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Research on Energy Distribution and Solidification Characteristics During Laser Cladding Based on Numerical Simulation

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Abstract: Laser cladding as an emerging surface modification technology can be widely adopted for surface modification. In this study, 27SiMn was selected as the substrate, the powder was a self-made iron-based alloy, and the thermophysical properties of the material were predicted by the CALPHAD algorithm. The numerical model of the laser cladding process is established by setting reasonable hypothetical condition, initial condition, boundary condition, and solver parameters. In order to verify the accuracy of the numerical model, 10 sets of experiments have been carried out, and the agreement between the model calculation results and the experimental results reached 92%. Through the study of energy distribution in the laser cladding process, it is found that about 10% of the laser energy is used to heat the substrate to form a melt-pool, and at least 53% of the energy is radiated into the environment. Finally, the effects of temperature gradient and solidification rate on the microstructure of the cladding layer were explored.

Keywords: Laser cladding, Numerical simulation, arbitrary lagrange-euler algorithm, Solidification characteristics, Surface modification

1 Introduction

Laser cladding is one of the additive manufacturing technologies using laser as the heat source. Compared with other additive manufacturing techniques, it holds advantages like high forming precision, small heat affected zone, and easy achievement of automation, and has been widely used in aerospace^[1], resource mining^[2], the nuclear industry^[3] and other industries.

Because a lot of light and heat would be released during the laser cladding process, in recent years, scholars have begun to use numerical simulation technology to study the temperature and flow of the melt-pool in the laser cladding process. Jiang Yichao^[4] used the Finite Volume Method (FVM) to simulate the temperature distribution and fluid flow of the laser cladding process in the form of preset-powder, and studied the influence of the Marangoni effect on the size of the melt-pool. Zhe Sun^[5] established a three-dimensional numerical model to study the mass transfer and heat transfer in the melt-pool in the laser molten in 316L stainless steel. However, the author did not consider the attenuation of laser in the laser cladding process. H.L. Wei^[6] established a three-dimensional model for coupling simulation of heat transfer and fluid flow, and a two-dimensional model for simulating grain formation in the melt-pool. It shows that the columnar grains grow in a bending mode, and the critical scanning speed of the columnar while transformed into equiaxed crystals was obtained. However, in the research process, the size of the melt-pool was limited in advance, which caused a large deviation between simulation results and experimental results. Wenyan Gao^[7] established a three-dimensional finite element model for simulating the temperature field in the laser cladding process, and used the life and death unit algorithm to represent the formation process of the cladding layer. The instantaneous temperature distribution and temperature curve were obtained, and the solidification and cooling rate of the moving solid-liquid interface and its influence on the microstructure of the cladding layer were systematically analyzed and calculated. Due to the characteristics of the life and death unit algorithm, it is not suitable for predicting the formation process of the cladding layer, which makes the cladding layer model seriously distorted.

In this study, 10 groups of different process parameters laser cladding processes were simulated, and corresponding experiments were conducted to verify the accuracy of simulation results. The effects of process parameters on the laser cladding layer were discussed. The substrate and powder physical properties are associated with temperature, and the temperature physical properties of the desired material were calculated by the CALPHAD algorithm. By measuring the verification of model

accuracy in the layered contour size, the effects of process parameters on the laser cladding layer are discussed. And a relatively reasonable energy allocation model was obtained after discussing the results of the model calculation, and the effects of temperature gradient and solidification speed on microstructure morphology and size were analyzed.

2 Experiments

2.1 Experimental Materials

The material of substrate was 27SiMn in this study, which was the main material of the domestic hydraulic cylinder. The powder material is self-made iron-based alloy powder with particle size distribution of 20-53 μ m, which has good wear resistance, corrosion resistance, and excellent machining properties, and the fluid phase temperature and the expansion coefficient are similar to 27SiMn. Therefore, the powder and the substrate can form a firm metallurgy binding. The element mass fractions of the two materials are shown in Table 1.

The the CALPHAD algorithm is used to calculate the thermophysical properties of the material in this study. Through repeated verification by some scholars^[8,9], the calculation result of the CALPHAD algorithm is close to the experimental result. The thermophysical properties of the substrate and powder are shown in Fig.1.

According to the Hagen-Ruben relational formula ^[10], the laser power absorptivity value of the substrate and powder can be obtained, as shown in eq.(1):

$$\beta_{s/p} = (8\varepsilon_0\varphi R(T))^{1/2} \quad (1)$$

In eq.(1), $\varepsilon_0 = 1/36\pi \times 10^9 \text{ F} \cdot \text{m}^{-1}$, $\varphi = 2\pi c/\lambda$, c represents the speed of light in the vacuum; λ is the laser wavelength; $R(T)$ represents the resistivity of the material, which is a function that changes with temperature. The laser absorption rate of the substrate is shown in Fig.2. In order to simplify the calculation, a constant is selected as the laser absorptivity value of powder. As the powder falls into the melt-pool in a liquid form, β_p is taken as 0.47.

2.1 Experimental equipment

The experimental parameters of this study are as shown in Table 2.

Schematic diagram of laser classes is as shown in Fig.3. In the experiment, in order to explore the mutual coupling of laser and powder and determine the diameter of the powder flow profile, the experimental photo is photographed as shown in Fig. 4 (a)., in which the replacement light is a red light having a power of 5W. The image recognition algorithm is used to extract the powder flow profile and 11 data points are selected. The establishment of the coordinate system is as shown in Fig. 4 (b), fitted to the expression of r_p in the z direction, as in the eq.(2), fitted image as shown in Fig. 4 (c).

$$r_p = 0.05z^2 - 0.28z + 1.38 \quad (0 \leq z \leq h_1) \quad (2)$$

2.3 Process parameters

This study adopts the method of orthogonal experiment, and the process parameters of the experiment were as shown in Table 3. Exp.1, 2, 3, 4 are used to explore the effects of different laser power on laser cladding processes; exp.1, 5, 6, 7 are used to explore the effects of different delivery rates on laser cladding processes; exp.1, 8, 9, 10 are used to explore the effects of different scanning speed on the laser cladding process. The size of the substrate is 300mm×300mm×20mm, and the room temperature is 298K. Before the experiment, the powder was dried at 373K for 2 hours.

2.4 Experimental detection

The cladding layers of the 10 groups of experiments were made into 10 sample blocks with a size of 10 mm×10 mm×15 mm, and the cross-section of those cladding layers were ground, polished, corroded, and cleaned. The height and width of the cladding layer were observed under a metallographic microscope, and the microstructure was photographed with a scanning electron microscope (SEM).

3 Simulation

The use of numerical simulation in the field of engineering study is increasing. The content of the simulation is based on basic control equations, set of reasonable assumptions, initial conditions and boundary conditions, so the numerical model is both efficient and realistic.

3.1 Assumptions

Appropriate assumptions can reduce the nonlinearity of the numerical model and enhance convergence. The basic assumptions in this study are:

1. The liquid metal in the melt-pool is Newtonian, incompressible, laminar fluid.
2. Laser, and powder flow complies with the Gaussian distribution, the powder flow profile is not affected by the powder feeding rate, and the particles in the air do not block or collide with each other.
3. Ignore the energy loss caused by evaporation.
4. The mushy zone between the solid line and the liquid line of the melt-pool is assumed to be isotropic porous medium.
5. The powder is a standard sphere and is heated evenly.
6. Ignore the laser energy entering the melt-pool through the reflection of powder particles.

3.2 Governing equation

The mass conservation equation ^[11] is as in eq.(3):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = S_{mass} \quad (3)$$

The energy conservation equation is as in eq.(4):

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p v \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q - Q_p - Q_{vd} \quad (4)$$

In eq. (3), S_{mass} represents the added powder mass; in eq. (4), the first term on the left is the transient heat transfer, the second term is the convective heat transfer, and the third term is the conduction heat transfer. The first term on the right is the heat source, the second term is the convection heat transfer with the outside, and the third term is the surface heat radiation.

The momentum conservation equation (Navier-Stokes equation) is as eq.(5):

$$\rho \frac{\partial v}{\partial t} + \rho (v \cdot \nabla) v = \nabla \cdot (\mu (\nabla v + (\nabla v)^T)) - pI + F \quad (5)$$

In eq.(5), the left side represents the inertial force, the first term on the right represents the viscous force and pressure, and the second term on the right represents the volume force of the liquid in the melt-pool.

3.3 Initial conditions

In order to save computational cost, a symmetric method is adopted to simplify the numerical model. A rectangular parallelepiped model with a size of 10mm×4mm×4mm is established and divided into two calculation domains. The shape of calculation domain A is 10mm×1.5mm×1.5mm. The mesh type is a free tetrahedral mesh. And computational domain A is the main area for melt-pool calculation. The required accuracy is high. The maximum element size is 0.2mm; Computational domain B is only used for heat transfer calculations, and the maximum element size is set to be 0.4 mm. As shown in Fig.5.

The parameters of the model are as follows: initial temperature $T_0=298K$, external pressure $P_0=1[atm]$, material convection velocity $V_0=0m/s$, initial displacement $d_0=0m$, and the concentration of each element of the substrate material is set as the initial concentration.

3.4 Boundary conditions

3.4.1 Thermal boundary conditions

The laser will pass through the powder flow before reaching the substrate, and the powder flow will attenuate the laser energy. Attenuation is caused by the combined effects of powder particles on laser energy absorption, diffraction, transmission and refraction, and reflection ^[12]. At the same time, the powder absorbs laser energy to increase its internal energy and change its physical state. Before reaching the substrate, the powder particles move in a straight line at a uniform speed. The speed is the same as the vertical speed component of the powder-carrying gas at the outlet, and the speed direction is perpendicular to the surface of the substrate.

The concentration of powder flow in space is as eq.(6) ^[13]:

$$C(x, y, z) = \frac{27m_f}{8\pi^2 r_0^3 \rho_p r_p^2 v_z} \exp\left(-\frac{9(x^2 + y^2)}{2r_p^2}\right) \quad (6)$$

The shading area of powder particles is shown in eq.(7):

$$S_p = 2\pi r_0^2 \quad (7)$$

The powder speed is as in eq. (8), and θ is the angle between the outlet of the

powder-carrying gas and the vertical direction.

$$v_z = \frac{V}{\pi(R_1^2 - R_2^2)} \sin \theta \quad (8)$$

The laser utilization rate is as in eq. (9) ^[14]:

$$\eta = \exp \left(-\frac{3m_f S_p}{4\pi^2 r_0^3 \rho_p r_{p0}^2 v_z} \int_0^{h_1} \left(1 - \exp \left(-\frac{9r_{p0}^2}{2r_p^2} \right) \right) dz \right) \quad (9)$$

The average temperature T_i of the powder before falling into the melt-pool is as in eq. (10):

$$T_i = \frac{(1 - \eta)P_0 \beta_p}{m_f C_{p,p}} + T_0 \quad (10)$$

The initial energy of the laser is as in eq. (11):

$$Q_0 = \frac{2P_0}{\pi \times r_l^2} \exp \left(\frac{-2(x^2 + y^2)}{r_l^2} \right) \quad (11)$$

The heat source formula added on the surface of the model is as in eq. (12) ^[15]:

$$Q_s = \frac{2P_0 \eta \beta_s}{\pi r_l^2} \exp \left(\frac{-2((x - v_x t)^2 + y^2)}{r_l^2} \right) - \frac{2m_f \eta_p}{\pi r_p^2} (L_H + C_p(T - T_i)) \exp \left(\frac{-2((x - v_x t)^2 + y^2)}{r_p^2} \right) \quad (12)$$

f_l is the liquid volume fraction, defined as in eq.(13):

$$f_l = \begin{cases} 1, & T_l < T \\ \frac{T - T_s}{T_l - T_s}, & T_s < T < T_l \\ 0, & T_0 < T < T_s \end{cases} \quad (13)$$

In eq. (13), T_0 is the ambient temperature; T_s , T_l are the solidus and liquidus temperatures of the material, respectively

When the temperature is between the solidus temperature and the liquidus temperature, the metal material is in a molten state, and the thermophysical properties

of the material in this region are as shown in eq.(14)~eq.(17).

$$\begin{aligned} & \rho \\ & = (1 - f_l)\rho_s \\ & + f_l\rho_l \end{aligned} \quad (14)$$

$$\begin{aligned} & k \\ & = (1 - f_l)k_s \\ & + f_lk_l \end{aligned} \quad (15)$$

$$\begin{aligned} & \alpha_m \\ & = \frac{1}{2} \frac{f_l\rho_l - (1 - f_l)\rho_s}{(1 - f_l)\rho_s + f_l\rho_l} \end{aligned} \quad (16)$$

$$\begin{aligned} & C_p = \frac{1}{\rho} ((1 - f_l)\rho_s C_{ps} + f_l\rho_l C_{pl}) \\ & + L_H \frac{\partial \alpha_m}{\partial T} \end{aligned} \quad (17)$$

When the temperature of the substrate rises, it will form heat convection with the surrounding air and generate heat radiation to the environment, as shown in eq. (18) and eq. (19) respectively,

$$\begin{aligned} & Q_p \\ & = h(T \\ & - T_0) \end{aligned} \quad (18)$$

$$\begin{aligned} & Q_{vd} \\ & = \varepsilon\sigma(T^4 - T_0^4) \end{aligned} \quad (19)$$

h is the convective heat transfer coefficient, which takes 0.7; ε is surface emissivity; σ is Stephan Boltzmann's constant, the value is $5.67 \times 10^{-8} \text{W}/(\text{m}^2 \cdot \text{K}^4)$

3.4.2 Fluid boundary conditions

The volume force received by the liquid in the melt-pool in eq.(5) can be expanded to eq.(20):

$$F = -\rho g + \alpha(T - T_l)\rho g - K_0 \frac{(1 - f_l)^2}{f_l^3 + m} v \quad (20)$$

In the formula, the first term on the right represents gravity; the second term on the right represents thermal buoyancy, α is the thermal expansion coefficient of the mixed material in the melt-pool, and the direction is vertically upward; the third term

on the right represents the Momentum dissipation of the porous media layer between the solid phase and the liquid phase on the liquid metal in the melt-pool, where K_0 takes the larger value, $10^6 \text{kg}/(\text{m}^3 \cdot \text{s})$; and in order to avoid division by zero errors, m takes the smaller value, 10^{-4} [16].

On the surface of the melt-pool, the liquid metal is subject to surface tension. The surface tension coefficient is a physical quantity that changes with temperature and concentration. In this study, the influence of concentration changes on surface tension is not considered. The curve of the surface tension coefficient with temperature can be obtained based on the CALPHAD algorithm, as shown in Fig.6. It can be seen from Fig.6 that the higher the temperature, the smaller the surface tension coefficient, that is, the surface tension temperature coefficient is negative. Since the temperature decreases from the center of the melt-pool to the edge, the surface tension also decreases from the center of the melt-pool to the edge, forming a surface tension gradient. The liquid flows from the direction of low surface tension to high tension, thereby driving the transmission of mass. This phenomenon is called the Marangoni effect.

As a dimensionless number, the Marangoni number is proportional to the ratio of the surface tension divided by the viscous force, indicating the degree of the Marangoni effect on the flow of liquid metal.

$$Ma = - \frac{d\gamma}{dT} \cdot \frac{L\Delta T}{\mu\alpha} \quad (21)$$

$d\gamma/dT$ is the temperature coefficient of surface tension, L is the characteristic length, μ is the dynamic viscosity, and ΔT is the maximum temperature difference in the melt-pool.

The force on the surface of the melt-pool is as follows (22):

$$F_s$$

$$= \gamma n_m \kappa - \frac{d\gamma}{dT} \nabla_t T \quad (22)$$

γ is the surface tension coefficient, n_m is the normal vector of the melt-pool surface, κ is the average curvature of the melt-pool surface, and ∇_t is the tangential guide number operator of the melt-pool surface.

3.4.3 Mass transfer boundary conditions

In the numerical simulation, the adding process of powder can be resolved into volume change and element change. The volume change is characterized by the dynamic grid algorithm, and the element change is represented by the matter flux equation. The transmission speed of the element and the velocity field are set in a coupling relationship.

The material flux^[17] on the surface of the melt-pool is as in eq. (23):

$$q_i = \omega_i \frac{2m_f \eta_m}{M_i \pi r_p^2} \exp\left(\frac{-2((x - V_x t)^2 + y^2)}{r_p^2}\right) \quad (23)$$

During the cladding process, the powder falls into the melt-pool and fully mixes with the substrate under the action of the Marangoni effect. Therefore, the thermophysical properties of the liquid metal in the melt-pool are determined by the properties of the substrate and the powder.

$$P = P_p \times \sigma_p + P_s \times (1 - \sigma_p) \quad (24)$$

In eq.(24)^[18], P represents the thermophysical properties of the model, including density, thermal conductivity, dynamic viscosity, constant pressure heat capacity, surface tension coefficient, etc., P_s and P_p represent the thermophysical properties of the powder and the substrate, respectively. σ_p represents the degree of powder mixing in the melt-pool, and is calculated by eq.(25)^[16]:

$$\sigma_p = \frac{c_{Fe} - c_{Fe_s}}{c_{Fe_p} - c_{Fe_s}} \times 100\% \quad (25)$$

c_{Fe} represents the iron element concentration of the model in the transient calculation process, c_{Fe_s} and c_{Fe_p} represent the initial iron element concentration in the substrate and powders respectively, the unit is mol/m^3 .

3.4.4 Mesh boundary conditions

The algorithms currently used to represent volume changes mainly include life and death units^[7,19], level sets^[20], and the Arbitrary Lagrangian Eulerian (ALE) moving mesh approach^[21]. Given that the forming accuracy of the life and death unit algorithm is low, the level set algorithm is complex and is difficult to set, while the moving grid algorithm is simple to set up and can form a more accurate interface, the dynamic grid algorithm is used to characterize the formation of the cladding layer.

The moving speed of the melt-pool surface is mainly affected by the addition of powder and the flow of liquid metal in the melt-pool, therefore in the ALE moving mesh approach, the moving speed of the melt-pool surface^[21] is

$$V_s = V_p \cdot n_m + v \cdot n_m \quad (26)$$

In eq.(26), V_s is the moving speed of the melt-pool surface, V_p is the moving speed of the melt-pool surface due to powder addition, v is the flow velocity of the liquid metal on the melt-pool surface, and n_m represents the unit normal vector of the melt-pool surface.

The moving speed of the melt-pool surface due to powder addition is

$$V_p = \frac{2m_f\eta_p}{\rho_p\pi r_{p0}^2} \exp\left(\frac{-2((x - V_x t)^2 + y^2)}{r_p^2}\right) \cdot z_m \quad (27)$$

In eq.(27), η_p is the powder utilization rate, ρ_p is the density of the powder, r_{p0} is the radius of the powder flow on the substrate, and z_m is the unit vector in the z direction

4 Results and discussion

4.1 The results of numerical calculation

A heat source is applied on the upper surface of the model, initial conditions and boundary conditions are given in 2.4.1, and the temperature field at different times is obtained.

Temperature distribution at different times is as shown in Fig.7. At the initial stage of laser cladding, the laser starts to heat the substrate, the melt-pool has not been formed at this time, and the temperature is reduced from the center to the surrounding. When the local temperature is higher than the material liquid phase line temperature,

the substrate changes into a melt-pool. As the powder continues to accumulate in the melt-pool, the model surface begins to deform. As the laser beam moves in the scanning direction, the temperature gradient in the melt-pool exhibits high front end and low back ends.

Fig.8 is the distribution profile of velocity at different times. At the initial stage of melt-pool formation, the liquid metal in the melt-pool does not flow. As the temperature increases, the volume of melt-pool expands, and the liquid metal in the melt-pool flows under the action of surface tension, gravity and thermal buoyancy. Because the temperature coefficient of surface tension is negative, the liquid metal on the melt-pool surface flows from the center to the edge under the influence of Marangoni effect. Due to the existence of gravity and thermal buoyancy, liquid metal flows into the bottom of the melt-pool along the solidification interface, and then rises to the surface of the melt-pool, forming eddy current from inside to outside. Under the action of eddy current, wide and shallow melt-pool is formed. As the melt-pool moves, the temperature rises and the shape of the melt-pool gradually changes from a semicircle to an ellipsoid. The flow velocity in the melt-pool accelerates until it becomes stable. As shown in Fig.8, the white line segment represents the liquid and solid phase lines of the model, and the arrow represents the flow direction of liquid metal in the melt-pool. The velocity direction is consistent with the research results of Acharya et al. ^[22], and the value is of the same order of magnitude.

When the model of exp.1 was calculated to 100ms, the temperature and velocity distribution curves of the melt-pool surface along the scanning velocity direction are as shown in Fig.9.

It can be seen from Fig.8 and 9 that the flow rate of liquid metal on the melt-pool surface presents a hump distribution, and the flow rate at the bottom of the melt-pool is lower than that on the melt-pool surface, and the maximum velocity in the melt-pool is 0.25m/s. Marangoni effect plays an important role in promoting the flow of liquid metal in the melt-pool. The greater the temperature gradient, the more intense the Marangoni effect, and thus the greater the acceleration. The flow at the bottom of the melt-pool is affected by the process of cellular crystal forming, resulting

in momentum loss. The liquid metal at the bottom of the pool flows upward under the action of thermal buoyancy. The velocity at the center of the melt-pool surface is close to that at the bottom of the pool because the thermal buoyancy is not sufficient to produce large flow acceleration.

4.2 Comparison of external dimensions

Comparing the profile size of cladding layer is the most intuitive and simplest method to verify the model accuracy. Fig.10 shows the dimensions of the cross section obtained by experiment and simulation.

It can be seen from Fig. 10(b) that when only the laser power is changed, the height of the cladding layer hardly changes, and the width increases with the increase of the laser power. The reason is that with the laser power becoming larger, the energy irradiated to the surface of the substrate increases, the temperature at the center of the melt-pool increases, and the width of the melt-pool becomes larger. While the height of the cladding layer is mainly related to the amount of powder falling into the melt-pool, so under the premise of constant powder feeding rate, the height of the center of the cladding layer remains unchanged.

It can be seen from Fig.10(c) that when only the powder feeding rate is changed, the width of the cladding layer has no obvious trend. Although in theory, the larger the powder feeding rate, the smaller the laser attenuation rate, in this experiment, the change in the attenuation rate caused by the change in the powder feeding rate is not obvious. The height of the cladding layer decreases significantly as the powder feeding rate decreases.

It can be seen from Fig. 10(d) that when only the scanning speed is changed, the width and height of the cladding layer have obvious changes. The increase of scanning speed will lead to the decrease of the instantaneous energy density and instantaneous powder concentration on the substrate, which will form a narrow and long melt-pool. The scanning speed should be selected in an appropriate interval. When the scanning speed is too high, the material on the surface of the substrate cannot be melted sufficiently, forming a cladding layer with poor bonding, or even no cladding layer. When the scanning speed is too low, disordered accumulation of

powder will be caused.

As can be seen from Fig.10, the height of the layer obtained by simulation is greater than the experimental measurement, and the width is slightly smaller. In the study, in order to reduce the degree of nonlinearity of the model, the dynamic viscosity of the liquid metal in the melt-pool is limited, resulting in deterioration of fluidity, so the width of the molten coating layer of the simulation will be smaller; During the laser cladding experiment, the powder is ejected from the nozzle, which causes some powder loss, and this phenomenon is ignored in the simulation, so the high degree of simulation is slightly higher than the height measured by the experiment. The maximum error of the experimental measured shape and simulation calculation is 8%, indicating the rationality of three-dimensional laser cladding model.

4.3 Energy distribution

The energy transfer process of laser cladding is shown in Fig.11.

The initial energy Q_0 output by the laser reaches the surface of the substrate after the attenuation of the powder. However, not all the attenuated energy will be absorbed by the substrate material, the substrate has a certain absorption rate β_s of laser energy, which is related to the resistivity of the material and the laser wavelength. During the experiment, the laser wavelength is a constant, the material resistivity is a physical property related to temperature, and the laser absorption rate of the substrate is as shown in Fig.2. Part of the energy attenuated by the powder is absorbed by the powder, and the rest is released to the outside world through refraction, scattering, and reflection. Only the powder falling into the melt-pool can play a role in the formation of the cladding layer, so the powder utilization rate η_p represents the ratio of the amount of powder falling into the melt-pool to the total amount of powder.

The laser energy absorbed according to Fig.11 is as shown in eq.28:

$$Q_s = Q_0 \eta \beta_s \quad (28)$$

According to eq.9, the laser utilization $\eta=0.2$ is obtained. According to Fig.2, it is known that the laser absorption rate of the substrate is $\beta_s = 0.475$, so $Q_s \approx 0.10Q_0$, that is 10% of the laser energy in exp.1 is used to heat the substrate to form a melt-pool.

During the transmission of laser energy, the dissipative energy is as shown in eq.29:

$$Q_{loss} = Q_0 \left(\eta(1 - \beta_s) + (1 - \eta)(1 - \beta_p) + (1 - \eta)\beta_p(1 - \eta_p) \right) \quad (29)$$

When powder utilization $\eta_p = 1$, $Q_{loss} \approx 0.53Q_0$ is calculated, that is at least 53% of the laser energy in the cladding process is released into the environment.

The thermal input in the melt-pool is as shown in eq.30:

$$\begin{aligned} Q \\ = Q_0(\eta\beta_s \\ + (1 - \eta)\beta_p\eta_p) \end{aligned} \quad (30)$$

After analysis and calculation, it is found that the energy for heating the substrate to form the fuse pool only accounts for 10% of the laser output energy; about 53% of energy is consumed. The research results of Gedda et al. ^[13] have proved this conclusion.

4.5 Solidification characteristics

The laser cladding process needs to undergo rapid heating and cooling. In this process, the temperature gradient (G) and the solidification speed (S) on the solidification interface are two crucial parameters. The changes of G and S will directly affect the microstructure of the cladding layer, and then affect the surface quality of the cladding layer. The influence of G and S on the microstructure is as shown in Fig.12 ^[23].

$G \times S$ is defined as the cooling rate, which directly determines the size of microstructure grains. The faster the cooling rate, the finer the microstructure grains. The value of G/S determines the microstructure morphology. As G/S gradually increases, the microstructure morphology changes from cellular to equiaxed dendritic.

The directions of G and S are perpendicular to the solidification interface, and the expressions are respectively ^[24]:

$$\begin{aligned} G \\ = \|\nabla T\| \end{aligned} \quad (30)$$

$$S = v_x \cos \delta = v_x \frac{-\partial T / \partial x}{G} \quad (31)$$

In eq.(31), δ represents the angle between the normal vector of the solidification interface and the scanning speed direction on the vertical plane. The minimum of which at the top of the cladding layer is almost 0° , and the maximum at the bottom is 90° , so the solidification speed at the top is most close to the scanning speed, and the minimum at the bottom is 0m/s. The projection diagram of the solidification interface on the melt-pool symmetry is as shown in Fig.13.

The simulation result when the time is 200ms in exp.1 is selected, and the size of G and S on the solidification interface is projected on a two-dimensional plane, as shown in Fig.14.

As can be seen from Fig.14 (a), G gradually increases from the top of the center of the solidification interface, and the variable region is at the edge; As can be seen from Fig.14 (b), S gradually decreases from the top of the center of the solidification interface.

The sample of exp.1 was selected for line cutting, grinding, etching, and the microstructure of the cladding layer under the SEM is as shown in Fig.15. From the top to the bottom of the molten coating symmetry, isometric measuring points A, B, C are selected. From point A to point C, $G \times S$ decreases from 9456 K/s from 1978K/s, and the microstructure grain gradually becomes larger; G/S increases from 66Ks/mm² to 495Ks/mm², and the microstructure is transformed from equiaxed dendritic to cellular. The experimental results are highly consistent with the simulation results, and the model has high reliability.

5 Conclusion

1. This study established a multi-physical field coupling non-organized three-dimensional numerical model. Based on energy conservation, matter conservation and momentum conservation, the thermal transfer phenomenon of the cladding process is simulated, in which the ALE method is used to characterize the formation process of the cladding layer. The accuracy of the model was found to be 92% by comparing the 10 sets of experimental results with the molten layers in the

simulation results.

2. The transfer process of laser energy during laser cladding was explored. After light powder coupling, the laser output energy is simply understood as the process of heating the substrate and the powder respectively. For limit of laser wavelength, laser absorption of the substrate and the powder is limited, thus a lot of energy cannot be absorbed. It could be concluded from research content that: 10% of laser energy is used to heat the melt-pool; and about 53% of laser energy is emitted divergently into the environment.

3. The microstructure can be predicted by numerical simulation. When the laser power is 1.9 kW, the powder feeding rate is 11.4 g/min, and the scanning speed is 1500 mm/min, from point A to point C on the cross section of the molten layer, $G \times S$ decreases from 9456 K/s to 1978 K/s, and the microstructure size gradually becomes larger; G/S increases from 66 Ks/mm² to 495 Ks/mm², and the microstructure is transformed into a column crystal. The value of $G \times S$ is negatively correlated with microstructure size, and G/S determines the change of microstructure.

Availability of data and materials

The findings of this work are available within the article.

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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.

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Fig.1 Thermophysical properties of substrate and powder (a) density (b) thermal conductivity (c) thermal expansion coefficient (d) constant pressure heat capacity

Fig.2 Laser absorption of the substrate

Fig.3 Schematic diagram of laser cladding

Fig.4 Determination of the powder flow radius relationship (a) Original image of the camera (b) Extracting data points on the contour (c) Fitting curve

Fig.5 Mesh division of the calculation area

Fig.6 Surface tension coefficient curve of the substrate and powder

Fig.7 Temperature distribution at different moments in the simulation results of exp.1
(a)30ms(b)50ms(c)100ms(d)150ms

Fig.8 Velocity distribution at different moments in the simulation results of exp.1
(a)30ms(b)50ms(c)100ms(d)150ms

Fig.9 Temperature and velocity distribution curve in the direction of scanning speed on the surface of the melt-pool

Fig.10. Numerical prediction and experimental results of the dimensions of the deposited single tracks for (a) Schematic cross section (b) varying laser power (c) varying powder feeding rate (d) varying laser scanning speed.

Fig.11 Energy distribution process in the cladding process

Fig.12 The influence of G and S on the microstructure

Fig.13 Projection of the solidification interface on the melt-pool symmetry

Fig.14 (a)The temperature gradient G and (b)the solidification rate S in the calculation results

Fig.15 The microstructure of points A, B and C of the cladding layer in exp.No.1

Table 1 Elemental mass fractions of substrate and powder (wt%)

element	Fe	C	Cr	Ni	Mn	Si	P	S	Mo
substrate	Bal.	0.3	0.3	0.2	1.25	1.25	0.03	0.03	-
powder	Bal.	0.15	18	2.5	-	-	-	-	0.5

Table 2 Process parameters of each experiment

Maximum output power of laser $P_{\max}$	2000W
Laser center wavelength λ	1080nm
Laser beam diameter $2r_l$	3mm
Powder jet diameter $2r_p$	$2(0.05z^2 - 0.28z + 1.38)$
Carrier powder gas flow V	9L/min
Shield air flow V_p	20L/min
Absorption of the the substrate β_s	β_s
Absorption of the powder β_p	0.47
Effective height of light powder coupling h_1	5.43mm
Distance between cladding head and substrate h_0	12mm

Table 3 Process parameters of each experiment

Expt. no.	Power P_0 (kW)	Powder feeding rate m_f (g/min)	Scanning speed v_x (mm/min)
1	1.9	11.4	1500
2	1.8	11.4	1500
3	1.7	11.4	1500
4	2.0	11.4	1500
5	1.9	9.8	1500
6	1.9	8.2	1500
7	1.9	13	1500
8	1.9	11.4	1700
9	1.9	11.4	1900
10	1.9	11.4	1300

校对报告

当前使用的样式是 [国家标准GB7714-87]

当前文档包含的题录共27条

有0条题录存在必填字段内容缺失的问题

所有题录的数据正常