Effects of Nano-WC on Microstructure and Wear Resistance of Laser Cladding Ni-based Coating on 42CrMoA Alloy Steel

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Abstract: In the paper, Ni45 coating was manufactured by laser cladding on 42CrMoA alloy steel using the 5 kW CO2 laser, four-axis CNC machines and the coaxial powder feeding system. It was investigated that the effects of nano-WC on microstructure and wear resistance of the Ni-based coating. The macromorphology and microstructures were analyzed by SEM, XRD and microhardness tester. The wear tests were conducted on the Friction and Wear tester. The microstructure was first refined and then coarsened as the increase of nano-WC addition. When the nano-WC addition is 3.0 wt.%, the coating showed the finest microstructure. The clad layers including γ-Ni, Ni3B, M23C6 and WC, W2C. Meanwhile, the wear rates of coating were gradually decreased.

1. Introduction

Laser cladding has been widely used in industrial manufacturing. At present, self-fluxing alloy powder has been widely used in the field of laser cladding technology. It mainly includes Co alloy powder, Ni alloy powder and Fe alloy powder. Since the coating formed by pure self-dissolving alloy powder cannot greatly enhance the wear resistance of the substrate [1,2]. It is considered to add carbide ceramic particles to the self-fluxing powder to improve the wear resistance of the coating. A large number of wear tests of clad layers with non-metal or metal carbide ceramic particles such as SiC [3], TiC [4], WC [5] have been studied. The results show that the presence of carbide ceramic particles can effectively alleviate the wear damage of the coating.

With the gradual development and promotion of nanotechnology, nano-ceramic particles are gradually being used in laser cladding. Nano-ceramic particles have significant advantages over micro-sized carbide particles in terms of plasticity, strength and toughness [6]. At present, the role of nano-ceramic powders such as nano-TiC [7], nano-TiB2 [8], nano-SiC [9] and nano-TiO2 [10] in different metal-based laser cladding coatings has been studied in detail at home and abroad. The fine grain strengthening effect of nanoparticles on the microstructure of the coating was analyzed, and the influence mechanism of the above-mentioned nano-ceramic powder on the wear resistance of the metal-based coating was discussed in depth. At the same time, it is proved that adding nano-ceramic powder to the metal powder can effectively strengthen the relevant mechanical properties and significantly refine the microstructure of the clad layers.
In this paper, the effect of nano-WC on the microstructure, microhardness and wear resistance of the Ni45 coating by coaxial powder feeding laser cladding will be revealed.

2. Experiment Methods

2.1 Material

The Ni45 coating was fabricated on the substrate of 42CrMoA alloy steel. The compositions of 42CrMoA were listed in Table 1. The dimensions of substrates were 45 mm x 20 mm x 15 mm. The compositions of Ni45 alloy powder were listed in Table 2. The size of powder is 45 μm-109 μm. The powders were blended for 2 hours in four ZrO2 bars with a powder mixture for crushing and preventing the powder aggregation.

Table 1. The composition of 42CrMoA (wt.%).

| Substrate | C   | Cr   | Si   | Mo   | Mn   | S   | P   | Fe  |
|-----------|-----|------|------|------|------|-----|-----|-----|
| 42CrMoA   | 0.38~0.45 | 0.9~1.2 | 0.17~0.37 | 0.15~0.25 | 0.5~0.8 | ≤0.025 | ≤0.025 | balance |

Table 2. The composition of experimental materials (wt.%).

| Powder | C | Cr | Si | B  | W | Fe | Mn | Ni |
|--------|---|----|----|----|---|----|----|----|
| Ni45   | 0.45 | 12.00 | 4.00 | 2.40 | - | 10.00 | 0.10 | balance |

2.2 Equipment

The laser cladding was conducted by a process device (a 5 kW CO2 laser, a 4-axis CNC platform and a powder feeder). The clad layers were produced by multi-track laser cladding with an overlapping rate of 40%. The laser process parameters on clad procedure were explored including 2100 W of laser power, 8.5 g/min of powder feed rate and 300 mm/min of laser scan speeds.

The cross-section of clad specimens was ground and polished. Afterwards, aqua regia was used to etch the sample. The microstructures of clad layers were characterized by a JEOL: JSM-6510F SEM microscope. An Empyrean sharp shadow X-ray Diffractometer was used to analysis the phases of the clad layers. The microhardness was measured by a MH-60 tester.

The wear test of the clad layers sliding against GCr15 steel ring were conducted with a method in Figure 1. Under condition of 98 N load, the GCr15 steel ring performs a 30 min wear test on the clad samples at a rotating speed of 400 r/min. The wear rate ω of the clad layers were calculated by the Eq. (1) [11]:

\[ \omega = \frac{V_{loss}}{L \times F} \]

\[ V_{loss} = B \left[ \frac{\pi R^2}{180} \arcsin \left( \frac{b}{2R} \right) - \frac{b}{2} \sqrt{R^2 - b^2} \right] \]

\[ L = 2\pi R v t \]

Volume loss \( V_{loss} \) is calculated by Eq. (2), \( B \) and \( b \) is the length and width of the wear track (mm), \( R \) is the radius of the GCr15 steel ring (25 mm), \( L \) is the wear distance (mm) as calculated by Eq. (3), \( v \) is the rotating speed of the GCr15 steel ring (400 r/min), \( t \) is the wear time (30 min), \( F \) is the load (98 N).
3. Result and Discussion

3.1. Macromorphology of Clad Layers
The cracks morphology of clad layers with different amount of nano-WC are shown in Figure 2, respectively. The number of cracks decreased as the amount of nano-WC increased initially and increased afterwards from 0.0 wt.% to 6.0 wt.%.

![Figure 2. Cracks morphology of clad layers with different amount of nano-WC. (a) 0.0 wt.%, (b) 3.0 wt.%, (c) 6.0 wt.%](image)

3.2. XRD Results of Clad Layers
Figure 3 shows the XRD results of the clad layers. the clad layers are mainly composed of γ-Ni, M23C6 and Ni3B. With the increase of the nano-WC content, the WC diffraction peaks in the spectrum of the coating gradually increase. At the same time, the part of the WC decomposed and produced W2C and C elements due to the high temperature in the melting process. So W2C appeared in the spectrum.

![Figure 3. XRD results of the clad layers.](image)
3.3. Microstructure of Clad Layers

Figure 4 shows the microstructure of clad layers. As shown in Figure 4a, there are large dendrites of the clad layer without WC. At the same time, the eutectic structure is distributed also precipitates bright white particles with different numbers and sizes. When 3.0 wt.% nano-WC is added to the clad layer (Figure 4b), the coating structure is significantly refined, while a uniform eutectic structure is formed and the distribution area is larger. In addition, an irregularly shaped off-white mass was newly formed in the eutectic region.

Because nano WC with the size of about 100 nm-500 nm will adhere to the front of the solid phase interface during the solidification of the molten pool and be pushed to gradually gather at the grain boundary position of the final crystal grains. The grain growth is hindered. Therefore, the microstructure of the clad layers with nano-WC has gradually changed from epitaxial dendritic growth to non-epitaxial equiaxed growth [12].

When the addition amount of nano-WC reaches 6.0 wt.% (Figure 4c), the eutectic structure of the coating continues to increase, and more off-white lumps are precipitated. The nano-particles agglomerate and significantly reduce the tendency of nano-particles to concentrate toward the grain boundary. The tendency of inhibiting grain growth is weakened, thereby making the coating structure coarse.

![Figure 4. Microstructure of clad layers with different amount of nano-WC. (a) 0.0 wt.%, (b) 3.0 wt.%, (c) 6.0 wt.%](image)

3.4. Microhardness of Clad Layers

The microhardness test of the clad layers are carried out, and the data is shown in Figure 5. Nano-WC can significantly increase the hardness of the Ni45 clad layer. With the increase of WC mass fraction, the content of hard phases (Ni3B, M23C6, WC and W2C) in the clad layers gradually increase, resulting in a gradual increase in microhardness.

![Figure 5. Microhardness of clad layers with different amount of nano-WC.](image)

3.5. Effect of Nano-WC in Reducing Crack Susceptibility
According to the characteristics of rapid solidification, high cooling rate and temperature gradient will lead to the formation of cracks [13]. In addition, the toughness of the clad layer can be reduced as the uneven distribution of the coarse brittle phase and the high density of the enhanced carbide phase [14]. Due to the refinement of nano-WC, the grains were refined and caused the increase in the number and area of grain boundaries. With the area increase of grain boundaries, the crack initiation may be hindered and the dragging effect is improved on the propagation of crack. Additionally, the development of grain boundaries decreases the concentration of impurity and the density of dislocation. The stress concentration can be relieved by the above advantages.

When too much nano-WC was added (6.0 wt.%), the clad layer showed many larger crystal grains. It could reduce the density of grain boundaries and aggravates dislocation slip. In addition, too much nano-WC produced more W2C and M23C6 and increased the brittleness of the grain boundary and the microhardness of clad layer. The above reasons cause the clad layer with 6.0 wt.% nano-WC to have a greater tendency to crack.

### 3.6. Wear Resistance of Clad Layers

Figure 6 shows the wear rate of clad layers with different content of nano-WC. It can be seen that nano-WC can effectively reduce the wear volume of the clad layer. With the WC content increases, the wear rate is gradually decreasing. The wear rate of clad layer with 6 wt.% nano-WC is the lowest value.

The wear morphology of the clad layers was characterized by SEM (Figure 7). The main form of wear is abrasive wear. The surface material of clad layer peels off to form abrasive debris, which enters the friction pair to form abrasive particles. The clad layers are cut by the abrasive particles and form furrows.

For the clad layer without nano-WC (Figure 7a), the scratches on the clad layer are relatively wide under the same wear conditions, and large-area adhesive wear occurs. After adding 3.0 wt.% nano-WC (Figure 7b), the clad layer has less WC content and lower hardness, so the furrow of the worn surface is wider, and peeling and adhesive wear appear in local areas. As the content of nano-WC increases, the ability to resist abrasive cutting is gradually enhanced, and the depth of the embedding of the microprojections decreases on the clad layer, and forming a narrower furrow. The morphology of peeling and adhesive wear is gradually reduced.

![Figure 6. Wear rate of clad layers with different amount of nano-WC.](image)

When the content increases to 6.0 wt.% (Figure 7c), the wear scar morphology has obvious abrasive wear. The furrows are narrower and the number is large. There is no obvious adhesive wear phenomenon. But there is still spalling in local areas. The increase in the addition of nano-WC will cause more carbide particles to be formed in the coating. Nano-WC particles are smaller and dispersed in the grain boundary and eutectic structure. In addition, the hardness of tungsten carbide is much...
greater than Ni45 alloy. The above reasons prove that nano WC can enhance the wear performance of the coating [15].

Figure 7. Wear morphology. (a) 0.0 wt.%., (b) 3.0 wt.%, (c) 6.0 wt.%.

4. Conclusions
(1) The clad layers are mainly composed of γ-Ni, M23C6, Ni3B, WC and W2C. With the content of nano-WC increases, the grains of clad layer gradually become finer. When 3.0 wt.% nano-WC is added, the clad layer obtains a refined and uniform microstructure morphology.
(2) The micro-hardness of the clad layers with nano-WC are higher than that of the clad layer without nano-WC. The microhardness of clad layers gradually increases with the increase of WC content.
(3) With the increase of nano-WC content, the wear rate of the clad layers gradually decreases, and the wear resistance gradually increases. When the content increases to 6.0 wt.%, The wear resistance is lowest value.

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