Study on the microstructure and heat affected zone of nickel-based alloy cladding layer

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Abstract—Six Ni-Cr-Mo cladding layers were prepared on the surface of Q235 steel by laser cladding technology. SEM and EDS were used to detect the crystal structure and element diffusion trend of the cladding layer, and the microhardness of the cladding layer and the substrate was tested with a micro hardness tester. The structure of the heat affected zone (HAZ) obtained by different preparation processes was analyzed. The experimental results indicated that the hardness of the cladding layer was about 1.5 times that of the substrate, which improved the wear resistance of the material. SEM / EDS results illustrated that the cladding layer and the substrate showed a good metallurgical bond, and the microstructure on the cross-section of the cladding layer from the junction to the surface gradually transitioned from cell crystals to dendrites. The element diffusion curves showed that the diffusion amount of Fe element is the largest and that of Mo element is the smallest. The morphology of the heat affected zone is very different from the substrate and the cladding layer, there are only pearlite and ferrite in the substrate, while martensite appears in the heat affected zone.

1. Introduction

Nowadays, with the increasing shortage of energy and the urgent needs of the rapid development of the industry, the uses of nickel-based alloys are becoming more and more diversified, and the performance requirements of nickel-based alloys are also beginning to increase. How to prepare high-performance corrosion-resistant and high-temperature nickel-based alloys has become an urgent problem to be solved.

Laser cladding is an emerging surface technology of remanufacturing using a high-energy laser beam as a cladding heat source, which can improve the surface properties, the corrosion resistance and hardness of materials[1]. It is a good metallurgical method, which can greatly reduce the loss of benefits compared with ordinary materials. The material synthesized by laser cladding technology has the following advantages: (1) The surface of the material processed by laser cladding is generally smooth and clean, and does not require excessive treatment. (2) The surface hardness and corrosion resistance of the processed materials are usually higher than those of ordinary materials. (3) The heating and cooling speed of laser cladding is very fast, which has the effect of self-quenching. (4) Laser cladding can process parts with irregular surface, so that it has better performance. (5) The laser cladding process is simple and easy to automate. (6) Laser cladding is safe, efficient and low material consumption. (7) The high melting point alloy is cladding on the surface of the low melting point
metal, and there is almost no limit to the powder[2]. In recent years, a number of studies have been conducted to investigate the microstructure and mechanical properties of laser cladding of different elements.

Wang Jinfeng et al. have found that the pattern obtained by laser cladding technology has better overall performance than plasma cladding technology[1]. In terms of cladding materials, iron-based, nickel-based and cobalt-based alloy powders have been widely researched and commercialized[3]. Cui Lujun et al. studied that adding Mo elemental substance can improve the deformation ability and reduce the friction factor of the cladding layer, the refinement and uniformity of the cladding layer structure improve the stability of the friction factor[4]. Qian Shaoxiang analyzed the structure of Fe-Cr-Mo coating on the Q345D substrate and found that Cr and Mo segregated when the cladding layer solidified, which played a good role in strengthening the coating[5]. Yu Yang used laser cladding technology to prepare Cu-Ni-Fe-Mo-xCr alloy coatings with different chromium contents on the surface of medium carbon steel. The results show the addition of Cr improves the content and oxidation resistance of the second phase[6]. The above research found that Ni, Cr, Mo and other elements have greatly improved the high temperature corrosion resistance of the material, but there are few studies on the cladding layer of Ni-Cr-Mo system. In order to improve the performance of the cladding coating, a comprehensive study of the cladding system of Ni-Cr-Mo system was carried out.

Q235 steel is the most common carbon structural steel with good strength, toughness and welding performance[7, 8]. In this work, six kinds of alloy with different process parameters were employed to prepare coatings on the surface of Q235 steel by laser cladding. The aim is to explore the structure, hardness and heat affected zone of the cladding layer.

2. Experimental

Q235 steel was chosen as the substrate of six patterns, and Ni-Cr-Mo cladding layer was cladding on the surface of the Q235 steel. The Ni-Cr-Mo powders were supplied by Beijing Xinzhulian New Material Technology Co., Ltd. The laser cladding layer in this experiment was prepared by the laser cladding system in the laboratory of high-temperature material properties of North China Electric Power University. This experiment is divided into two groups A and B, with a set power of 2000W and an overlap of 50% between successive tracks. Both group A and group B use the synchronous powder feeding method, and the feed amount of group A is twice that of group B. The two groups maintain other parameters. An argon atmosphere was used to protect the molten pool from the surrounding air. The cladding process parameters of the six patterns are shown in Table I.

| Sample | Overlapping ratio | Power (W) | Powder feeding rate(cm/s) | Cladding thickness (μm) |
|--------|-------------------|-----------|--------------------------|------------------------|
| A1     | 50%               | 2000      | 17.5                     | 228.4                  |
| A2     | 50%               | 2000      | 10.5                     | 413.3                  |
| A3     | 50%               | 2000      | 3.5                      | 885.1                  |
| B1     | 50%               | 2000      | 2.9                      | 972.0                  |
| B2     | 50%               | 2000      | 8.7                      | 314.4                  |
| B3     | 50%               | 2000      | 14.5                     | 167.2                  |

The Ni-Cr-Mo powders were mixed and dried by mechanical stirring at 120 °C for 3 hours, then the powders were put in the beaker, stir and mix manually more than 30min. The Ni-Cr-Mo coating was prepared by laser cladding technology on Q235 steel. The samples were polished with a
wire brush to remove impurities and slag on the surface. After the experiments, the metallographic samples were cut to the plate with size of 10 mm × 10 mm × 5 mm. A total of six samples with different thicknesses of the cladding layer were obtained in two groups. The samples were placed in an ultrasonic container and washed. The surfaces of the samples for microstructure observation were grinded with a series of sandpaper (from #400 to #1000), and polished with M1.5 # polishing paste.

The microhardness test of this experiment was completed by the FM-300 microhardness tester in the Key Laboratory of Power Station Equipment Monitoring and Control of North China Electric Power University with a load of 100g/N and a dwell time of 15s, and the indentation is observed under 400 times metallurgical microscope that comes with the micro hardness tester. The morphology was observed with FESEM (ZEISS SUPRA-55 with EDS analysis system), FEI Quanta 200F and SU8010 scanning electron microscope at an acceleration voltage of 20 kV. The element composition and distribution of elements were analyzed by energy dispersive X-ray spectroscopy (EDS).

3. Results&discussion

3.1. Micro vickers hardness
Fig.1 shows the microhardness curve of A1, A2, A3, B1, B2, B3 under the condition of 100g / N, from which we can see that the Vickers hardness is a clear upward trend from the substrate to the cladding
layer, while the hardness of the B3 sample is too thin, and the hardness changes greatly. From the hardness curve, it can be seen that the Q235 substrate hardness is around 150HV. In group A: the hardness of A1 cladding layer is 210HV, which is about 1.5 times the hardness of the Q235 matrix; the hardness of A2 cladding layer is about 230HV; the hardness of A3 cladding layer is about 270HV, which is 1.8 times the matrix. In group B: the hardness of B1 and B2 is 180HV and 260HV, respectively. The hardness of the cladding layer is significantly higher than that of the substrate. This phenomenon is mainly due to the hard phases generated in the coating, which increases the average hardness of the cladding layer. The presence of Mo refines the grain size of the coating and plays a role in strengthening the cladding layer due to refinement strengthening mechanism. The hardness of the heat affected zone is between the cladding layer and the substrate. This is because at high temperatures, the substrate undergoes a martensite transformation, resulting in higher hardness [9].

3.2. Elemental diffusion analysis

Fig. 2 depicts the cross-section element variation curve of the cladding layer of six samples. Because of the difference of powder feeding amount and the cladding rate, the element diffusion speed and diffusion amount of various samples are different.

As can be seen in Fig.2, maintaining the same powder feeding amount, while the powder feeding speed decreases, the diffusion rate of Fe element shows a downward trend. In group A, the powder feeding speed of A1 sample is 17.5cm / s, in this case, the highest Fe element diffusion rate reached more than 40%, while under the condition of A3 powder feeding speed of 3.5cm / s, the Fe element diffusion rate was about 20%. It can be indicated that the faster the powder feeding rate, the thinner the cladding layer, the greater the element dilution rate. The same applies to Group B, the cladding speed of B3 is 14.5cm/s, which is the fastest cladding speed among the three samples, and its Fe element dilution rate is also the highest. On the contrary, the cladding speed of B1 is 2.9cm / s, the dilution rate of Fe element is 30% ~ 40%, which is lower than that of B2 and B3.

While comparing Group A and Group B, the two groups have different powder feed rates. Group A delivered twice much powder as Group B. According to the comparison of the above figures, the smaller the amount of powder feed, the thinner the cladding layer, the higher the element dilution rate.

The common characteristics of the six samples are: Fe element has the largest diffusion amount, followed by Ni element, Cr element again, and Mo element with the smallest diffusion amount. The diffusion distribution of the Fe element and the Ni element is in the opposite trend. When the Fe element shows a peak, the Ni element is bound to appear a trough; otherwise, the Fe element appears a trough, the Ni element is bound to appear a peak.

The heat affected zone can be characterized by the element diffusion curve. The high-energy laser beam causes the atoms of the cladding layer and the matrix to migrate to each other, which affects the structure and performance of the base material. From the place where the Fe element of the substrate is 100% to the junction of the cladding layer and the substrate, it can be planned as the width of the heat affected zone [10].

![Elemental diffusion analysis](image-url)
3.3. SEM analysis

Figure 3. Q235 steel (substrate) secondary electron image

The matrix of the two groups of samples is Q235 steel. The carbon content of Q235 steel is moderate, the properties of strength and hardness are excellent, and it has a wide application field. As shown in Fig.3, after corrosion by aqua regia (HCl: HNO₃ = 3: 1), the oxides and oil stains on the surface were wiped clean with alcohol. The microstructure of Q235 steel is evenly distributed, the black part is ferrite, the white part is pearlite, and the two are mixed evenly[11, 12].

Figure 4. Cross-sectional view of cladding layers A2 and B1:(a) A2;(b) B1
Fig. 4 is a cross-sectional photo of representative cladding layers, and A2 and B1 are selected from Group A and Group B, respectively, and it shows that there is a clear dividing line between the cladding layer and the substrate. The cladding layer is above the boundary and the substrate is below. The dividing line is smooth and almost straight. This is because when the cladding layer solidifies, the growth rate of the liquid-solid interface is small, which makes it difficult to cause the components to be too cold. There is a large temperature gradient, which promotes the growth of the bonding plane[1, 13, 14]. It is noted from Fig. 4 that the cladding layer has a few holes and no obvious cracks. The cladding layer and the substrate show a good metallurgical combination. After aqua regia corrosion, the cladding layer corroded hardly, but the substrate corroded seriously.

Fig. 5(a) shows the upper part of A1 cladding layer. It can be observed that many small dendrites are generated in the cladding layer because the laser cladding has a large temperature gradient at the boundary between the substrate and the cladding layer. However, when reaching the upper part of the cladding layer, the temperature gradient gradually becomes smaller, the degree of supercooling increases, and the crystallization rate becomes larger, so the crystal grains form dendrites along the direction of the temperature gradient [5]. In Fig. 5(b), below the boundary, the tissue of A1 is slender and dense, and the growth direction is horizontal. This is because when preparing the cladding layer, the surface temperature of the substrate is extremely high, and the cooling rate is very slow, so it is in an overheated state, causing completely austenitized and forming thick lath martensite[7, 8].

The martensite structure can be found in Fig. 5(c), the grains have become smaller and shorter, and the phase arrangement is disordered. This could because the temperature is not high enough and incomplete austenitization has occurred. From the junction moves down, it can be seen that the amount of martensite gradually decreases[7, 8, 15]. We can find there is a layered pearlite in the substrate that is not affected by the high temperature of laser cladding in Fig. 5(d).

Fig. 5(e) illustrates the morphology of the cladding layer, the lower part is cell crystal, and the upper part is dendrite. It can be clearly observed under the SEM that from the junction to the surface of the cladding layer, it gradually transitions from cell crystal to dendrite. This is because at the junction, when the component undercooling is small, the grains have a tendency to grow, but the trend is not obvious, so a regular arrangement of cell crystals is generated. Above the cladding layer, the composition is too cold, and dendrites are formed [1, 9]. Fig. 5(f) can be observed that there is a clear white bright band area with a small thickness below the junction of the substrate and the cladding layer, which shows that the substrate and the cladding layer exhibit good metallurgical bonding [5, 9].

As shown in Fig. 5(g), it can be seen that after aqua regia corrosion, there is no obvious change in the cladding layer, and the substrate is corroded seriously. The presence of Ni, Cr, Mo elements causes solid solution strengthening and fine grain strengthening of the cladding layer, which greatly improves the characteristics of the cladding layer. Fig. 5(h) presents that the white grains in the heat affected zone are fine and disorderly distributed, and the black part is ferrite, which is arranged in an orderly phase relationship under the effect of thermal stress.

From Fig. 5(i), dendritic crystals appear in the cladding layer and grow perpendicular to the junction. In Fig. (j), the distribution of martensite near the junction is disorderly and irregular, and the farther away from the junction, the less martensite content. At the bottom of the substrate, the presence of pearlite can be seen in the Q235 steel without phase transformation.

The existence of cell crystals can be clearly observed in Fig. 5(k). They have no uniform growth direction and are randomly arranged. This is because at the bottom of the cladding layer, the temperature gradient is large, the solidification speed is small, and there is no fixed growth direction when the crystal growing. As shown in Fig. 5(l), the martensite in different phases has a large-angle grain boundary in the middle, and part of ferrite appears next to the martensite. This is because incomplete austenitization causes uneven distribution of the structure[16].
Figure 5. SEM images of six samples: (a) A1; (b) A1; (c) A2; (d) A2; (e) A3; (f) A3; (g) B1; (h) B1; (i) B2; (j) B2; (k) B3; (l) B3

4. Summary
In this paper, two sets of six experimental samples were successfully prepared using semiconductor laser system. The base material of the experiment was Q235 steel, and the cladding material was Ni-Cr-Mo cladding. The cladding layer of the produced sample is smooth, without obvious pits, cracks, holes, etc. The six samples made with different parameters were analyzed for hardness, element diffusion change trend and microstructure, which are summarized as follows:

- The average hardness of Q235 steel is 140HV and the surface hardness of the cladding layer reaches 260HV, which is about 1.5 times that of the substrate. The hardness of the HAZ lies between the hardness of the substrate and the cladding layer.
- According to the SEM / EDS analysis results, the junction of the cladding layer and the substrate is basically a white and smooth horizontal line, indicating that the cladding layer and the substrate exhibit a good metallurgical bond. The microstructure on the cross-section from the junction to the surface gradually transitions from cell crystal to dendrite.
- Among the six samples, Fe element has the largest diffusion amount, followed by Ni element, Cr element again, and Mo element with the smallest diffusion amount. The diffusion distribution of Fe element and Ni element is opposite. In addition, the smaller the amount of powder feeding, the thinner the cladding layer, the higher the dilution rate of Fe element.
- Both the hardness curve and the element diffusion curve can characterize the HAZ, and the structure morphology can also characterize the heat affected zone. It is reflected in the hardness curve as a curve segment with a large slope near the junction, and on the element diffusion curve as the width where the Fe content of the matrix is 100% suddenly begins to fall to the junction. There is no obvious boundary line between the HAZ and the substrate, but it can be observed that as the junction changes to the substrate, the martensite content gradually decreases, the distribution gradually becomes chaotic and irregular, and finally the mixed distribution matrix of ferrite and pearlite is formed.
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