Temperature Field Distribution for Laser Cladding on Axially Symmetrical Parts

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Abstract. Laser cladding surface modification technology is widely used to strengthen and repair the surface of axially symmetrical parts. Based on the Gauss heat source model and COMSOL Multiphysics finite element analysis software, the surface modification process characteristics of laser cladding on the rotating substrate were studied by numerical simulation. The transient temperature field distribution under different process parameters was solved. Laser cladding pool corresponding to numerical simulation parameters was photographed by infrared high-speed camera. The results show that the temperature distribution of the Gauss heat source is delayed due to the normal distribution of heat flow and the cumulative effect of heat. In addition, with the increase of the rotational speed of the substrate, a cyclic preheating temperature band will be formed on the surface. The shape of molten pool obtained by temperature field analysis is droplet shape, which is basically consistent with the actual morphology of laser cladding molten pool.

1. Introduction
Axially symmetrical parts occupy more than 70% of the total number of parts and are widely used in various mechanical equipment. During the operation of axially symmetrical parts, due to the influence of some factors, such as the change of force on the surface of the rotating body, impurities in lubricating oil, etc, scratches, pitting wear, abrasive wear and adhesion wear are produced on the surface of the parts which makes the parts invalid. Using laser cladding surface modification technology to prepare corrosion-resistant and wear-resistant coatings, strengthen the surface of the substrate or repair with additives can improve the service life of rotary parts, thereby saving costs. In addition, the technology is efficient and easy to realize automation [2, 6]. However, because of the high central temperature of the laser cladding heat source, the size of the molten pool formed by laser cladding is small, and it is difficult to monitor it by conventional methods [4]. Therefore, numerical simulation has become one of the main methods to study the temperature distribution and pool morphology of laser cladding.

In the numerical simulation of laser cladding, the laser heat source model not only considers the distribution of laser energy in space domain, but also considers the movement of light source and the
distribution in time domain [3]. At present, the numerical simulation of laser cladding is mostly based
on the plane, which can not meet the needs of laser cladding on the rotating body. In order to obtain
more accurate results, it is necessary to establish numerical analysis model and heat source model
which are in line with the characteristics of laser cladding on the axially symmetrical parts [5].

2. Numerical simulation of laser cladding

2.1. Heat Source Model
Mathematical expression of energy distribution of heat source using Gauss heat source as external
continuous heat flow input model is:

\[ q_{\text{Laser}} = \frac{2 \cdot \alpha \cdot P}{\pi r_1^2} \cdot e^{-2 \left( \frac{x^2+y^2}{r_1^2} \right)} \] (1)

According to the actual setting of the motion path of the heat source on the surface of the rotating
substrate, the moving direction of the heat source is opposite to that of the rotating substrate along the
x-axis and counter-clockwise along the surface of the substrate. The modified moving Gauss heat
source is:

\[ q_{\text{Laser}} = \frac{2 \cdot \alpha \cdot P}{\pi r_1^2} \cdot e^{-2 \left( \frac{(x+u)^2+(y-r_p \cos(2\pi v t))^2+(z-r_p \sin(2\pi v t))^2}{r_1^2} \right)} \] (2)

The clockwise rotation speed of the substrate with the x-axis as the rotation axis is added by
dynamic mesh method. The simplified formula for converting the moving heat source into a laser
scanning motion direction is:

\[ q_{\text{Laser}} = \frac{2 \cdot \alpha \cdot P}{\pi r_1^2} \cdot e^{-2 \left( \frac{(x+u t)^2+y^2+z^2}{r_1^2} \right)} \] (3)

Where \( q_{\text{Laser}} \) is heat source density (W/m²), \( \alpha \) is laser absorptivity of the rotating substrate, \( r_p \) is
the Radius of the rotating substrate (mm), \( r_1 \) is the Radius of laser heat source (mm), \( u \) is laser
scanning speed (mm/s), \( v \) is the rotating speed of the substrate (r/min), \( t \) is the time of cladding (s), \( P \) is
laser power (w).

2.2. Mathematical Model
In order to improve the efficiency of numerical simulation of laser cladding, the following simplified
model assumptions were made: neglecting the flow factor of the molten pool, only considering the
thermal convection between the substrate material and air, the thermal convection between the
substrate and the supporting materials on both sides and the thermal radiation on the surface of the
substrate, the ambient temperature and initial temperature of the rotating substrate are 293.15K. The
whole mathematical model follows the energy conservation equation and Fourier law. The
mathematical expressions are:

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p \cdot u \cdot \nabla T + \nabla \cdot q = Q \] (4)

\[ q = -k \nabla T \] (5)

Where \( \rho \) is substrate microelement density, \( C_p \) is constant pressure specific heat capacity (J/\( \text{kg} \cdot \text{K} \)),
\( k \) is thermal conductivity (W/m²·K), \( P \) is pressure (Pa), \( Q \) is substrate heat flux density (W/m²), \( \nabla T \) is substrate temperature gradient
(K · m⁻¹), K is thermal conductivity (W · m⁻¹ · K⁻¹), q is local heat flux (W · m⁻²), u is heat source velocity field (m/s), T is temperature (K)

2.3. Geometric Model and Mesh Generation
A cylindrical substrate which spatial position is centered on the x-axis with a geometric size of 50mm and a radius of 15mm is established. ALE method (Arbitrary Euler-Lagrange method) and tetrahedral mesh method are used to mesh the revolving substrate. The cladding path on the surface of the revolving substrate is set by the rotating substrate and applying the scanning speed of the laser heat source, as shown in Fig 1(a). In order to improve the computational ability, the partition method of local refinement is used to refine the mesh on the surface of rotating substrate, as shown in Fig 1(b).

![Figure 1. (a) Laser Cladding Path and (b) Geometric Model.](image)

2.4. Boundary conditions
The heat source acts on the surface of the substrate, and the continuous heat input is accompanied by the heat convection between the interfaces and the radiation heat dissipation on the surface of the substrate. The mathematical expression is:

\[ q_{\text{Laser}} = h(T - T_\infty) + \varepsilon\sigma(T^4 - T_{\infty}^4) - k\frac{\partial T}{\partial z} \tag{6} \]

The mathematical expression of the heat convection and radiation heat dissipation surfaces on both sides is:

\[-k\frac{\partial T}{\partial n} = -h(T - T_\infty) - \varepsilon\sigma(T^4 - T_{\infty}^4) \tag{7} \]

Where: \( q_{\text{Laser}} \) is heat source density (w/m²), h is convective heat transfer coefficient, \( \sigma \) is Stefan-Boltzmann constant, \( \varepsilon \) is the surface radiation coefficient of the substrate, T is the substrate temperature (K), \( T_{\infty} \) is the ambient temperature (K), n is the surface normal vector.

2.5. Physical model parameters and experimental equipment
The substrate is steel 45, in which density, heat conductivity and specific heat capacity at constant pressure are functions of temperature, and some thermophysical parameters are shown in Table 1 [1].
Table 1. Some thermophysical parameter of 45 steel.

| Parameter                        | Value       |
|----------------------------------|-------------|
| Heat transfer coefficient (w/m·k) | 40          |
| Laser absorptivity (η)           | 0.6         |
| Melting point (K)                | 1788        |
| Radiation Coefficient (ε)        | 0.3         |
| Stefan-Boltzmann constant        | 5.670373×10⁻⁸|

Based on the RF-A2500D fiber laser with a maximum output power of 2500W, the small horizontal lathe and infrared high-speed camera CAVILUX® Smart (including laser unit, control unit, illumination optical system and control software), infrared camera shooting parameters are shown in Table 2.

Table 2. Infrared camera shooting parameters.

| Parameter                        | Value       |
|----------------------------------|-------------|
| Aperture                         | 5.6         |
| Exposure time (μs)               | 60          |
| Infrared light source current (A)| 55          |
| Shooting distance (mm)           | 500         |
| Camera angle (°)                 | 45°         |

3. Numerical simulation results

Based on the above conditions, the temperature field of laser cladding on the rotating substrate is simulated by COMSOL Multiphysics software. The process parameters are shown in Table 3.

References are cited in the text just by square brackets [1]. Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under heading references, see our example below.

Table 3. Technological parameters of laser cladding numerical simulation.

| Number | Laser power (kW) | Laser scanning speed (mm/s) | The substrate rotating speed (r/min) |
|--------|------------------|----------------------------|-------------------------------------|
| 1      | 1.5              | 6                          | 120                                 |
| 2      | 2.0              | 6                          | 120                                 |
| 3      | 2.5              | 6                          | 120                                 |
| 4      | 2.5              | 6                          | 240                                 |
| 5      | 2.5              | 6                          | 300                                 |
| 6      | 2.5              | 6                          | 360                                 |

The simulation results of No. 1 to No. 3 show that the temperature field of laser cladding reaches quasi-steady state at t=0.1s. Fig.2 shows the temperature field distribution of laser cladding on the rotating substrate with power of 1.5kW, 2kW and 2.5kW at t=1.0s. The temperature field distribution of laser cladding has obvious trailing phenomenon. With the increase of laser power, the central temperature of heat source increases significantly. The isotherms in front of the heat source are dense, the temperature gradient is large, the isotherms behind the heat source are sparse and the temperature gradient is small.
The results of simulation 4-6 show that when the laser power remains unchanged at 2.5kW, the heat input of the substrate increases continuously with the increase of the rotational speed of the substrate, while the heat transfer is relatively slow. This phenomenon of unbalanced heat input and output increases the trailing state of the temperature field and gradually forms a ring-shaped temperature band on the substrate by the characteristics of repeated heating of the substrate rotation, as shown in Fig.3.

The experiment of laser cladding without powder feeding was carried out by using the process parameters of numerical simulation 1-3, and the laser cladding pool with 45 degrees of elevation angle was photographed. With the increase of laser power, the size of molten pool increases obviously, and the whole molten pool is liquid droplet. By comparing the numerical simulation results with the molten pool images at 45 angle of view, it is found that the Gauss heat source model and the temperature field distribution and morphology of the molten pool in laser cladding accord with the characteristics of normal distribution of heat flux density, and basically accord with the actual situation of laser cladding of revolving body, as shown in Fig.4.
Figure 4. Comparison of numerical simulation and experimental photography of molten pool in laser cladding.
(a) 1.5kW, (b) 2.0kW, (c) 2.5kW

4. Conclusion
According to the characteristics of laser cladding on axially symmetrical parts, a heat source model suitable for numerical simulation of laser cladding on rotating parts is proposed. The tailing phenomenon of laser cladding temperature field forms a continuous annular preheating temperature zone with the increase of rotating speed, and the shape of the molten pool is droplet. The distribution of temperature field in laser cladding is characterized by the normal distribution of heat flux of compound Gauss heat source. The morphology of laser cladding pool under infrared camera basically coincides with that of numerical model of laser cladding temperature field under the same process parameters.

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