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Relation of thermal behavior and microstructure evolution during multi-track laser melting deposition of Ni-based material

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A three-dimension finite element model was proposed to understand thermal behavior and microstructure evolution in multi-track laser melting deposition (LMD) of Inconel 625. The latent heat of phase change, multiple heat transfer, temperature dependent thermal physical properties were considered to ensure the accuracy of the simulation. Based on the simulated results, solidification characteristics, including temperature gradient (G), solidification growth rate (R), cooling rate (G × R) and G/R, could be obtained to predict the morphology and scale of the solidification microstructure. The results showed that the G/R was increased from $7.3 \times 10^4 \, ^\circ \text{C} / \text{s} \cdot \text{m}^2$ at the top of the molten pool to $1.22 \times 10^5 \, ^\circ \text{C} / \text{s} \cdot \text{m}^2$ at the bottom. As a result, columnar dendrites were generated at the bottom of the molten pool, while equiaxed dendrites were formed at the top. Simultaneously, columnar dendrites were observed at the edge of the molten pool, which was attributed to the high G/R (1.18 $\times 10^4 \, ^\circ \text{C} / \text{s} \cdot \text{m}^2$) at the edge of the molten pool. Furthermore, due to the lower cooling rate at the overlapping region than that at the bottom region, columnar dendrites generated at the overlapping region were coarser compared with those at the bottom of the molten pool. Specially, it should be noted that as increasing the number of deposited track, the G/R at the top of the molten pool exhibited with a slight increase and the G/R at the bottom presented with no obvious change. However, the G/R at the edge of the molten pool had an apparent decrease. The above simulation results showed a good agreement with the experimental results.

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1. Introduction

Unlike the conventional material removal methods, additive manufacturing (AM) technology based on an opposite principle of material added manufacturing. Laser melting deposition (LMD) is a newly-developed and fast-growing technique in promising AM technique, which exhibited extensive application perspective such as aerospace, automobile, medical and other industries [1,2]. LMD, based on track-by-track as well as layer-by-layer deposition mechanisms, is an advanced computer-aided AM technology. LMD has been widely used to build, and coat components with complex geometries and even repair worn-out parts [3,4]. Comparing with the traditional materials manufacturing technique LMD has obvious benefits, such as its low thermal strain, narrow heat affected zone (HAZ), finer grain size, high bonding strength and low porosity. In the process of deposition, high-energy laser beam melts the substrate or previously deposited layers quickly, creating a molten pool in which the powder delivered by the inert gas is injected inside steadily through a coaxial nozzle [5].

A variety of alloys and metals have been deposited with tailored microstructures and higher performance, in addition, metal matrix composites (MMCs) and functionally graded materials (FGMs) have been reported [6,7]. Inconel 625 is widely used in application like aerospace, aviation, chemical and petrochemical industries because of its extraordinary properties. Inconel 625 is endowed with good balance of tensile strength, fatigue strength, creep strength and toughness [8,9]. Inconel 625 can be strengthened mainly by the solid solution hardening, precipitation hardening [10], and the solid solution hardening by adding niobium and molybdenum into nickel–chromium matrix, which was due to the precipitation hardening with the precipitation of fine metastable phase $\gamma''$ [Ni3Nb] and the precipitation of various forms of carbides. Consequently, it is meaningful to develop the technology of LMD Inconel 625 owing to its outstanding properties mentioned above. Generally, the microstructures of Inconel 625 are greatly sensitive to the thermal behavior, and the properties of the components are directly affected by the microstructure. The high-energy input
and high cooling rate during LMD process lead to the complicated solidification behavior in the molten pool, providing a great potential to modify the microstructure evolution and mechanical properties of as-fabricated Inconel 625.

Multi-physical and multi-scale phenomena, such as laser powder interaction, heat transfer, mass transport, convection flow, melting and solidification behavior, simultaneously occur during the LMD process [11]. Nevertheless, numerical simulation has offered an efficient way to understand the complexity of the physical process in the process of LMD. To date, many numerical models have been developed, especially finite element model (FEM), and proposed to calculate the temperature field and stress field [12–15]. Generally, taking into consideration difficulty in modeling and high computational costs, many models focused on the single-track and thin walls multilayer structure AM simulation process. Alamardani et al. [16] proposed a thin wall multilayer structure model to investigate the temperature field, stress field, and the model was applied to study the impact of preheating and clamping the workpiece to the positioning table. A simplified, three-dimensional, transient heat transfer and fluid flow model was developed by Mukherjee et al. [17], simulating transient temperature field for the residual stress and distortion modeling. Wen et al. [18] incorporated additional source terms into the set of governing equations, leading to obtain more accurate of simulation. The physical behaviors in coaxial laser deposition processes including interaction between laser and powder, mass addition, fluid flow in the molten pool, melting and solidification were studied within this finite volume model. Costa et al. [19] established an a multi-layer thin wall with single-track model to investigate the influence of substrate size and idle time between the deposition of consecutive layers on the microstructure and hardness of AISI 420 steel. Generally, the deposited tracks were built with a pre-defined rectangular shape in many models, however, little attention was given to predict geometrical development of the molten pool during the LMD process. A simple but realistic three-dimension model to predict melt-pool morphology and clad geometry was built by Fallah et al. [20]. The thermal behaviors of the LMD process, including temperature evolution, temperature gradient (G) and solidification growth rate (R) are the main determining factors for the final microstructure and mechanical properties of deposited parts. Otherwise, it was well known that as the ratio of the G/R decreasing, the morphology of the microstructure varies from planar front to cellular dendrites to columnar dendrites to equiaxed dendrites. Moreover, the scale of the grain significantly depends on the cooling rate [21]. Higher cooling rate provides finer size of grain. However, the models mentioned above were concentrated on predict temperature field and stress field during LMD process, Thermal behavior and its influence on microstructure evolution were studied in a limited research situation. Gao et al. [22] proposed a three-dimension thermal FEM to obtain the thermal field in the laser cladding. The thermal characteristics and the cooling rate of moving solid–liquid interface have been studied to investigate the complex process of molten pool solidification. The model simulated the shape and geometry of the molten pool and the local solidification conditions at the solid–liquid interface were predicted. Xiong et al. [23] built a three-dimension FEM to simulate the characterization of temperature gradients and cooling rates of the entire sample, which contribute to obtain a fundamental insight into the evolution of microstructures. A three-dimension, transient, heat and mass transfer, considering in the liquid metal flow numerical model was developed by Gan et al. [24] for the laser AM of Ni-based alloy on cast iron to understand the heat transport, solidification behavior and solute transport. The results showed that the cooling rate tended to decline gradually as the subsequent layers was deposited, which led to the coarser solidified grains in the upper layers although thermal behavior and its influence on microstructure evolution were studied in these models, they focused on single-track or thin-walled LMD model. The thermal behavior and its influence on microstructure evolution in multi-track did not considered in their models.

In this paper, an improved three-dimension finite element model was developed using ANSYS software to understand the thermal behavior and microstructure evolution in multi-track LMD process. The thermal behavior of the track-by-track deposited process and the overlapping region were investigated. In this model, latent heat of phase change, multiple heat transfer, temperature-dependent thermophysical properties were considered to obtain accurate simulation results. Meanwhile, the temperature gradient, solidification growth rate, cooling rate and the ratio of G/R in depth and width direction of the molten pool were obtained by thermal analysis to predict and investigate the morphology and scale of final solidification microstructure of LMD process. Subsequently, experiments were carried out to verify the simulation results.

2. Finite element modeling and experiment procedure

2.1. Thermal analysis

The spatial and temporal distribution of temperature field conform to the heat conduction equation, which can be expressed as:

\[ \frac{\partial}{\partial t}(\rho(T) \cdot C_p(T) \cdot T) = \nabla \cdot (K(T) \cdot \nabla T) + \frac{\partial}{\partial t} (\rho(T) \cdot \nabla T) + Q(x,y,z) \]

(1)

where \( \rho(T) \) is the temperature-dependent material density, \( C_p \) is temperature-dependent specific, \( K(T) \) is thermal conductivity, \( Q(x,y,z,t) \) is heat generated per unit volume. In this paper, when the powder and the substrate are melted by laser heating. Taking into account the effects of Marangoni-Rayleigh-Benard convection on heat transfer within the molten pool, thermal conductivity is enhanced by a factor \( \sqrt{K} \) [25].

The distribution of laser power intensity is assumed to be a circular Gaussian mode:

\[ q = \frac{2AP}{\pi R^2} \exp \left( \frac{2r^2}{R^2} \right) \]

(2)

where \( R \) is the laser beam radius, \( r \) is the distance from center of the laser beam, \( A \) is laser energy absorbability and \( P \) is the laser power.

The latent heat occurred in the phase change, such as the transition of solid-liquid.

In this paper, the enthalpy is used to define the latent heat, expressed as a function of temperature:

\[ H = \int \rho C_p \,dT \]

(3)

where \( H \) is the enthalpy, \( \rho \) is the material density of Inconel 625 (8440 kg/m³), \( C_p \) is the specific heat capacity and \( T \) is the temperature of the melt formed in LMD process.

2.2. Initial and boundary conditions

The initial condition of the temperature distribution in the deposition part and substrate at time \( t = 0 \) is defined as:

\[ T(x,y,t)|_{t=0} = T_{amb}(x,y,z) \in D \]

(4)

where \( T_{amb} \) is the ambient temperature.

The convection and radiation boundary condition can be considered as:

\[ \partial T/\partial n = h(T - T_{amb}) \]

(5)

where \( h \) is the convection and radiation heat transfer coefficient.
$kT \cdot n_{\Omega} = \left[ -(T - T_s) - \nu \sigma (T^4 T_s^4) \right]_{\Omega} \quad \text{if } \nu \neq \Omega \quad (5)

where $n$ is the normal vector of the surface, $\varepsilon$ is the emissivity, $h$ is the heat convection coefficient, $\sigma$ is the Stefan Boltzmann constant, $S$ represents the surface which is imposed heat fluxes, radiation and convection, $\Omega$ represents the surface that is exposed to laser beam. Furthermore, the influence of the moving laser beam can be regarded as the surface heat source in the boundary condition as follows:

$$ kT \cdot n_{\Omega} = \left[ q - (T - T_s) \nu \sigma (T^4 T_s^4) \right]_{\Omega} \quad \text{if } S \in \Omega \quad (6) $$

where $\nu$ is the absorptivity, and $q$ is the laser energy distribution on the work piece.

The incident laser beam irradiates the top surface of the work piece, a part of laser energy is dissipated by radiation and convection, a combined heat transfer coefficient $(h_1)$ is used to avoid the analysis non-linear [26]. It can be stated mathematically as follows.

$$ h_1 = 24.1 \times 10^{-4} \varepsilon T^{1.61} \quad (9) $$

where $T$ is the solution temperature. and $\varepsilon$ is the emissivity of the substrate material which can be expressed as;

$$ \varepsilon = \varepsilon_{\text{sub}} + (1 - \varepsilon_{\text{sub}}) \varepsilon_{\text{add}} \quad (10) $$

where $\varepsilon_{\text{sub}}$ is the emissivity of the powder, $A_{\text{sub}}$ and $A_{\text{add}}$ are the area fraction of the surface that is occupied by the radiation-emitting holes and the emissivity of the hole, respectively.

2.3. Model description

The FEM was constructed as a deposition layer with shape of circular arc placed on a block as the substrate, which was based on real deposition geometry in LMD process. In transient thermal analysis, the thermal conduction element SOLID70 was utilized to mesh entire FEM. The mesh density affects the calculation accuracy and the calculation time directly, so a non-uniform mesh was used to assure the accuracy of the simulation and reduce the computational cost. The FEM model is shown in Fig. 1 During LMD process, laser beam was directed onto substrate surface to create a moving molten pool, which contributed to the formation of strong temperature gradient in the whole molten pool. Hence, fine mesh was utilized in deposited layer and the contact area with substrate.

Multi-track laser melting deposition process with laser power of 800 W, scanning speed of 500 mm/s, and powder flow rate of 2.4 g/min was used in this simulation. In order to depict the process of mass transfer due to powder deposition on substrate, the technique of element birth and death was applied to the three-dimensional thermal model. Before applying any heat loads, such as heat flux or heat generation rate, the elements of deposition part must be killed. But not meant the elements of deposition were not exit, but the dead elements referred to the element’s stiffness matrix being multiplied by a small factor, so contribute a near-zero conductivity value to the overall matrix, in the other words, dead elements were not contributing to the solution before they were activated. While the heat loads were applied to the laser-scanned region, the dead elements would be activated with the moving heat source gradually. The movement of laser beam was achieved by APDL (ANSYS Parametric Design Language) program to provide a heat flux boundary condition varying with time and location [27]. The number of new elements activated over a time interval was then a function of the scanning speed. Furthermore, some assumptions were made to simplify the solution process. The material in this simulation process was isotropic and homogeneous. Material properties were temperature dependent, the thermal-physical parameters of Inconel 625 are shown in Table 1. Powder particle size distribution and laser scan velocity will affect the laser absorption rate [28]. Nevertheless, the absorption rate was set a constant value (0.37) in this paper [29].

2.4. Experiment procedure

The spherical Inconel 625 powder with the particle distribution of 15–45 μm prepared by gas atomization was used in this experiment. The chemical compositions of Inconel 625 powder are shown in Table 2. The experiment was carried out with an integral LMD processing system, which consisted of a continuous-wave Nd: YAG laser source with a maximum output power of 3 kW and a focused spot diameter of 0.6 mm, a six-axis computerized numerical control system, a powder feed system and a coaxial powder nozzle. The substrate material is C45 steel. Then, the Inconel 625 powder delivered by the inert gas was injected into the molten pool that melts due to the laser rapid heating. Furthermore, high purity argon was utilized as the carrier and shield gas to avoid oxidation during LMD process. Experiment was carried out to confirm the simulation results with parameters: Laser power of 800 W, scanning speed of 500 mm/s, and powder feeding rate of 2.4 g/min.

After the experiment, the specimen was obtained by cutting the plate with deposited sample in a direction perpendicular to the laser scanning direction According to the standard procedures, the microstructure of the cross section of the specimen was observed by grinding, polishing and etching., an etchant consisting of HNO₃ (10 ml), HCl (15 ml) and CH₃-COOH (10 ml) was used with an etching time of 10 s. The microstructure of sample was analyzed by optical microscopy (OM) and field emission scanning electron microscopy (FE-SEM; Hitachi, Tokyo, Japan) at an accelerating voltage of 3 kV.
3. Results and discussion

3.1. Temperature evolution

Fig. 2 shows the computed temperature distribution at different simulation time (0.008 s, 0.04 s and 0.064 s) during LMD process. As the simulation time progressed, the shape of temperature field changed and temperature was unstable (Fig. 2). The temperature field distribution of the N-1 deposited track presented a towed semi-elliptical, and the shape of temperature field was symmetrical along the laser scanning direction (Fig. 2a). It showed that the temperature field was no longer symmetrical along the laser scanning direction due to the heat accumulation and heat conduction between the two adjacent tracks. Moreover, heat affected zone (HAZ) has become larger as the simulation proceed. The maximum temperature and relatively dense isothermal curves appeared in the front of the molten pool because of the main of heat input focused on a limit area (Fig. 2). The peak temperature increased progressively as the subsequent tracks deposition. At the time of 0.008 s, the peak temperature was 2415 °C, which was higher than the liquidus temperature of Inconel 625 (1350 °C). The peak temperature at the time of 0.04 s was increased by about 100 °C compared with the time of 0.008 s due to the heat accumulation effect. The temperature of adjacent part of the N-1 and N deposited track also exceeded the liquidus temperature of Inconel 625, which meant that the N-1 track has been remelted during the process of depositing the N deposited track (Fig. 2b). This phenomenon was beneficial to form good metallurgical bonding between adjacent tracks, improving the relative density of deposition parts. At the time of 0.064 s, the peak temperature was 2590 °C (Fig. 2c).

Fig. 3 illustrates the transient temperature distribution at different time (0.008 s, 0.04 s and 0.064 s) during LMD process on the cross-section of the molten pool. In the LMD process, the laser energy was attenuated by the absorption and reflection of the...
Along the width direction. The simulated temperature history of B, D and E represented the center to the edge of the molten pool the top, center and bottom of the molten pool, respectively. Point A, B and C represented mechanism of microstructure evolution, depth direction and width direction were defined, respectively. Point A, B and C represented the top, center and bottom of the molten pool, respectively. Point B, D and E represented the center to the edge of the molten pool along the width direction. The simulated temperature history of representative points during the deposition process such as the cooling rate and existent time of the molten pool. The temperature of point A and B reached the peak rapidly when the laser beam scanned to the corresponding location and decreased sharply when the heat source was moved off. Nevertheless, temperature of point C raised slowly due to the heat conduction before the laser beam scanned to the corresponding location. Subsequently, the temperature increased fleetly when the laser beam scanned to the corresponding location (Fig. 4b). The temperature history curve of point C was different from that of point A and point B. The points A and B were the nodes of deposition part, while the point C was the node of substrate. The points A and B were at the initial temperature before applying any heat loads as they were killed by technique of element birth and death. It showed that the peak temperature appeared at the top of the molten pool along the depth direction. The temperature evolution of the three marked points in the width direction was obtained. It could be noticed that the temperature gradually decreased from the center to the edge because of the Gauss distribution of laser energy (Fig. 4c). However, the peak temperature of the point D was slightly higher than that of the center of the molten pool (point B) (Fig. 4e). It meant that the peak temperature of the N deposited track was not in the center of the molten pool, but it shifted towards the N-1 deposited track because of the heat accumulation effect. Because of a function of temperature and time, the slopes of the temperature history curves represented the cooling rate of the diverse points in the molten pool. A steep slope meant a relatively high cooling rate. In the depth direction of the N deposited track, the instantaneous cooling rate of the top of the molten pool (point A) was $6.2 \times 10^5 \, ^\circ C/s$, whereas, the instantaneous cooling rate of the bottom of the molten pool was $3.7 \times 10^5 \, ^\circ C/s$. Due to the existence of a certain heat accumulation in the N – 1 deposited track, resulting in generation of the lower cooling of the N deposited track of the molten pool boundary. In

![Image](image_url)

**Fig. 3.** Temperature counters at diverse times during LMD process on the cross-section of the molten pool (X-Z plane): (a) the processing time of $N - 1$ track, $t = 0.008$ s; (b) the processing time of $N$ track, $t = 0.04$ s; (c) the processing time of $N + 1$ track, $t = 0.064$ s.

The direction diagram and the selection of different points in different directions are shown in Fig. 4a. In order to explain the thermal behavior of different directions in LMD process and the mechanism of microstructure evolution, depth direction and width direction were defined, respectively. Point A, B and C represented the top, center and bottom of the molten pool, respectively. Point B, D and E represented the center to the edge of the molten pool along the width direction. The simulated temperature history of powder before reaching the substrate. The remainder laser energy was absorbed by substrate or previously deposited layers, leading to the rapid heating and resultant local melting and good metallurgical bonding between adjacent tracks and layers. It could be observed that substrate was melted by the high-power laser beam and molten pool with certain depth formed (Fig. 3). The transient temperature distribution consisted of a series of isothermal curves. The dash line was the isothermal line of Inconel 625 powder liquidus temperature. The internal area of the dash line curve was the formative molten pool during the manufacturing process. The laser energy was Gaussian distribution, and as a result, the temperature of the molten pool decreased progressively from the center to the edge. It could be found that the molten pool was symmetry of isotherms along the laser scanning direction and the depth of the molten pool is 0.83 mm (Fig. 3a). As the LMD process continued, the part of previously deposited track has been remelted, giving rise to the formation of the metallurgical bonding between the adjacent deposition tracks (Fig. 3b and c). The depth of the molten pool of the N deposited track was 0.75 mm, which decreased by 0.08 mm compared with that of the N-1 deposited track. There was a slight increase compared with the depth of the N deposited track, and the depth of the molten pool of the N + 1 deposited track was 0.76 mm. When the N deposited track was processed, a part of laser energy was absorbed by the former deposited track, leading to the formation of the decreased depth within the molten pool. The rise of temperature slowed down and the dimension of the molten pool tended to be stable as the deposition process continued, because the energy reached a balance status between the heat input and the heat sink.

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represent the overlapping region between adjacent tracks. It could be found that the cooling rate of the point E was slower than that of the point C, therefore, it meant that the overlapping region had relatively slower cooling rate compared with the bottom region.

3.2. Solidification characteristics

Temperature gradient ($G$) and solidification growth rate ($R$) are two main parameters which influence the final morphology of the solidified structure, the scale of grain and the mechanical performance of the deposition part. The solidification growth rate, $R$, refers to the velocity of the solidification front. The type of final solidification microstructure was highly sensitive to the ratio of the temperature gradient and the solidification growth rate ($G/R$). Generally, with the decrease of the $G/R$, the morphology of the final grains changed from plane to cell, cell dendrite, columnar dendrite and then to equiaxed dendrite [30]. It was well known that the grain size was highly dependent on the cooling rate ($V$), and the cooling rate can be expressed as: $V = G \times R$ [31]. Generally, the higher value of $V$, the finer the grain size. Grain refinement could significantly improve the comprehensive mechanical properties of the deposition parts which was defined by the Hall-Petch. Meanwhile, $G$ and $V$ could be obtained directly through the results of simulation, and, thus $R$ could be calculated according to the formula ($V = G \times R$).

Fig. 5 shows the temperature gradient distributions along the molten pool depth and width orientation, respectively. There was a large temperature gradient within molten pool in LMD process.

![Diagram](image_url)
The larger temperature gradient was produced at the area that closed to bottom or edge of molten pool (Fig. 5). Higher temperature gradient always appeared at the bottom of the molten pool reported by other previous some researchers [32]. The major heat of bottom part of the molten pool would dissipate by the thermal conduction of substrate or former solidified layers, resulting in large temperature gradient at the bottom of the molten pool. Meanwhile, the major heat of overlapping region would dissipate by the thermal conduction of former deposited tracks, with the formation of a large temperature gradient at the edge of the molten pool. It could be seen that the maximum temperature gradient in the width direction was larger than that predicted in the depth direction. The heat dissipation was not sufficient in the process of the \( N-1 \) deposited track, which provided preheating effect of the \( N \) deposited track and the resultant smaller temperature gradient. It was obvious that the maximum temperature gradient of the \( N \) deposited track was significantly decreased compared with that of the \( N-1 \) deposited track. The maximum temperature gradient in the depth direction of the \( N-1 \) deposition track was \( 4.9 \times 10^5 \) °C/m, whereas the maximum temperature gradient in depth direction of the \( N \) deposited track was decreased to \( 2.5 \times 10^5 \) °C/m (Fig. 5a). In addition, comparing the maximum temperature gradient in the width direction of the \( N-1 \) and the \( N \) deposited track, the maximum temperature gradient decreased from \( 7.2 \times 10^5 \) °C/m to \( 4.6 \times 10^5 \) °C/m (Fig. 5b).

Fig. 6 depicts the calculated solidification growth rate at diverse points along the molten pool depth and width orientation, respectively. It showed that ascending from the bottom of the molten pool solidification growth rate was prone to increase. Along the depth direction of the \( N-1 \) deposited track, the solidification growth rate increased from 0.283 m/s at the bottom to 0.927 m/s at the top of the molten pool. While the solidification growth rate of the \( N-1 \) and the \( N \) deposited tracks did not change evidently in the depth direction (Fig. 6a). In the width direction, the solidification growth rate was decreased from the center to the edge of the molten pool (Fig. 6b). In the width direction of the \( N-1 \) deposited track, the maximum solidification growth rate was 0.174 m/s at the center and the minimum solidification growth rate was 0.042 m/s at the edge of the molten pool. Furthermore, in the width direction of the \( N \) deposited track, the solidification growth rate at the center of the molten pool (0.201 m/s) was noticeably higher than that at the edge of the molten pool (0.039 m/s).

Fig. 7 presents the diverse \( G/R \) values at diverse points along the molten pool depth and width direction, respectively. In the depth direction, higher \( G/R \) was observed at the lower region of the molten pool, on the contrary, lower \( G/R \) was noticed at the upper region of the molten pool. It could be inferred that there might be different microstructures along the depth direction of the molten pool. The larger temperature gradient was produced at the area that closed to bottom or edge of molten pool (Fig. 5). Higher temperature gradient always appeared at the bottom of the molten pool reported by other previous some researchers [32]. The major heat of bottom part of the molten pool would dissipate by the thermal conduction of substrate or former solidified layers, resulting in large temperature gradient at the bottom of the molten pool. Meanwhile, the major heat of overlapping region would dissipate by the thermal conduction of former deposited tracks, with the formation of a large temperature gradient at the edge of the molten pool. It could be seen that the maximum temperature gradient in the width direction was larger than that predicted in the depth direction. The heat dissipation was not sufficient in the process of the \( N-1 \) deposited track, which provided preheating effect of the \( N \) deposited track and the resultant smaller temperature gradient. It was obvious that the maximum temperature gradient of the \( N \) deposited track was significantly decreased compared with that of the \( N-1 \) deposited track. The maximum temperature gradient in the depth direction of the \( N-1 \) deposition track was \( 4.9 \times 10^5 \) °C/m, whereas the maximum temperature gradient in depth direction of the \( N \) deposited track was decreased to \( 2.5 \times 10^5 \) °C/m (Fig. 5a). In addition, comparing the maximum temperature gradient in the width direction of the \( N-1 \) and the \( N \) deposited track, the maximum temperature gradient decreased from \( 7.2 \times 10^5 \) °C/m to \( 4.6 \times 10^5 \) °C/m (Fig. 5b).

Fig. 6. The calculated results show the solidification growth rate at different monitoring points in different directions: (a) along the depth direction from top to bottom within molten pool of variable tracks; (b) along the width direction from center to edge within molten pool of variable tracks.
molten pool. The maximum G/R in the depth direction of the N-1 deposited track located at the bottom of the molten pool and, the G/R was 1.22 \times 10^7 \text{C s/m}^2, meanwhile, the minimum G/R was 5.08 \times 10^5 \text{C s/m}^2. In addition, the G/R in the depth direction of the N deposited track was decreased from 1.22 \times 10^7 \text{C s/m}^2 to 7.3 \times 10^5 \text{C s/m}^2 from the bottom to the top of the molten pool (Fig. 7a). The G/R had a dramatic increase from the center to the edge of the molten pool, and the G/R of the N/C0 deposited track increased from 1.0 \times 10^7 \text{C s/m}^2 to 1.69 \times 10^8 \text{C s/m}^2. Simultaneously, the G/R had no apparent fluctuation at the center of the molten pool of variable deposited tracks. However, the G/R value at the edge of the N deposited track was decreased to 1.18 \times 10^8 \text{C s/m}^2 compared with that at the edge of the N-1 deposited track (1.69 \times 10^8 \text{C s/m}^2) (Fig. 7). It was noteworthy that the maximum G/R value was occurred at the edge of the molten pool (Fig. 7).

3.3. Microstructure

The simulation results showed that sound metallurgical bonding might be obtained in the simulated process parameters. Fig. 8 shows the optical microscopy image of the cross-sectional morphology characteristics of LMD-processed Inconel 625 according to the simulated process parameters. The sample obtained with a sufficiently high densification, the relative density is about 99.3%. At the same time, the deposited part with no obvious defects such as apparent pores or cracks (Fig. 8a), which meant Inconel 625 might be an adequate material for LMD. Sound metallurgical bond formed between adjacent tracks and neighbor layers. Due to the track-by-track and layer-by-layer deposition of the LMD forming process, the layer-wise microstructure characteristics of the deposited part with apparent molten pool outline curve was observed (Fig. 8b).

Fig. 8 shows the SEM images of molten pool and microstructure the LMD-processed Inconel 625. Constitutional supercooling occurred with solute redistribution which caused the liquid at the solidification front to be cooler than the liquids temperature. The degree of constitutional supercooling was determined by G and the kinetics of mass transfer (i.e., R). As stated previously, the type of final solidification microstructure was highly sensitive to G/R. Complex thermal history and thermal behavior in LMD process brought about different microstructural in different regions of the molten pool (Fig. 9). It was well known that the dendrite growth orientations are aligned with the principal heat flux direction [33,34]. Consequently, it was apparent that columnar dendrites grew epitaxially from the boundary of the molten pool and along the direction perpendicular to the boundary. At the lower region of the molten pool, a higher value of G (Fig. 5a) and a lower R were observed (Fig. 6a), leading to a higher value of G/R ratio (Fig. 7a) in the region A (Fig. 9b). Similar results were also reported by other researchers [35,36]. Ascending from the bottom of the molten pool, R tended to increase gradually and G tended to decrease gradually, giving rise to a lower value of G/R at the upper region of the molten pool. Thus, equiaxed dendrites were observed at the upper region of the molten pool (Fig. 9c). In the width direction, from the center of the molten pool to the edge of the molten pool, the G/R value had a dramatic increase. In the width direction, the maximum G/R value was occurred at the edge of the molten pool as mentioned above. Hence, the epitaxial building direction
of the columnar dendrites was nearly along width direction in the region C (Fig. 9d). In addition, the region C represented overlapping portion between previously deposited track and the subsequently deposited track. The simulation results showed that the lower cooling rate of $1.8 \times 10^5 \, ^\circ \text{C/s}$ was obtained at the overlapping region, whereas the cooling rate at the bottom of molten pool was relatively larger ($3.7 \times 10^5 \, ^\circ \text{C/s}$) because of the impact of relatively stronger heat dissipation. The faster cooling rate improved the nucleation site and nucleation quantity inducing increased nucleation rate, which resulted in the refined grains [37]. That was the result why columnar dendrites generated in the region C were coarser compared with that in the region A. The microstructure of LMD-processed Inconel 625 was agreed with the simulation results.

4. Conclusions

A three-dimension finite element model was proposed to simulate thermal behavior during LMD of Inconel 625. The LMD experiment was carried out and microstructure of LMD-processed part was investigated. According to the present study, several conclusions were summarized below:

1. The rise of temperature slowed down and the dimension of the molten pool tended to be stable as the deposition process continued. High cooling rate located at the top of the molten pool, meanwhile, low cooling rate occurred at the bottom and the edge of the molten pool. Besides, it could be found that the cooling rate at edge of the molten pool was higher than that at the bottom.

2. The maximum temperature gradient was noticed at the boundary of the molten pool. The maximum temperature gradient in the width direction was larger than the temperature gradient in the depth direction. In the depth direction, $R$ gradually increased from the bottom of the molten pool to the top of the molten pool. Simultaneously, in the width direction, the change trend of the solidification growth rate was decreased from the center to the edge of the molten pool. Generally, there was an inverse distribution behavior between the $G/R$ and $R$.

3. It could be noticed that columnar dendrites grew epitaxially from the boundary of the molten pool and along the direction perpendicular to the boundary, while equiaxed dendrites were observed at the upper region of the molten pool. The morphology of the solidified structures were in consistency with $G/R$ and coarser columnar dendrites generated in the low value of $G \times R$. The independent observation of microstructure strongly agreed with the simulation results.

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