Study on laser cladding process parameters of Fe-based alloy based on numerical simulation

Ximing GENG*

1Queen Mary University of London Engineering School, Northwestern Polytechnical University, 1 Dongxiang Road, Xi'an, 710129, China
Corresponding author’s e-mail: gxmsevensam@mail.nwpu.edu.cn

Abstract. Using 45 steel as the substrate, laser cladding Fe-based alloy powder on the surface was proposed to improve the surface wear resistance and hardness, and partially replace the cold working die steel in the small batch production stage. ANSYS Workbench was used to simulate the heat transfer and temperature field distribution in the laser cladding process of iron base alloy. The thermal properties of the substrate and the cladding material were set up, and the finite element model was established by Gaussian heat source. The temperature field under different laser cladding process parameters was simulated to obtain the temperature distribution of molten pool. According to the metallurgical bonding between the substrate and the coating, and taking the dilution rate of the cladding layer as the basis of quality evaluation, the optimal process parameter combination of laser cladding Fe-based alloy powder of 45 steel substrate is determined as follows: laser power1400W, scanning speed 8mm/s, spot diameter 3mm. The results provide technical data support for the engineering application of laser cladding of Fe-base alloy on 45 steel substrate.

1. Introduction

45 steel is an inexpensive medium carbon tempered structural steel, used by some automotive mould manufacturing enterprises as a cold work mould steel material for small batch production stage[1]. However, the working surface hardness and wear resistance of the moulds made from it are insufficient and with the short service life, which seriously limits the production efficiency. Laser cladding technology was widely used in the field of preparing composite coatings on substrates to achieve substrate surface modification[2]. The Fe-based alloy powder composition is close to the base 45 steel, the carbide and boride in the eutectic can significantly improve the hardness and wear resistance of the coatings, which is suitable for parts with high local wear resistance requirements. The difference between the two thermal expansion coefficients is small, has good bonding, and not easy to peel and low cost[3,4]. Thus Fe-based alloy cladding can effectively compensate for the wear resistance and hardness defects of the substrate[5,6].

The main theme of this paper was the laser cladding of Fe-based alloys on 45 steel substrates instead of cold working die steels at the small batch production stage. Based on numerical simulation of the temperature field, the effect of process parameters on the temperature distribution of the melt pool was studied to explore the best combination of process parameters and to provide data support for the engineering application of laser cladding of Fe-based alloys on 45 steel.
2. Numerical simulation of temperature field

Considering the interaction of various factors in the actual process of laser cladding, the finite element model needs to be reasonably simplified to a certain extent: (1) the anisotropy of the material was not considered. (2) the temperature field was assumed to be influenced only by the process parameters and the thermophysical parameters of the material. (3) the flow of the liquid in the melt pool and the surface tension were neglected. (4) the initial temperature is 22°C.

The substrate material was 45 steel and the cladding material was iron-based alloy powder, the thermophysical parameters of both were listed in Table 1 and Table 2 respectively[7]. The process parameters were laser power, scanning speed and spot diameter. In this paper, the laser power was chosen to be 1200W, 1400W and 1600W, the scanning speed was 8mm/s, 12mm/s and 16mm/s, and the spot diameter was taken as a constant value of 3mm according to the actual working conditions.

| Temperature/K | 600 | 1200 | 1800 | 2400 | 3000 |
|---------------|-----|------|------|------|------|
| thermal conductivity/ (W/m·k) | 41.9 | 27.75 | 33.9 | 44.85 | 55.65 |
| specific heat capacity/ c(J/kg·k) | 0.59 | 0.618 | 0.769 | 0.769 | 0.769 |

| Temperature/K | 600 | 1200 | 1800 | 2400 | 3000 |
|---------------|-----|------|------|------|------|
| thermal conductivity/ (W/m·k) | 17.67 | 21.15 | 33.78 | 42.65 | 51.9 |
| specific heat capacity/ c(J/kg·k) | 0.578 | 0.708 | 0.888 | 0.888 | 0.888 |

Due to the symmetry of the single-pass laser cladding structure, one half of the model was selected for the numerical simulation. The cross section of the melting layer is 1/4 ellipse with long and short half axes of 1.5 mm and 1 mm respectively. The model was meshed as shown in Figure 1. In this paper, a Gaussian heat source model with a similar heat flow density to that of the actual process was adopted. Combined with the heat source model and the process parameters, a heat transfer model was generated through a parametric design language and the laser melting temperature field was simulated numerically in ANSYS Workbench.
3. Result and discussions

3.1. Influence of process parameters on melt pool temperature and distribution patterns

A cloud plot of the temperature distribution from the melt to the end of the model at 1200W laser power and different scanning speeds was shown in Figure 2. As can be seen from the figure, the maximum melt pool temperatures corresponding to the scanning speeds of 12 mm/s, 16 mm/s and 20 mm/s were 2829.7°C, 2686.9°C and 2514.3°C respectively at 1200 laser power. At the same power, the maximum melt pool temperature and temperature influence range gradually decreases with increasing scanning speed as the laser energy per unit area decreases due to the increase in scanning speed. When the laser power were 1400W and 1600W, the maximum temperature of the melt pool has a significant increase, the maximum temperature of the melt pool and the temperature distribution was consistent with the distribution law of 1200W, 1400W and 1600W temperature distribution clouds were shown in Figure 3 and Figure 4 respectively.

![Figure 2](image2.png)

Figure 2 Image of temperature distribution at 1200W.
(a)1200W-12mm/s, (b)1200W-16mm/s,(c)1200W-20mm/s.

![Figure 3](image3.png)

Figure 3 Image of temperature distribution at 1400W.
(a)1400W-12mm/s, (b)1400W-16mm/s,(c)1400W-20mm/s.
3.2. Determination of optimum process parameters

The temperature distribution curve along the depth direction for different process parameters was shown in Figure 5. 45 steel has a melting point of 1433°C. In this paper, the numerical simulations were carried out for pre-placement powder laser cladding with a thickness of 1 mm. The thickness of the cladding layer formed was assumed to be the same, so the temperature at 1 mm in the temperature distribution curve was chosen to be compared with the melting point of 45 steel. When the temperature is greater than the melting point of 45 steel, the substrate is considered to be able to melt and form a metallurgical bond. As can be seen in Figure 5, when the laser power was 1200 W, the temperatures at 1 mm at the three scanning speeds were 1341.2°C, 1192.2°C and 1028.9°C respectively, all of which are less than the melting point of 45 steel and cannot form a metallurgical bond. When the laser power was 1400 W and the scanning speed was 8 mm/s, the temperature at 1 mm is 1558.4°C. Both the substrate and the cladding powder can be melted and a metallurgical bond can be formed. When the laser power was 1600 W, at the scanning speed of 8 mm/s and 12 mm/s, the temperature at 1 mm was 1783.5°C and 1584.6°C respectively, metallurgical bonding can also be formed. In all parameter combinations, 1400W-8mm/s, 1600W-8mm/s and 1600W-12mm/s can form metallurgical bonding.
In order to obtain the best combination of process parameters for cladding effect, dilution rate was used as the evaluation standard. The smaller the dilution the better, provided that a metallurgical bond can be formed. Figure 6 shown that a cross-sectional view of the clad layer, where $H$ is the clad height, $D$ is the clad depth and $W$ is the clad width. The degree of bonding of the clad layer to the substrate is expressed in terms of dilution:

$$A = \frac{D}{H + D} \quad (1)$$

In Figure 5, the distance from the surface corresponding to the 45 steel melting point of 1433°C was defined as the depth of the cladding layer. The dilution rates for the process parameters 1400W-8mm/s, 1600W-8mm/s and 1600W-12mm/s were calculated in conjunction with the temperature distribution curves and are listed in Table 3. As can be seen from the table, the dilution rate of 0.120 for the process parameter 1400W-8mm/s was the smallest value among the three sets of parameters, which ensures the formation of metallurgical bonding on the basis of the smallest dilution rate. Therefore, the laser power
of 1400W and scanning speed of 8mm/s were determined as the best process parameters for the numerical simulation of the temperature field.

| Process parameter | 1400W-8mm/s | 1600W-8mm/s | 1600W-12mm/s |
|-------------------|-------------|-------------|--------------|
| Distance          | 1.137mm     | 1.355mm     | 1.142mm      |
| Dilution          | 0.120       | 0.262       | 0.124        |

4. Conclusions
With the aid of numerical simulations, temperature field simulations were carried out for the laser cladding of Fe-based alloy powders on 45 steel substrates. By simulating the temperature field for different combinations of laser power, scanning speed and spot diameter, the maximum melt pool temperature and temperature distribution patterns are obtained for the corresponding combinations of process parameters, and the metallurgical bond and the dilution rate of the clad layer were used as the evaluation criteria for the clad quality. The optimum combination of laser cladding process parameters was obtained: laser power of 1400 W, scanning speed of 8 mm/s and spot diameter of 3 mm. The results provide process data to support the engineering application of laser cladding of Fe-based alloys on 45 steel substrates.

References
[1] Chen Jufang, Li Xiaoping, Xue Yaping. Friction and Wear Properties of Laser Cladding Fe901 Alloy Coating on 45Stell Surface[J]. CHINESE JOURNAL OF LASERS, 2019, 46(05): 326-34.
[2] Zhou Shaowei, Xu Tianyu, Hu Chang, et al. A comparative study of tungsten carbide and carbon nanotubes reinforced Inconel 625 composite coatings fabricated by laser cladding[J]. Optics and Laser Technology, 2021, 140.
[3] Li Jianning. Laser cladding technology and application[M]. Chemical Industry Press, 2016.
[4] Gu Yufen, Liu Chenheng, Li Guang, et al. Study on the microstructure and properties of Fe-based amorphous composite coatings by different processes[J]. Electric Welding Machine, 2019, 49(05): 43-48.
[5] Fan Pengfei, Sun Wenlei, Zhang Guan, et al. Microstructure, Properties and Applications of Laser Cladding Fe-based Alloy Gradient Coatings[J]. MATERIALS REPOUTS, 2019, 33(22): 3806-3810.
[6] Qian Shaoxiang. Microstructure and Properties of Fe-based Alloy Coating by Laser Cladding[J]. FOUNDRY TECHNOLOGY, 2019, 40(06): 613-616.
[7] Jia Yunjie. Numerical simulation of ultra high speed laser cladding of Fe based alloy[D]. Tianjin University of Technology and Education, 2020.