Effect of laser energy density on microstructure and properties of laser cladding coating by powder feeding method

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Abstract: In this paper, the microstructure of laser cladding layer was studied under two laser conditions. The microstructure of laser cladding layer was characterized as directional rapid solidification. On the premise of forming a good metallurgical bond between the coating and the matrix, higher laser energy density was harmful to refine the coating structure and reduce the microhardness of the coating.

1. Introduction

Laser cladding surface strengthening technology is an emerging metal surface modification technology. It is formed by adding a cladding material on the surface of the matrix and using a high-energy laser beam to fuse with the surface layer of the matrix to form a Metallurgically bonded cladding layer on the surface of the matrix [1-3]. The process has the advantages of concentrated heat input, fast heating speed, small heat affected zone, low dilution rate, wide selection of materials and strong controllability of the process, and is widely used in coal, steel, metallurgy, aerospace and other fields [4-6]. The specific energy or energy density $E$ is commonly used in actual processes to evaluate and control the quality of the cladding layer [7-9].

$$E = \frac{P}{Dv} \quad (1)$$

Among them:
$E$ is the energy density, the unit is J/mm\textsuperscript{2}; $P$ is the laser power, the unit is kW; $v$ is the scanning speed, the unit is mm/s; $D$ is the spot diameter, the unit is mm.

As can be seen from equation (1), the laser energy density is proportional to the laser power $P$ and inversely proportional to the scanning speed $v$ and the spot diameter $D$. The predecessors have carried out a lot of exploration work on the powder and process adaptability of the synchronous powder feeding method, but the analysis of the reasons that the process affects the laser energy density and causes the change of the coating structure was insufficient. In this paper, the difference of microstructure between two energy densities and the trend of microhardness change from coating to matrix have been analyzed from the perspective of solidification of molten pool. It has analyzed the causes of the difference, and tried to explore the correspondence the between the laser energy density and solidification structure.
2. Materials and Methods

2.1. Experiment materials
In this study, the commercially available laser cladding special powder KF-JG-3 was used for the synchronous powder feeding. The main chemical composition and physical properties of the alloy powder are shown in Table 1. The matrix is a tube steel 27SiMn.

| Chemical element | C   | Cr  | Ni  | Mn  | V   | B   | Si  | Fe  |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| content (wt%)    | 0.17| 20.0| 5.0 | 1.0 | 0.5 | 1.0 | 1.0 | margin |

2.2. Experiment method
In this paper, the main equipment of the laser cladding system is a 6kW high-power semiconductor laser. The process is shown in Table 2.

| Serial number | Power (P, kW) | Scanning speed (v, mm/s) | Laser energy density (E, J/mm²) | Spot diameter (D, mm) | Cladding thickness (mm) | Lap rate (δ, %) |
|---------------|---------------|--------------------------|--------------------------------|-----------------------|------------------------|----------------|
| a             | 3             | 6                        | 160                            | 3                     | 2                      | 50             |
| b             | 6             | 8                        | 250                            |                       |                        |                |

The sample was cut along the depth direction of the cladding, and the obtained sample had a size of 10×10×5 mm. The cut sample was cold-set, polished and etched. The corrosive composition was aqua regia (HNO₃: HCl =1:3). Using the LETTZ microhardness tester to determine the cross section microhardness of the coating to the matrix, the experimental loading force was 200g, the dwell time was 10s; using the Hitachi SU5000 scanning electron microscope (SEM) to observe the metallographic phase tissue and morphology, using the energy spectrometer (EDS) to detect the phase composition in the tissue. X-ray diffractometer (XRD) was used to detect the phase composition of the coating, scanning Angle is from 20° to 90°, and scanning rate is 10°/min.

3. Results and discussion

3.1. Coating structure
According to the foregoing, the laser energy density of the a process was $E_a=160 \text{ J/mm}^2$; the laser energy density of the b process was $E_b=250 \text{ J/mm}^2$. The cooling rate of laser cladding was fast, so there was a large temperature gradient, and the formation morphology was also very different. Generally, the cross section of the cladding layer is divided into four layers, namely, a coating zone (CZ), a bonding zone (BZ), a heat-affected zone (HAZ), and a matrix zone (MZ), as shown in figure 1 and figure 2.

![Figure 1](image-url)
As can be seen from Figure 3(a), the two materials had exhibited a good metallurgical bond at the interface. It has been observed that there is a layer of no dendritic structure with a thickness of about 10 μm at the junction between the bottom layer of the cladding layer and the matrix. This is because in the melt solidification, when the temperature gradient G is large, and the crystal growth rate R is small, the interface front is not supercooled, and the phase interface is always flat. If it happens to protrude into the superheated melt, it will be remelted and the interface will still be flat. This forms a white plane crystal region, which is the layer of tissue that closely bonds the dendrites of the upper layer to the matrix.

During the entire crystallization process, solidification always advances with the liquid-solid phase interface, and the crystallization process is carried out on the solid phase matrix which is first condensed. It is not difficult to find that the epitaxial growth of dendrites has a strong directivity, which is basically perpendicular to the matrix, as shown in figure 3(b). The metallographic structure inside the cladding layer is composed of a large number of columnar dendrites and equiaxed crystals. In addition, due to the temperature gradient, the closer to the surface of the coating, the finer the grain size.

After the matrix material is irradiated by laser, the heat-affected zone is mainly quenched structure, which is mainly composed of a large number of lath martensite and a small amount of retained austenite. Due to the large degree of undercooling in the early stage, the number of austenite grains are large, but the rate of grain growth decreases exponentially with decreasing temperature, at the same time it is difficult to form large austenite grains, because the phase change is kept for a short time. Because martensite phase transition is a non-diffusion phase transition, it can be carried out at a low temperature. Most of the austenite undergoes martensite shear, and the unchanged austenite is retained.
As the laser energy density increases, it will lead to a change in the cooling rate of the coating. The structure near the fusion line between the coating and the matrix is different from the process a, and the planar crystal region is enlarged to nearly 20 μm, as shown in Figure 4(a)(b). In addition, the energy density increases which results in the increase of dendrite size. This is because the heat input is proportional to the energy density. When the energy density is small, the formed molten pool is shallow, and the surrounding matrix has better heat dissipation conditions, so that the length and width direction of the crystal embryo in the subsequent solidification process are not sufficiently grown, the cooling rate is large, the dendritic crystal size is finer. On the contrary, as the energy density increases, the formed molten pool is deeper, the dendrite growth space increases, the cooling rate decreases, the dendritic crystal growth is easier, and the dendrite size also increases. In addition, as the laser energy density increases, the dendrite size increases in length much more than the width. This is because during the heating of the laser, the heat dissipation in the molten pool mainly depends on the reverse outward discharge of the matrix, and the molten pool has the characteristic of directional solidification, so that the growth of the dendrites in the longitudinal direction is much larger than the growth in the width direction.

3.2. Segregation of elements

This is a SEM photograph in figure 5, which is the microstructure of the laser cladding alloy coating zone (CZ). This is an equiaxed crystal structure, and the distinct particle phases can be seen at the grain boundaries. The EDS line scan spans a grain, and the illustration in Figure 6 shows the location and path of the line scan. It can be seen from the figure that under the two laser energy density conditions, there are differences in the chemical composition between the intergranular and grain interior of the coating, which are composition segregation phenomenon. The strong carbide forming element Cr is segregated between the dendrites, the content of Fe at the grain boundary is significantly reduced, and the segregation of other alloying elements at the grain boundaries is not obvious. This is due to the redistribution of solute during the solidification of the molten pool. The diffusion between the liquid phase and the solid phase and the liquid-solid phase does not reach the equilibrium concentration at the corresponding temperature, which leads to dendrite segregation of Cr.

![Figure 5](image-url)

**Figure 5.** The SEM and EDS line scan of coating region under the energy densities of $E_a=160\text{J/mm}^2$ & $E_b=250\text{J/mm}^2$
With the increase of energy density, the solidification rate of the molten pool is reduced, and the degree of segregation of Cr is weakened. Figure 6 shows the XRD patterns of the coating surface under two energy density conditions. The Cr element is easily dissolved in the γ-Fe lattice to form a solid solution and a part of the intermetallic compound (Fe, Cr)7C3. Among them, the diffraction angle 2θ is 44.4°, which is the martensite diffraction peak, and the diffraction peak intensity value is the highest. It can be seen that the coating is mostly composed of martensite structure, and martensite is a supersaturated solid solution of carbon in α-Fe. The austenite phase diffraction peak at 2θ is 43.5°, and its diffraction peak intensity is second only to martensite. However, as the laser energy density increases, the amount of intergranular retained austenite decreases significantly, and the diffraction peak intensity decreases.

![Figure 6. XRD spectra of laser cladding layer](image)

3.3. Microhardness

In order to obtain a coating with good wear resistance, a high hardness material is usually coated on the surface of the matrix, and the laser energy density affects the hardness of the cladding layer in addition to the coating formability. Figure 7 is a graph showing the microhardness of the coating to the matrix under two laser energy density conditions.

When the laser energy density $E_a=160 \text{J/mm}^2$, the microhardness of the cladding layer is increased from $200 \text{HV}_{0.2}$ of the matrix to $615 \text{HV}_{0.2}$; and when the laser energy density $E_b=250 \text{J/mm}^2$, the microhardness of the cladding layer is increased from $230 \text{ HV}_{0.2}$ of the matrix to $550 \text{ HV}_{0.2}$. The microhardness of the coating is higher than that of the matrix under the two conditions, and the curves show a trend of increasing first and then decreasing. The difference of microhardness can be clearly seen on both sides of the BZ zone. The hardness distribution in the CZ region is substantially uniform. As mentioned above, the coating structure is fine columnar dendrites and equiaxed grains, and fine grains promote the effect of fine grain strengthening. Furthermore, the interaction of Ni, Cr, V with B,
C forms a variety of intermetallic compounds, and these dispersed second phases also increase the strength of the coating.

4. Conclusion
(1) The laser cladding CZ region is a rapidly solidified structure composed of a large number of columnar dendrites and equiaxed crystals. The dendrite growth direction is consistent with the temperature gradient direction and exhibits an epitaxial growth morphology. As the laser energy density increases, the size of the BZ region extends from 10 μm to 20 μm.
(2) Increasing the laser energy density, the grain refinement degree of the coating is reduced, and the ratio of the length and width of the dendrite is correspondingly reduced. The microhardness of the coating decreased from 615 HV0.2 to 550 HV0.2, but both were more than double the microhardness of the matrix.

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