perturbations; this makes the sensitivity of the dendrite spacing to changes in the cooling rate slightly lower than predicted by classical diffusion models. Furthermore, under a rapid solidification rate of up to 3.68 mm/s, the advancement speed of the solid-liquid interface approaches the diffusion speed of solute atoms, enhancing the non-equilibrium solute trapping effect and altering the constitutional undercooling distribution at the interface front. This synergistic action of thermal-solute fields significantly compresses the effective constitutional undercooling zone ahead of the solid-liquid interface, reducing the sensitivity of the dendrite spacing to the cooling rate, thereby manifesting the characteristic exponent $n = 0.28$ specific to the rapid laser forming of the Inconel 625 alloy.

The evolution of the primary dendrite arm spacing λ exerts a direct regulatory effect on the mechanical properties of the deposited layer. According to the classical Hall-Petch grain refinement strengthening mechanism, a reduction in the characteristic crystal size can significantly increase the resistance to dislocation movement. The microhardness test results in this study highly align with this strengthening law: as the increment ΔZ increases, the elevated cooling rate drives λ to refine significantly from 10.17 μm in the bottom region to 4.62 μm in the top region, with the corresponding average microhardness concurrently increasing from 245 HV to 283 HV. Simultaneously, the finer dendritic network also helps mitigate the microscopic segregation of refractory elements such as Nb and Mo in the Inconel 625 alloy, further enhancing the solid solution strengthening effect and local yield strength. Although the excessively large increment of 1.70 mm yields the finest λ and exhibits the highest microhardness, the severe defocusing it induces highly increases the propensity for macroscopic defects, such as morphological instability, porosity, and poor interlayer bonding. When subjected to stress, these defects easily become stress concentration sources, and their destructive impact on the overall service performance of the component often far outweighs the localized hardness gains brought by microstructural refinement. The optimization of the layer-by-layer stacking process must prioritize ensuring the relative density of the macroscopic forming. Therefore, the 1.10 mm insufficient increment strategy determined in this study achieves a comprehensive optimal solution balancing forming quality and localized mechanical properties, premised on ensuring steady-state molten pool rheology and dense macroscopic bonding.

4. CONCLUSIONS

This study systematically investigated the morphological evolution, thermo-fluidic behaviors, and microstructural properties of Inconel 625 alloy during fundamental double-layer laser directed energy deposition (LDED). A VOF-based dynamic molten pool model was established and experimentally validated. The main conclusions are as follows:

The established thermo-fluidic coupling model accurately captures the transient heat transfer and convective flow behaviors during layer-by-layer stacking. With dimensional prediction errors for single-track and double-layer depositions controlled within 8.84%, the model demonstrates high reliability under complex thermal boundary conditions.

Based on the optimized single-track parameters of 1500 W laser power, 8 mm/s scanning speed, and 13.5 g/min powder feed rate, an insufficient Z-axis increment of 1.10 mm was identified as the optimal strategy for double-layer stacking. While an excessively large increment further refines dendrites and increases local microhardness, the resulting severe positive defocusing elevates the risk of morphological instability and macroscopic defects. The 1.10 mm increment effectively compensates for thermal accumulation-induced layer height loss, balancing macroscopic density with mechanical potential. For subsequent depositions approaching a thermal steady state, a dynamically decreasing Z-axis compensation strategy is recommended.

The optimized insufficient increment maintains a steady laser defocusing distance and enables the molten pool to sustain a stable laminar flow. This suppresses drastic free surface fluctuations driven by intense Marangoni convection, thereby preserving macroscopic geometric stability.

The Z-axis increment dictates the microstructural evolution by altering local cooling conditions. An increase in the increment weakens the interlayer thermal insulation and accelerates the cooling rate, refining the primary dendrite arm spacing λ . A modified Kurz-Fisher predictive model formulated as $\lambda = 45.72(G \cdot R)^{-0.28}$ was established. The extracted characteristic exponent $n = 0.28$ quantitatively captures the unique solute trapping effect and intense interfacial thermal constraints inherent to the rapid solidification of LDED.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

REFERENCES

- [1] Tan Q, Liu K, Li J, Geng S, Sun L, Skuratov V. A review on cracking mechanism and suppression strategy of nickel-based superalloys during laser cladding. *J Alloys Compd.* 2024; 1001:175164.
- [2] Chen Y, Jiang M, Chen X, Bi G, Chen Y. Effect of annular laser beam on the forming quality, microstructure and phase evolution of Ti6Al4V thin wall fabricated by coaxial-wire-feed laser directed energy deposition. *Thin-Walled Struct.* 2026;225: 114766.
- [3] Li W, Jia C, Sun G, Yao Q, Wang Z, Chen C, Wang S. Enhanced strength-ductility synergy in directed energy deposition Ti alloy via interlayer laser cladding heterogeneous particles. *J Mater Process Technol.* 2026; 349: 119230.
- [4] Zhang Y, Sun J, Sun Z, Wang Y, Yu T. Effects of different interlayer bonding modes on the microstructure and properties of laser clad In625. *Opt Laser Technol.* 2025; 182: 112191.
- [5] Tao S, Zhang G, Zhao Y, Wu G, Jiang E, Wang Y, Guo X, Huang Y, Wu Z, Piao Z. Preparation and corrosion resistance of Inconel 625 laser cladding coating for high temperature supercritical carbon dioxide environment. *J Mater Res Technol.* 2025; 38: 2751–65.
- [6] Wang H, Wu M, Miao X, Jin X, Cui C, Ma C, Wang Q. Effect of Nb on the microstructure and wear resistance of In625/(Nb+SiC0.5) composite coatings by laser cladding. *Ceram Int.* 2023; 49: 38 420–31.
- [7] Hao J, Hu F, Le X, Liu H, Yang H, Han J. Microstructure and high-temperature wear behaviour of Inconel 625 multi-layer cladding prepared on H13 mould steel by a hybrid additive manufacturing method. *J Mater Process Technol.* 2021; 291:117036.
- [8] Yao M, Sheng J, Kong F, Tong W. A multi-sensor based online monitoring system for laser hot-wire surface cladding process. *Opt Laser Technol.* 2024;177:111074.
- [9] Tanaka K, Yamaguchi T. Direct observation of bubble generation processes inside a molten pool during laser cladding. *Surf Coat Technol.* 2022; 447:128831.
- [10] Gao S, Zhang Z, Li Y, Li J, Wei Z. In-situ observation and simulation of melt pool evolution and single-track formation in laser cladding. *J Mater Res Technol.* 2025; 39: 5986–6000.
- [11] Li G, Wang F, Liu M. Study on the finite element simulation for the cutting of Ni60 laser cladding layer based on heterogeneous modeling. *Opt Laser Technol.* 2025; 190: 113239.
- [12] Yong Y, Fu W, Deng Q, Chen D. A comparative study of vision detection and numerical simulation for laser cladding of nickel-based alloy. *J Manuf Process.* 2017; 28: 364–72.
- [13] Mo B, Li T, Xiao C, Shi F, Liu W. Numerical simulation and experimental study of temperature and stress fields during laser cladding of multi-layer Ni60A alloy. *Opt Laser Technol.* 2025; 192: 113536.
- [14] Jin K, Yang Z, Chen P, Feng P, Qiao X. Modeling of solidification process during multi-track laser cladding with 3D cellular automata coupling gas-

- liquid interface tracking and solute suppression nucleation. *J Mater Process Technol.* 2023; 315: 117927.
- [15] Hao J, Liu Y, Yang S, Liu H, Yang H, Liu H, Liu X. Numerical simulation and morphological analysis of laser cladDED 316L stainless steel on inclined substrates. *Opt Laser Technol.* 2024;177: 111137.
- [16] Zhou H, Zhu G, Li J, Zhang X. A review of the flow behavior of laser cladding pools based on inclined substrates. *J Manuf Process.* 2024; 120: 391–403.
- [17] Ouyang C, Deng R, Wei R, Li H, Wang R, Zhao C. Methods and techniques for enhancing wear resistance of laser cladding coatings: a comprehensive review. *J Manuf Process.* 2025; 152:1123–49.
- [18] Liu M, Cai Y, Duan C, Li G. Key techniques in parts repair and remanufacturing based on laser cladding: a review. *J Manuf Process.* 2024; 132: 994–1014.
- [19] Quan GZ, Meng FX, Ran WJ, Quan MG, Xiong W. Influence of cladding distance and interlayer cooling time on residual stress in multi-layer laser cladding process. *Opt Laser Technol.* 2026; 193: 114295.
- [20] Liverani E, Ascari A, Fortunato A. Multilayered WC–Co coatings by Direct Energy Deposition-based cladding: effect of laser remelting on interface defects. *Surf Coat Technol.* 2023; 464: 129556.
- [21] Gao Z, Xiao G, Zhang H, Chen H, Zhang J, Yi M, Chen Z, Xu C. Investigation of the microstructure, mechanical properties and cutting performance of multi-layer Fe-based ultrafine-grained laser cladding layers. *Surf Coat Technol.* 2025; 507: 132163.
- [22] Li Y, Shi Y, Jiang G, Tang S, Wu J, Wang J. Effect of WC on microstructure, molten pool and properties of Ni based coatings by multi-layer laser cladding. *Opt Laser Technol.* 2024; 174:110612.
- [23] Ferreira AA, Emadinia O, Amaral RL, Cruz JM, Reis AR, Vieira MF. Mechanical and microstructural characterisation of Inconel 625 - AISI 431 steel bulk produced by direct laser deposition. *J Mater Process Technol.* 2022; 306: 117603.
- [24] Gao Z, Zhang J, Xiao G, Zhang H, Chen H, Yi M, Chen Z, Xu C. Influence of Si-content on the microstructure and wear resistance of multilayer Fe-based ultrafine-grained coatings deposited by laser cladding process. *Tribol Int.* 2026; 218: 111704.
- [25] Liu Y, Ding Y, Yang L, Sun R, Zhang T, Yang X. Research and progress of laser cladding on engineering alloys: a review. *J Manuf Process.* 2021; 66: 341–63.
- [26] Tamanna N, Crouch R, Naher S. Progress in numerical simulation of the laser cladding process. *Opt Lasers Eng.* 2019; 122: 151–63.
- [27] Gao Z, Cheng T, Zhang N, Bi Q, Gao Z, Zhang C, Yu Y. Thermal-mechanical coupling simulation and experimental study of ultrasound-assisted laser cladding of Ni60 coating. *J Alloys Compd.* 2025; 1024: 180270.
- [28] Zheng X, Hao J, Liu Y, Liu H, Liu H, Yang H. Thermomechanical coupled modeling and microstructural solidification mechanism of IN625 alloy in multi-track multi-layer laser directed energy deposition. *Opt Laser Technol.* 2025; 192: 113925.
- [29] Lei X, Du Y, Chen H, Peng Y, Ma W, Tu J. A hybrid optimization method for determining laser cladding process parameters to control geometric morphology in CoCrFeNiMn high-entropy alloy. *J Mater Res Technol.* 2025; 39: 1038–52.
- [30] Lőrincz B, Hatos I. Determination of Johnson–Cook parameters and evaluation of Charpy impact test performance for 1.2709 steel produced via L-PBF, *FME Transactions*, 54, No. 2, 2026, pp. 331–342.
- [31] Ji D, Zhang J, Liu Y, Zhang B, Chen X, Li R. Microstructural evolution and fatigue performance of 25CrMo4 steel remanufactured by high-speed laser cladding of Inconel 625 alloy. *Int J Fatigue.* 2026; 203: 109291.
- [32] Sevel P, Mahadevan S, Satheesh C, Srinivasan D, Jaiganesh V. Experimental investigation on the improvement of the properties of the AZ80A Mg alloy joints using friction stir welding, *FME Transactions*, 47, No. 3, 2019, pp. 452–460.
- [33] Pourmand S, Kermanpur A, Rezaeian A, Jafari-Ramiani A. Phase field simulation of solidification microstructure for Fe-17 wt%Cr model alloy fabricated by laser powder bed fusion. *Mater Des.* 2025; 260: 115226.

УТИЦАЈ КОРАКА ПО Z-ОСИ НА КВАЛИТЕТ ОБЛИКОВАЊА И ЕВОЛУЦИЈУ МИКРОСТРУКТУРЕ ЛЕГУРЕ INCONEL 625 ИЗРАЂЕНЕ ПОСТУПКОМ ЛАСЕРСКОГ НАНОШЕЊА МАТЕРИЈАЛА УЗ УСМЕРЕНУ ЕНЕРГИЈУ (LDED)

**К. Бан, Ј. Хао, Ф. Ванг, М.Р. Ислам, Д. Ванг,
С. Лиу**

Током слојевитог наношења материјала поступком LDED, нагомилавање топлоте између слојева значајно мења обрасце конвективног струјања и стварне димензије слојева, чинећи корак по Z-оси (ΔZ) кључним фактором за термо-флуидну стабилност. Ради разумевања овог нестационарног механизма, у овој студији се истражују термо-флуидно понашање и процеси очвршћавања легуре Inconel 625 при различитим вредностима ΔZ током основног наношења два слоја. Развијен је нестационарни 3D модел који повезује пренос топлоте и струјање флуида применом методе „запремине флуида” (VOF), а модел је експериментално валидиран. Резултати показују да превелика вредност ΔZ појачава ефекат по-

зитивног дефокусирања ласера и температурне градијенте, изазивајући интензивну Марангонијеву конвекцију која дестабилизује слободну површину растопљене зоне и повећава порозност. Насупрот томе, оптимизована вредност ΔZ од 1,10 mm ублажава смањење висине слоја узроковано нагомилавањем топлоте, одржавајући стабилно ламинарно струјање и континуирани унос топлоте. Поред тога, ΔZ снажно одређује локалну брзину хлађења и морфологију очвршћавања. Повећање вредности ΔZ доводи до веће брзине хлађења, што смањује растојање између кракова примарних дендрита (λ) и повећава локалну микротврдоћу. На основу тер-

мичке историје процеса брзог очвршћавања, успостављен је модификовани Курц-Фишеров (Kurz-Fisher) модел: $\lambda=45.72(G \cdot R)^{-0.28}$. Карактеристични експонент $n=0,28$ квантитативно описује јединствене појаве заробљавања растворених елемената и интензивна термичка ограничења на међуповршини, који су својствени LDED процесу. Овај рад разјашњава међусобне везе на различитим скалама између термо-флуидног струјања, одступања висине слоја и еволуције микроструктуре, пружајући механистичку основу за адаптивну контролу Z-осе при LDED изради делова од легуре Inconel 625.