Microstructure and wear resistance of Fe-based, Co-based and Ni-based coating of AISI H13

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Abstract. H13 coating, Stellite156 coating and WC/Ni62 composite coating were prepared on AISI H13 hot working die steel by laser cladding. By means of metallographic microscope, scanning electron microscope, microhardness tester and friction and wear tester, the microstructure, hardness and wear resistance of H13 and three cladding layers were compared and analysed. The results show that H13 alloy coating, Stellite156 alloy coating and WC/Ni62 composite coating all show good metallurgical bonding characteristics with H13 steel substrate. The H13 alloy coating is mainly composed of white reticular dendrite, black intercrystalline carbide, martensite and residual austenite; the Stellite156 alloy coating is mainly composed of primary γ-Co dendrites and eutectic tissues; the WC/Ni62 matrix composite coating is mainly composed of WC particles, dendrites and fine eutectic tissues. The average microhardness of the three cladding layers is obviously higher than that of the substrate. WC/Ni62 composite coating has the best wear resistance under dry wear conditions.

1. Introduction

Since it has excellent wear resistance, fatigue resistance and thermal shock resistance, the AISI H13 steel (4Cr5MoSiV1) after quenching and tempering is widely used in hot-forging die, hot-extrusion die, die-casting die, etc. However, due to the severe working environment such as high temperature and high pressure, impact load, and cold and hot fatigue, components would be damaged in a short time because of thermal wear, hot fatigue crack, deformation, and heat corrosion [1,2]. Moreover, the cost of a new die is expensive, but also the manufacturing cycle is long. The failed parts were usually repaired by machining or welding process [3]. However, when using the machining process, the number of cycles of reuse is limited, and it is irreversible and wastes a lot of materials. When using welding repair, porosity and other problems easily occur because of the high heat input. Compared with the traditional repairs, laser cladding technology has the characteristics of high machining accuracy, small thermal deformation degree, and less follow-up processing. Hence, it has more economic benefits and application value, especially in the surface repair of large and expensive failure equipment.

From the perspective of cladding materials, the iron-based cladding layer with compositions similar to the H13 substrate is more resistant to cracking and wear. The cobalt-based coating has good characteristics of high temperature strength, hardness and thermal fatigue resistance, and it has been
widely used in laser cladding surface strengthening of mold steel. Previous researches have shown that the high-temperature friction and wear [4] and impact toughness [5] of the iron-base and cobalt-based coating were reported. Telasang G [6-8] obtained the uniform microstructure by laser cladding H13 powder on H13 mold steel and by laser surface tempering for 2 hours, and the microstructure obtained by laser surface tempering was finer. Moreover, laser phase-change hardening of H13 [9] was investigated.

Nickel-based coating can obtain a coating with better wettability, but the hardness and wear resistance of the coating are relatively low. Ceramic particles such as WC can be added to significantly improve the coating performance, which has become a trend and hotspot in the research on mold surface strengthening. Nickel base alloy powder is spherical or nearly spherical, and has good wettability with cast WC, high hardness, good wear resistance, excellent impact resistance, used in mining, mechanical processing, oil drilling, shield equipment and other wear-resistant and impact surface pre-strengthening or wear repair. Hossein Mazaheri Tehrani [10] studied the WC-Ni composite powders were fabricated on an AISI 321 steel by laser cladding method. The micro-hardness of the WC-Ni coating was 1.2–1.6 times higher than the WC-Ni, WC-Co and WC-Co-Ni coatings, made by thermal spray coating. Yang Jiaoxi [11-15] et al. studied the NiCrMoAl/WC composite coatings with different contents of WC particles were deposited on P550 steel by laser cladding. the microstructure and magnetic properties of the coatings by the first-principles based on the density functional theory were investigated. Weng Zhikun [16] et al. studied the Ni/WC composite coatings with different weight percentage of WC particle were produced on a stainless steel by diode laser-cladding technology with the aim to improve wear resistance of the stainless steel. The influences of WC content on microstructure and hardness were investigated.

Therefore, H13 steel (4Cr5MoSiV1) was selected as the substrate, and the Co-based layer with heat-resistant fatigue, the Fe-based layer with similar components to the substrate and WC/Ni62 composite coating with excellent hardness were selected in this work. The microstructure, hardness, and friction and wear properties of three cladding layers and substrate were compared and studied. It provides reference for laser cladding technology experimental evidences.

2. Experimental materials and methods
In the test, a hot-work die steel H13 in quenching and tempering state was used as the substrate. The size of the test block is 40mm×40 mm×20 mm, and the main alloying elements (mass fraction, %) are shown in Table 1. The cladding materials are H13 powder, Stellite156 powder and Ni62+50%WC powder. The chemical compositions of the H13, Stellite156 and Ni62 power are listed in Table 2, Table 3 and Table 4, respectively. Each powder cladding the whole test block by the laser cladding method, preheating 350℃ for 2h before the test. The spot diameter is 5 mm and the cladding parameters are listed in Table 5.

| C   | Si  | Mn  | Cr  | Mo  | V   | P   | S   |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.37-0.42 | 0.80-1.20 | 0.20-0.50 | 4.75-5.50 | 1.10-1.75 | 0.80-1.20 | ≤0.03 | ≤0.006 |

| C   | Cr | Mn  | Mo  | Si  | V   | Fe  |
|-----|----|-----|-----|-----|-----|-----|
| 0.35 | 5  | 0.3 | 1.5 | 1   | 1   | Bal. |

| C   | Cr | Fe | Mn  | Mo  | Ni  | Si  | W   | Co  |
|-----|----|----|-----|-----|-----|-----|-----|-----|
| 1.58 | 28 | 0.5 | 0.05 | 0.21 | 2.66 | 0.87 | 4.08 | Bal. |
### Table 4. Chemical compositions of the Ni62 powder (wt.%).

|   | C   | Cr  | Fe  | B   | Ni  | Si  | W   | Ni  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
|   | 1.15| 15.51 | 11.36 | 3.04 | 2.66 | 3   | 11.3| Bal. |

### Table 5. Laser technology parameters.

| Cladding materials | laser power (W) | sweep rate (mm/s) | powder feed rate(r/min) | overlap rate | cladding direction between the layers |
|--------------------|-----------------|-------------------|-------------------------|--------------|--------------------------------------|
| H13                | 3400            | 8                 | 24.75                   | 40%          | Vertical cross cladding              |
| Stellite156        | 3500            | 9                 | 26.85                   | 40%          | Vertical cross cladding              |
| WC/50%Ni62         | 3600            | 8                 | 24.75                   | 40%          | Vertical cross cladding              |

Different coatings were sectioned from the center portion by wire electrical discharge machining (WEDM). The specimens were prepared using silica carbides discs from 150 up to 1200 grit and then polished with diamond paste. DMI5000M inverted metallographic microscope and microhardness meter were used to observe the metallographic layer and microhardness, respectively.

MMW-1A friction and wear tester was used to test the wear resistance of the cladding layer. The upper sample was the cladding layer sample, size 10*10*20mm, and the lower sample was the four-wheel and one-piece chain link material 35MnB, size 40*20mm, load of 300 N, speed of 185r/min, friction radius of 5 mm, test time of 600s. The abrasion loss was measured by electron microbalance, and all the test data were the average values of the three measurements under the same conditions. Finally, the wear morphologies were observed by scanning electron microscope.

### 3. Experimental results

#### 3.1. Microscopic observation

Fig. 1 shows the microstructure of the cladding layer. It can be seen that the substrate H13 structure is tempered Martensite, tempered Tortensite and residual carbide, as shown in Fig.1a. The H13 alloy coating is a hypereutectoid structure, consisting of white reticulated dendritic crystal, black intergranular carbide, Martensite and residual austenite. As shown in Fig.1b, white reticulated dendritic crystal is carbide, and black intergranular carbide is caused by the aggregation and distribution of fine particle carbide at grain boundary. Stellite156 alloy coating consists of primary -Co dendrites and eutectic structures between them, as shown in Fig.1d. The WC/Ni62 composite coating is composed of spherical WC particles, dendrites and fine eutectic tissues, as shown in Fig.1f. As you can see from the Fig.1c, Fig.1e and Fig.1g, H13 alloy coating, Stellite156 alloy coating and WC/Ni62 composite coating all show good metallurgical bonding characteristics with H13 steel substrate.
Figure 1. Metallographic structure of three cladding layers and substrate (a) H13 substrate (b) H13 alloy coating (c) H13 coating interface (d) Stellite156 alloy coating (e) Stellite156 coating interface (f) WC/Ni62 composite coating (g) WC/Ni62 composite coating interface.

The backscattered electrons of the three cladding layers were observed and their microstructure was further clarified by energy spectrum analysis. Fig.2 shows the backscattered electron image of H13 alloy coating, which is composed of dendrite and matrix of Co-Cr solid solution. Surface scanning was performed on Fig. 2b and EDS results of H13 alloy coating were shown in Table 6.

Fig. 3 shows the SEM morphology of Stellite156 alloy coating. It can be more clearly seen that Stellite156 alloy coating is composed of Co-Cr solid solution dendrite and matrix structure, which the capture point 1, 2 and 3 was analyzed by energy spectrum analysis, as shown in Table 7. The position 1 is primary crystal axis and position 2 is secondary dendritic crystal axis. They are Co-Cr solid solution. Different from primary crystal axis and secondary dendritic crystal axis, there are more W, Si and C elements in the substrate, indicating that strengthening phase exist and dispersedly distributed in dendrites and branches.

Figure 2. BSE images on the H13 alloy coating.
Table 6. EDS results of H13 alloy coating

| Element | wt. / % | at. / % |
|---------|---------|---------|
| C       | 2.63    | 6.69    |
| Si      | 1.11    | 2.46    |
| V       | 1.11    | 1.36    |
| Cr      | 7.54    | 6.64    |
| Fe      | 85.6    | 81.55   |
| Mo      | 2.01    | 1.3     |

Figure 3. BSE images on the Stellite156 alloy coating.

Table 7. EDS results of Stellite156 alloy coating

| Element | 1        | 2        | 3        |
|---------|----------|----------|----------|
|         | wt. / %  | at. / %  | wt. / %  | at. / %  | wt. / %  | at. / %  |
| C       | 4.13     | 15.64    | 5.72     | 18.49    | 5.37     | 21.82    |
| Si      | 0.99     | 1.72     | 1.07     | 1.81     | 0.86     | 1.22     |
| Cr      | 24.61    | 23.04    | 24.29    | 22.28    | 34.75    | 26.70    |
| Mn      | 0.49     | 0.43     | 0.57     | 0.49     | ——       | ——       |
| Co      | 66.79    | 55.16    | 66.32    | 53.68    | 48.46    | 32.86    |
| W       | 2.42     | 0.64     | 2.44     | 0.63     | 4.43     | 0.96     |

Fig. 4 is Backscattered electron images of WC/Ni62 composite coatings. The WC/Ni62 cladding layer is composed of spherical WC particles, dendrites and fine eutectic structures. As shown in Fig. 4a and Fig. 4b, there are mainly gray transition belts at the WC/Ni62 composite coating and H13 steel substrate, indicating that the matrix and coating show good metallurgical bonding characteristics. The energy spectrum analysis was used to observe three locations of the coating as shown in Table 8. Position 1 is spherical WC particles, and position 2 is small broken WC particles with Ni elements. There are a large number of Ni elements in position 3.
Figure 4. BSE images on the WC/Ni62 composite coating.

Table 8. EDS results of WC/Ni62 composite coating.

| Element | 1 wt. / % | 2 at. / % | 3 wt. / % | 4 at. / % | 5 wt. / % | 6 at. / % |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|
| C       | 14.64     | 72.42     | 12.27     | 59.28     | 12.48     | 44.03     |
| Cr      | ——        | ——        | 2.92      | 3.26      | 2.14      | 1.74      |
| Fe      | ——        | ——        | ——        | ——        | 1.79      | 1.36      |
| Ni      | ——        | ——        | 15.90     | 15.72     | 68.43     | 49.38     |
| W       | 85.36     | 27.58     | 68.90     | 21.74     | 15.16     | 3.49      |

3.2. Microhardness
Microhardness tests were conducted on the three cladding layers and the substrate, and the results were shown in Fig.5. The microhardness values of the cladding layer and the substrate fluctuated slightly, indicating that the microstructure was uniform. The average microhardness of H13 alloy coating was 595 HV1 and Stellite156 alloy coating was 609 HV1, both of which were higher than that of the substrate (490 HV1). The average microhardness of WC/Ni62 composite coating was 1760 HV1.

Figure 5. Microhardness of three kinds of cladding layers and substrate.
With regard to H13 alloy coating and Stellite156 alloy coating, compared with the H13 substrate, the addition of Mo, Cr, Si in the cladding layer effectively prevents grain growth, which plays multiple roles of dispersion strengthening, solid solution strengthening and fine grain strengthening. It effectively improves the hardness and wear resistance of steel. The chromium content of cladding layer is higher, so the amount of carbide is more, which will lead to an obvious increase in hardness.

3.3. **Wear resistance**

![Figure 6. Average mass loss of three kinds of cladding layers and substrate.](image)

The average weight loss of the three cladding layers and the base material is shown in Fig. 6. WC/Ni62 composite coating is the most wear-resistant, followed by H13 alloy coating, and Stellite156 alloy coating is the least wear-resistant, but still higher than the base material. Fig. 7 shows the wear morphologies of the three cladding layers and the substrate. Fig. 7a shows the wear morphologies of the substrate, and the groove formed by significant plough wrinkles on the friction surface is typical abrasive wear.

![Figure 7. Worn morphologies of three kinds of cladding layers and substrate.](image)
Fig. 7b shows the wear morphology of H13 alloy coating. There are lumps falling off in the wear marks. Under the cutting action of abrasive particles, some tiny cracks are generated, and the exfoliation resulting from convergence forms pits. Local adhesion occurs on the friction surface, and then the adhesion area is broken. Some debris is pulled down or scraped from the friction surface. Fig. 7c shows the wear morphology of Stellite156 alloy coating. There is plastic deformation on the wear surface, and a large number of abrasive particles are constantly rolled. More furrows and pits appear on the surface, which is typical of adhesive wear. There is metal transfer between friction pair, smear, scratch, tear, bite dead, a sticking point cut, and in the new place to produce sticking, then cut, transfer, so stick, shear, shear, transfer, and then adhere to the cycle endlessly, constitute a sticking wear process. Fig. 7d shows the wear morphology of WC/Ni62 composite coating. Small abrasive particles and fine scratch furrows exist on some areas of the friction surface, showing a strong grinding resistance. When abrasive particles encounter hard phase, the furrows formed are shallow, small, or even terminated, resulting in a small amount of wear loss.

With regard to WC/Ni62 composite coating, on the one hand, the solid solution based on Ni itself has good strength and toughness, which is not easy to crack and has high fatigue and wear resistance. On the other hand, due to the presence of many dispersed carbide hard points in the substrate of the coating, the wear resistance of the coating is improved, while WC particles with high hardness and high wear resistance further improve the coating's resistance to ploughing wear and adhesion wear.

4. Conclusion
H13 alloy coating is mainly composed of white reticular dendrite, black intercrystalline carbide, Martensite and residual austenite. Stellite156 alloy coating is mainly composed of primary-Co dendrite and its intercrystalline eutectic tissues. The WC/Ni62 composite coating is mainly composed of WC particles, dendrite and fine eutectic tissues. The average microhardness of the three cladding layers is significantly higher than that of the substrate. The WC/Ni62 composite coating is the most wear resistant, followed by H13 alloy coating.

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