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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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ABSTRACT

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 ($G \times R$) 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 7.3×10^5 °C s/m^2 at the top of the molten pool to 1.22×10^7 °C s/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 (1.18×10^8 °C s/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.

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 endued 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 γ'' [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

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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. Alimardani 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 in this finite volume model. Costa et al. [19] established a multilayer 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:

$$\frac{\partial(\rho(T) \times C_p(T) \times T)}{\partial T} = \frac{\partial}{\partial x}\left(K_x(T) \times \frac{\partial T}{\partial x} + \frac{\partial}{\partial y}(K_y(T) \times \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z(T) \times \frac{\partial t}{\partial z}\right) + \dot{Q}(x, y, z) \quad (1)$$

where $\rho(T)$ is the temperature-dependent material density, C_p is temperature-dependent specific, $K_x(T)$ is temperature-dependent thermal conductivity, and $\dot{Q}(x, y, z, t)$ 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 ζK [25].

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

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

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:

$$H = \int \rho C_p dT \quad (3)$$

where H is the enthalpy, ρ is the material density of Inconel 625 (8440 kg/m^3), 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:

$$T(x, y, t)|_{t=0} = T_{amb}(x, y, z) \in D \quad (4)$$

where T_{amb} is the ambient temperature.

The convection and radiation boundary condition can be considered together as: