Numberical Simulation and Process Research of Laser Cladding on 738H Injection Mold Steel Surface

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Abstract. Laser cladding coating is the focus of development in the field of die repair. It has the characteristics of uniform and compact coating, good bonding strength, little thermal impact on the substrate, and easy to realize automation. FeCr alloy coating was prepared on 738H die steel by laser cladding process. Based on MSC Marc finite element software and life-and-death element method, the numerical analysis model of laser cladding repair was established, and the temperature field, stress field and deformation under different process parameters were solved. According to the simulation results, the cladding process was formulated, the hardness and linear thermal expansion coefficient of the cladding coating were characterized, and the effects of the process parameters on the structure and properties of the coating were studied. The cladding coating matched well with the substrate performance was obtained, and the high quality repair of the die surface was realized.

1. Introduction
Die is one of the important equipment which affects the quality of workpiece forming. It has complex manufacturing process, long production cycle and high production cost. With the increase of service times, the surface of the die is prone to different degrees of scratches, pits and wear, which affects its service life and processing accuracy, and reduces the product quality under the action of high pressure and high impact force. Laser cladding is a technology of adding cladding material on the surface of substrate by prefabrication or synchronous supply. High energy density laser beam is used to melt the cladding material and the thin layer on the surface of substrate at the same time to form a high strength metallurgical bonding coating with the substrate. Compared with other repairing processes, laser cladding can use cladding materials to repair the local failure parts of the die quickly. The process is simple, efficient and easy to realize robotization [1,2]. In addition, the laser cladding coating has compact structure, concentrated energy and little heat effect on the substrate. It has broad application prospects and practical value in the field of die repair research [3-5].

738H die steel is the most widely used general plastic die steel at present. It is suitable for the preparation of plastic die with high hardness, high toughness and wear resistance. FeCr alloy coatings with high hardness and good wear resistance were prepared on 738H die steel by laser cladding. The
temperature field and stress field under different process parameters are solved by life and death element method through the non-linear finite element numerical analysis software MSC Marc [6-9]. According to the simulation results, the cladding process is formulated to characterize the hardness and linear thermal expansion coefficient of the cladding coating. The effect of process parameters on the structure and properties of the coating was studied. The cladding coating with good matching between hardness and linear thermal expansion coefficient and the die steel substrate was obtained, and the high quality repair of the die surface was realized [10,11].

2. Experimental materials and process parameters
The substrate material is 738H die steel, and the composition is shown in Table 1. According to the actual needs of die repair, the V-sharped groove with a width of 4 mm and a depth of 2 mm is machined at the position to be repaired and cleaned with acetone before cladding.

| Parameter       | Value |
|-----------------|-------|
| Laser spot diameter (mm) | 2.5   |
| Powder feeding rate (r/min) | 6     |
| Flow rate of powder gas (L/min) | 6     |
| Protective Pressure (Mpa) | 0.25 |

FeCr alloy powder with particle size of 270-500 mesh is selected as cladding material. The composition is shown in Table 2. The powder was dried before the test. The drying temperature was 150 °C and the drying time was 30 minutes.

![Table 1. Chemical composition of 738H steel (Wt%)](image1)

| C    | Si | Mn | Cr  | Mo | Ni |
|------|----|----|-----|----|----|
| 0.26 | 0.18 | 1.45 | 1.28 | 0.58 | 1.08 |

Table 2. Chemical composition of iron alloy (Wt%)

| C | Si | B | Cr | Ni | Fe |
|---|----|---|----|----|----|
| 0.2 | 1 | 16 | 1 | Bal. |

Based on the self-designed annular coaxial powder feeding nozzle, synchronous powder feeding laser cladding experiments were carried out. The maximum output power of 2500W RF-A2500D fiber laser and ZB-80F powder feeder were used. Laser cladding of V-sharped groove was carried out by means of multi-layer filling. The constant technological parameters in the experiment are shown in Table 3.

Table 3. Processing Parameter of laser cladding

| Parameter                      | Value |
|--------------------------------|-------|
| Laser spot diameter (mm)       | 2.5   |
| Powder feeding rate (r/min)    | 6     |
| Flow rate of powder gas (L/min)| 6     |
| Protective Pressure (Mpa)      | 0.25  |

3. Numerical simulation of laser cladding

3.1. Geometric Model and Computing Settings
The geometric model is established based on MSC Marc numerical simulation software. The size of the substrate is 30mmx60mmx10mm. According to the repair requirements, the V-shaped groove with a width of 4mm and a depth of 2mm is set on the surface of the substrate to be repaired, and the cladding path is set to 3 channels, each with a length of 30mm. The repairing path of laser moving along Z axis is shown in Figure 1.
The life and death element method was used to simulate the coaxial powder feeding laser cladding process. The temperature field is simulated by using SOLID 7 total integral hexahedron element. According to the substrate 738H die steel and the cladding material FeCr alloy powder, the corresponding thermal physical parameters such as specific heat capacity, elastic modulus, thermal conductivity and linear thermal expansion coefficient are set, and the thermal physical parameters of the material change with temperature.

In order to improve the computational ability, the mesh of the geometric model is refined in the cladding area of V-sharped groove and the cladding coating by using Local Mesh Refinement Method, as shown in Figure 2. The laser surface heat source is used as an external continuous heat flow input. The heat source model is a moving Gauss surface heat source. The energy distribution of the heat source can be seen in formula (1). For the laser absorptivity, the higher the blackness of the material surface is, the higher the absorptivity of laser energy is, and the color of iron-based alloy powder is light gray, so the laser absorptivity \( \eta \) is set to 0.37. Laser cladding is a complicated multi-physical field coupling process. For the convenience of calculation, the finite element model is simplified: the flow of molten pool is neglected, and only the thermal convection between substrate material, cladding material and air, thermal convection between substrate and bottom supporting material, thermal radiation on the surface of substrate and initial temperature of workpiece are considered. The initial temperature of the workpiece is set to 22°C.

\[
I(r) = \eta I_0 \exp \left[ -\frac{\left( \frac{r}{r_1} \right)^2}{v} \right]
\]

(1)

Where \( I_0 \) is heat source density (w/ m²), \( \eta \) is laser absorptivity, \( r \) is the distance of the calculate spot and the spot center (mm), \( r_1 \) is the Radius of laser heat source (mm), \( v \) is laser scanning speed (mm/s), \( t \) is the time of cladding (s), \( P_l \) is laser power (w).

In the process of simulating laser cladding, the cladding material is set as the life-death unit activated by temperature, and the initial state is the "death" unit. With the radiation of laser heat source, the cladding material is heated sharply. After reaching the melting point of the material, it is activated as the "life" unit. Then the cladding material is rapidly cooled and solidified to form a coating. The cooling term after cladding is set as static air heat exchange cooling, which stops when the temperature is lower than 50 C. The numerical simulation process is completed.
3.2. Numerical Simulation Result

The heat affected zone (HAZ), as the transition zone between the substrate and the cladding coating, directly affects the deformation, residual stress and properties of the substrate in the whole repair area. Laser power can effectively control the heat input of the substrate and determine the size of the HAZ, which is the main control factor of the HAZ. In the process of laser cladding, the heating and cooling speed is very fast. If the scanning speed is too high, the solidification time of the molten pool will be shortened. The gas generated in the laser cladding process can not escape in time and will remain in the cladding coating to form pore. On the contrary, too low scanning speed will increase the heat input to the coating and substrate, increase the temperature gradient in the repair area and increase the residual stress. The above factors will directly affect the performance of the cladding coating. Therefore, in the process of making cladding process, the appropriate parameters of laser power and scanning speed need to be selected.

Based on the established geometric model, three sets of heat source parameters are used to simulate the transient temperature field and stress field in the cladding process with laser power and scanning speed as variables. The specific parameters are shown in Table 4. In order to ensure a good metallurgical bonding between the coating and the substrate, the first layer laser cladding parameters are set as laser power of 1.5 kW and scanning speed of 5 mm/s, and only the second layer laser cladding parameters are used as variables to simulate.

| Number | the first laser power | the first scanning speed | the second laser power | the second scanning speed |
|--------|-----------------------|-------------------------|-----------------------|-------------------------|
| 1      | 1.5kW                 | 5mm/s                   | 1.8kW                 | 5mm/s                   |
| 2      | 1.5kW                 | 5mm/s                   | 1.5kW                 | 5mm/s                   |
| 3      | 1.5kW                 | 5mm/s                   | 1.5kW                 | 8mm/s                   |

After the simulation is completed, the temperature distribution contour of the central XY plane in the geometric model during each process is intercepted as shown in Figure 3, the equivalent residual stress contour of the central XY plane and the top XZ plane in the cooled geometric model is shown in Figure 4, and the final deformation distribution of the central XY plane in the cooled geometric model is shown in Figure 5.

It can be seen from figures. 3 (a) and 3 (b) that under the condition of constant laser scanning speed, with the decrease of the second laser power from 1.8 kW to 1.5 kW, the heat input on the surface of the substrate decreases, and the range of heat affected varies little, but the heating temperature of the substrate in the cladding area decreases significantly. As shown in Figure. 4 (b), the residual stress in the repaired area decreases as a whole after the laser power is reduced, and the obvious stress concentration in the cladding coating in Figure. 4 (a) is also alleviated. When the laser power is constant at 1.5 kW, the scanning speed of the second layer increases from 5 mm/s to 8 mm/s. As
shown in Figure. 3 (c), the heat affected range of the substrate decreases significantly, and the heating temperature of the substrate in the cladding area decreases further. In Figure. 4 (c), the residual stress after cooling decreases as a whole, and the trend of stress concentration in the cladding coating decreases. Figure. 5 shows that under the above three parameters, the deformation of the repair area mainly concentrates on the surface of each coating, and concentrates on the interior of each coating. Under the third group of parameters, the deformation of the cladding coating and the substrate is the smallest. In summary, the laser heat source parameters selected in the third group have little effect on the substrate heat, the residual stress distribution is more uniform, and the deformation is the smallest.

Figure 3. Temperature field Contours
4. Analysis of cladding process test results

4.1. Microstructure and morphology of cladding coatings

According to the numerical simulation results, the laser cladding process test was carried out with the third group of parameters, filling V-sharped grooves on the surface of die steel, and the other process parameters were the same as Table 3. The macroscopic surface morphology of the laser cladding pattern is shown in Figure 6. It can be seen from the figureure that the surface of the cladding coating is smooth and flat, and there are no defects such as pore and crack. Samples of 10mm×10mm×15mm size were cut along the line perpendicular to the laser scanning direction. After grinding, polishing and cleaning, the samples were corroded by aqua regia for 30 seconds. The cross-section morphology of the coatings in the vertical direction and along the cladding direction is shown in Figure 7. It can be seen from the figureure that the width of the HAZ is relatively small, the cross section of the coating has only a very few number of pore, and there is no crack defect, so the formation of the coating is good.
Figure 6. Macro-morphology of cladding coating sample

Figure 7. Morphology of cladding coating sample

The microstructures of the substrate and the cladding coating are shown in figure 8. Figure 8 (a) is the middle part of the cladding coating in the vertical cladding direction. Because the temperature gradient of the front part of the solid-liquid interface in the middle part of the cladding coating is smaller than that in the bonding area, the crystallization is relatively slow and the dendritic structure is formed. Figure 8 (b) is the upper part of the cladding coating along the cladding direction, which dissipates to the substrate and surrounding environment through heat conduction and convection. The cooling rate is higher and the grain size is smaller. Figure 8 (c) is the HAZ. During laser cladding, the pool of the cladding coating formed rapidly cooled and solidified, and heat was transferred to the substrate, so that the temperature of the HAZ exceeded its phase transformation temperature, and lath martensite was formed. Figure 8 (d) is tempered martensite with good toughness in the substrate.

Figure 8. Microstructures of substrate and cladding coating
4.2. Microhardness
The surface along the cladding direction is the final surface of the repaired die steel, and the microhardness of the area is characterized. From Fig.9, it can be seen that the microhardness distribution is uniform in all areas along the cladding direction. The hardness of the cladding coating is basically the same as that of the substrate. The hardness of the HAZ is higher because of the existence of high hardness and high strength martensite structure. Fig.10 shows the microhardness in different positions in the vertical direction of cladding. It can be seen from the figure that the hardness distribution in each area is uniform, the hardness in HAZ is higher, and the hardness of cladding coating is close to that of the substrate, which is significantly higher than that of the substrate. The higher hardness of the cladding coating is due to the orientation during dendrite solidification, which leads to the anisotropy of the cladding coating and the different hardness in different directions. As the surface along the cladding direction is the repaired surface of die steel, the hardness of the coating along the cladding direction is basically the same as that of the substrate, which indicates that the cladding material selected is reasonable.

![Figure 9. Microhardness along cladding direction](image)

![Figure 10. Microhardness in Vertical Cladding Direction](image)

4.3. Linear thermal expansion coefficient
Cylindrical samples with diameter of 3 mm were taken in the substrate and cladding coatings respectively for thermal expansion experiments. The temperature curve is shown in Fig.11. The average linear expansion coefficient of substrate is $14.02 \times 10^{-6} \text{ K}^{-1}$ in the range of 27.6 ~400 C, and that of cladding coating is $13.55 \times 10^{-6} \text{ K}^{-1}$, with a difference of $4.5 \times 10^{-7} \text{ K}^{-1}$. 
5. Conclusion

The conclusions drawn from the analysis are as follows:

1. According to the results of transient numerical simulation, the laser cladding process was developed, and the cladding coating with smooth surface, narrow HAZ and good bonding with the substrate was prepared.

2. The cladding coating is dendrite growing upward, the HAZ is lath martensite with high strength, and the substrate is tempered martensite.

3. There is anisotropy in the cladding coatings and the hardness is different in different directions. Along the cladding direction, the hardness of HAZ is higher, and the hardness of the cladding coating is basically the same as that of the substrate. The micro-hardness of the cladding coating in the vertical cladding direction is close to that of the HAZ, which is significantly higher than that of the substrate, and the hardness distribution in each region is uniform.

4. Within the range of service temperature of the die, the linear expansion coefficient of the substrate and the cladding coating is small, and the possibility of cracking and failure due to thermal cycling is low.

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