Coupling Analysis of Temperature Field and Stress Field of Laser Cladding Die Steel

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Abstract—A 3D parametric model was established for the die steel whose matrix material was H13. Ni60 alloy powder was used to cladding the matrix, and a single-layer multichannel finite element model of heat-force coupled laser was established. The laser power 𝑃=600W, scan rate 𝑣=20mm/s, laser spot radius 𝑅=1mm were selected as simulation parameters. The temperature field and stress field in the process of laser cladding are analyzed by finite element method.

1. INTRODUCTION

Die steel is an important metal material in the field of material forming and plays an irreplaceable role in the manufacturing industry. Due to the complex manufacturing process of the mold itself, the processing process is more than one procedure, the production cycle is long, and the mold material is often expensive, resulting in a very high cost of the mold. The working environment of the mold is complex and harsh, and the mold failure and scrap forms are multifarious due to various working conditions. A large amount of metal resources are consumed in industrial production, which leads to the gradual depletion of metal mineral resources, so it is particularly urgent and important to save metal resources. Under this background, many scholars have carried out research on the repair technology of mold, namely the remanufacturing technology. The commonly used remanufacturing methods include electric spark, arc surfacing welding, and laser cladding technology of thermal spraying machine, etc., among which the laser cladding technology is widely used due to its advantages of dense cladding layer, low dilution rate and small heat affected area.

Laser cladding has low requirements on the selection of coating powder and substrate, so it is widely used in the remanufacturing and repairing of different kinds of substrate materials[1] . The most common feeding methods of cladding materials are powder prepositioning method and synchronous feeding method[2] . Laser cladding technology has the advantages of fast heating speed, small heat affected area and low surface temperature of substrate, so it can ensure the size accuracy of parts. In recent years, it has developed into a widely used surface modification technology.
Prakash Kattire et al.[3] conducted an experimental study on laser cladding of H13 die steel. The effect of laser cladding parameters on the geometry of cladding layer and cladding quality of CPM9V H13 die steel was studied.

Y. Javid et al.[4] simulated the laser cladding process of tungsten carbide (WC) on inconel 718 by establishing an uncoupled finite element model, and analyzed the significant influence of laser power and cladding speed on residual stress.

Shu Linsen et al.[5] simulated three-dimensional temperature field and stress field during laser cladding repair of milling cutter disc, in order to determine whether thermally induced stress cracking will occur during laser cladding repair of milling cutter disc.

In this paper, the cladding process of Ni60 alloy powder laser cladding H13 die steel is simulated by ANSYS software, and the temperature field and stress field are coupled.

2. MATHEMATICAL MODEL

2.1. Establishment of finite element model

The thermal process of laser stereo forming satisfies the three-dimensional transient thermal conduction control equation[6] (in the domain $\Omega$).

$$\rho \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) - \nabla \cdot (\rho Q) = 0$$

In formula (1), $\rho$ is material density, $c$ is material specific heat capacity, $Q$ is unit volume heat generation rate, $t$ is time, $k$ is heat conduction coefficient, $T$ is temperature.

The thermal strain with respect to temperature is:

$$\varepsilon_{th}^{ij} = \alpha(T - T_{ref})$$

In formula (2), $\alpha(T)$ is the coefficient of thermal expansion with temperature, and $T_{ref}$ is the reference temperature. The constitutive equation between stress and strain is:

$$d\sigma_{ij} = D_{ijkl} \left( d\varepsilon_{kl}^t - d\varepsilon_{kl}^p - d\varepsilon_{kl}^e - d\varepsilon_{kl}^T \right)$$

In formula (3), $D_{ijkl}$ is the elastic constitutive tensor coefficient. $d\varepsilon_{kl}^t$, $d\varepsilon_{kl}^p$, $d\varepsilon_{kl}^e$, $d\varepsilon_{kl}^T$ are the total strain, plastic strain, elastic strain and thermal strain respectively. In this study, the stress and strain reinforcement mechanism is follow-up reinforcement, and the mechanical model adopts Bilinear model.

2.2. Parameter setting of matrix material and cladding material

| Temperature ($\degree C$) | 20 | 200 | 350 | 650 |
|----------------------------|----|-----|-----|-----|
| Thermal conductivity (W/($m^2 \cdot C$)) | 32.2 | 28.6 | 28.4 | 28.8 |
| Temperature ($\degree C$) | 20 | 500 | 600 |
| Specific heat (J/($kg \cdot \degree C$)) | 460 | 548 | 590 |

The matrix material selected in this study is H13 steel, and the cladding material is Ni60 alloy powder. Thermal physical properties of H13 steel and Ni60 alloy with temperature variation[7] are shown in table 1-2.
Table 2 Thermal physical properties of Ni60 steel

| Temperature (°C) | 300 | 400 | 600 | 700 | 800 | 1200 |
|-----------------|-----|-----|-----|-----|-----|------|
| Thermal conductivity (W/(m·°C)) | 90  | 83  | 67  | 65  | 68  | 74  |
| Specific heat (J/(kg·°C)) | 428 | 460 | 520 | 526 | 538 | 533 |

The density of H13 steel is 7760 kg/m³, the elastic modulus is 210GPa, and the Poisson's ratio is 0.3. Ni60 alloy material density is 8900 kg/m³, elastic modulus is 180GPa, Poisson's ratio is 0.24.

2.3. Geometric model and grid division
The finite element model of laser cladding is established by using ANSYS finite element simulation software, as shown in figure 1. The matrix model size is 50*25*20mm, the cladding layer model size is 50*3*1mm (1 layer,3 tracks), the mesh division size of the model is 0.001mm, the unit type is solid70, and the mesh division is shown in figure 2. Absorption rate $\eta$ =0.3 ;Power P=600W ; Scanning rate $v$=0.02m/s ; Laser spot radius $R=0.001$m were selected as simulation parameters. The laser parameters used in the laser cladding process are shown in table 3.

| Absorption rate $\eta$ | Power (W) | Scanning rate (m/s) | Laser spot radius (m) |
|------------------------|------------|---------------------|-----------------------|
| 0.3                    | 600        | 0.02                | 0.001                 |

Fig. 1 Finite element model of laser cladding

Fig. 2 Grid division diagram of the model
2.4. Heat source model and boundary conditions

Gaussian heat source model is adopted to apply the heat source, and the governing equation of heat conduction is:

$$\rho C \left[ \frac{\partial T}{\partial t} - v \frac{\partial T}{\partial y} \right] = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right)$$

(4)

In formula (4), $\rho$ is density; $C$ is specific heat capacity; $v$ is scanning speed; $T$ is temperature; $t$ is time; $k$ is the thermal conductivity.

The boundary condition of convective heat transfer is adopted in the finite element simulation process, and the influence of heat radiation on the simulation process is not considered. The formula of convective heat transfer is as follows:

$$q^* = H(T_S - T_B)$$

(5)

In formula (5), $H$ is the convective heat transfer coefficient, and 20 (W/(m·℃)) is taken. $T_S$ is the temperature of the solid surface; $T_B$ is the ambient temperature, 25℃.

3. Analysis of Simulation Results of Temperature Field and Stress Field

Based on ANSYS finite element simulation software, Ni60 alloy powder laser cladding H13 mold steel was simulated, and TEMP simulation diagram of temperature field was selected under the conditions of laser power $P=600W$, scanning speed $v=20mm/s$, and laser spot radius $R=1mm$, as shown in figure 3. Stress-time simulation diagram of STRESS field, as shown in figure 4.

4. Conclusion

In this paper, ANSYS finite element analysis software is used to simulate the single-layer 3-channel laser cladding of H13 die steel, and the temperature field distribution in the laser cladding process is observed and analyzed. The results of temperature field simulation are used as the load for indirect
coupling, the stress field of cladding layer is calculated, and the minimum stress value is obtained. The laser power, scanning rate and laser spot radius may have significant influence on the experiment.

1) Through finite element simulation of Ni60 alloy powder laser cladding H13 die steel, the temperature field simulation shows that the temperature change is positively correlated with the cladding time first, with a peak value, and negatively correlated after the peak value.

2) When the laser power $P=600\text{W}$, the scanning rate $v=20\text{mm/s}$, and the laser spot radius $R=1\text{mm}$, the minimum stress is $440\text{MPa}$.

3) Adjusting the parameters of laser power ($P$), scanning rate ($v$) and laser spot radius ($R$) will affect the process of laser cladding die steel.

REFERENCES
[1] Zhao C S, Xing Z G, Wang H D, Li G L, Liu Z. (2018) Research Progress of Laser Cladding on Iron-carbon Alloy Surface [J]. Materials Review,32(03): 418-426.
[2] Chen X M, Wang H J, Zhou X L, Zhao J, Fu L, Liu W. (2018) Laser Surface Modification Technology and Its Research Progress [J]. Materials Review,32(S1):341-344.
[3] Prakash Kattire, Santanu Paul, Ramesh Singh, Yan W Y. (2015) Experimental Characterization of Laser Cladding of CPM9V on H13 Tool Steel for Die Repair Applications [J]. Journal of Manufacturing Processes,20.
[4] Y. Javid, M. Ghoreishi. (2017) Thermal mechanical Analysis in Pulsed Laser Cladding of WC Powder on Inconel 718 [J]. The International Journal of Advanced Manufacturing Technology,92(1-4).
[5] Shu L S, Wang J S. (2019) Finite Element Simulation of Temperature Field and Stress Field during Laser Cladding Repair of Milling Cutter Disc [J]. China Mechanical Engineering,30(01):79-84.
[6] Liu D X, Qin Q X, Wang X G, Mao H L. (2014) Design of Hydrostatic Tube for Precise Atmospheric Hydrostatic Pressure Measurement Based on Orthogonal Experiment [J]. Journal of Instrumentation,35(02):360-367.
[7] Chen W, Wang H J, Xie B, Zhou C Y. (2019) Effects of Annealing Temperature on the Microstructure and Hardness of Ni60/WC Cladding of H13 Steel [J]. Metal Heat Treatment,44(02):131-136.