Tribology Property of Laser Cladding Crack Free Ni/WC Composite Coating

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In order to improve wear resistance, the Ni/WC composite coating was prepared on NAK80 mold steel surface by laser cladding technology. Phase and microstructure had been investigated by scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS) and X-ray diffraction (XRD). Dry sliding tribological properties at room temperature of the coating had been researched by ball-on-disc wear tests. Results indicated that phase constituents of the coating were mainly composed of WC, W₂C, Cr₂₃C₆, NiCr, CrB₂ and γ-Ni, etc. There was a chemical metallurgical bonding between the coating and the steel substrate. Higher wear resistance of NAK80 mold steel was achieved after cladded by the Ni/WC composite coating, which was mainly related to dendrite phases Cr₂₃C₆ and hard phases WC, W₂C dispersing in the coating. [doi:10.2320/matertrans.M2012237]

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1. Introduction

NAK80 mold steel was used for precise and complex plastic mold cavity material due to its good mechanical property, high harden-ability and good mirror polishing ability. However, the poor wear resistance would seriously shorten the life of NAK80 steel. So the wear resistance of NAK80 steel should be improved, especially used for precise mold cavity. Miao *et al.* found that the surface quality and fatigue life of NAK80 steel could be improved by the shot peening.¹⁾ However, the shot peening would cause deformation or cracking of the work pieces easily, which can't meet the surface quality requirements of precise mold. Therefore, some other advanced surface treatment technologies should be used in order to reduce the deformation of mold during surface treatment. Laser cladding was a hardfacing process that used high power density to melt the feeding material and formed a thin coating with thin heat-affected zone, minimum deformation and low dilution with the substrate,^{2,3)} which had a bright application prospects in the field of mold surface treatment.⁴⁻⁷⁾

Due to relatively high hardness and high wear resistance of WC, and good wet-ability of Ni on WC surface, studies on laser clad Ni/WC composite coatings were reported extensively,⁸⁻¹²⁾ these researches mainly focused on the tribological properties of the coatings. K. Van Acker *et al.* and Wu *et al.* analyzed the influence of WC particle (including size, distribution etc.) on the wear resistance of the laser clad Ni/WC composite coatings.^{9,10)} Chen *et al.* studied the microstructure and phase transformation of laser clad WC/Ni60B coatings during dry sliding wear. Results indicated that under higher load, the new fine precipitated phase WC or WC_{1-x} made the hardness increase of the coatings and the amount of the precipitated phase increased with the nanometer WC content increasing in the coatings.¹¹⁾ However, there were still some urgent problems to be solved about how to improve the wear resistance of Ni/WC coating prepared by laser cladding, for example, WC phase dissolution into Ni-based alloy and too much cracks in coating both would decrease the wear resistance of Ni/WC coating. So it was crucial to reduce the dissolution of WC phase, and provide dense (cracks free) coating for increasing

wear resistance of Ni/WC coating prepared by laser cladding.

In this paper, the dense and nearly crack free Ni/WC coating was prepared on NAK80 steel substrate by laser cladding technology. Moreover, the effect of Ni/WC coating on wear resistance of NAK80 steel was investigated.

2. Experimental Aspects

The chemical compositions (mass%) of NAK80 mold steel were shown in Table 1. It was machined into rectangular bulk with the dimension of 50 × 50 × 20 mm. The substrate surface was polished and degreased in acetone before coating.

The Ni/WC powders were uniformly mixed with 80% Ni based alloy powder (its chemical compositions were shown in Table 2) and 20% tungsten carbide powder, and selected as the precursor materials for fabricating the Ni/WC composite coating by laser cladding process. The particle size of Ni based alloy powder ranged from 200 to 300 mesh, and that of tungsten carbide powder ranged from 100 to 150 mesh. They were mixed with a binder to form a slurry and then pre-placed on the substrate and then dried in a furnace at 100°C for 10 h. The mixed alloy powder thickness used in laser cladding experiment was about 1.0 mm, and the NAK80 steel substrate was heated to about 350°C before laser cladding. The laser cladding experiment was carried out with an applied power of 2.0 kW, a beam diameter of 3 mm, a defocusing amount of 40 mm and lap of 30% at a low scanning speed of 6 mm/s by CO₂ laser.

Table 1 Chemical compositions of NAK80 mold steel (mass%).

C	Si	Mn	Ni	Al	Cu	Mo	Fe
0.05–0.18	0.15–1.0	1–2	2.5–3.5	0.5–1.5	0.7–1.5	0.1–0.4	Bal.

Table 2 Chemical compositions of Ni-based alloy powder (mass%).

C	Cr	B	Si	Mo	Fe	Ni
0.5	15	4	3	3.5	3.3	Bal.

After laser cladding, metallographic samples were prepared using mechanical polishing procedures, and chemically etched in $\text{HF} : \text{HNO}_3 : \text{H}_2\text{O}$ (volume ratio 1 : 6 : 7) solution for approximately 30–40 s. Microstructure characterization of the coating was carried out by Hitachi S-4800 scanning electron microscope (SEM), and energy dispersive spectroscopy (EDS). Phase analysis of the coating and raw powder was conducted by using a Philips PW type X-ray diffraction (XRD) (CuK_α radiation). Hardness of the coating surface and cross-section were measured by using a HXD-1000T Vickers microhardness tester with a test load of 5 N and a load-dwell time of 15 s.

Wear tests were conducted on a ball-on-disc metallic dry sliding wear tester (made in Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences). The samples of the coating and NAK80 mold steel for wear tests were machined to $10 \times 10 \times 5$ mm in size by electric discharging machining. The 10×10 mm surface was used as the tested surface. The surface roughness of the samples were about $R_a 0.4 \mu\text{m}$ after polishing. The disc counterpart was an AISI 52100 bearing steel ball with an average hardness of HV 600. The wear tests were carried out at room temperature with a load of 0.33 kg, sliding velocity about $0.5 \text{ m} \cdot \text{s}^{-1}$ and operating time of 30 min. The 3D topography, average width and depth of wear scars were measured by a 3D surface profilometer. To evaluate the wear resistance of the samples, the wear volume V_w and wear rate K were given as follows:¹³⁾

$$V_w = 2\pi hr(3h^2 + 4b^2)/6b \quad (1)$$

$$K = V_w/PS \quad (2)$$

where h was the wear average depth (μm), b was the wear average width (mm), r was the wear orbital radius (mm), P was the normal load (N) and S was the slide distance (m).

3. Results and Discussion

3.1 The phases and microstructure analysis

As indicated by XRD analysis results in Fig. 1, the phase constituents of the composite coating were mainly composed of WC, W_2C , Cr_{23}C_6 , NiCr, CrB_2 and $\gamma\text{-Ni}$ etc. Figure 2 showed the surface morphology of the coating, it can be seen that the quality of the coating was good and there were nearly no cracks, pores and other inclusions in the coating. Many white and block phases and dendrite phases were dispersed in the coating. EDS analysis was carried out to determine the structure of white and block phases. The result taken from

one of those white and block phases gave the composition of C14 and W86 in mass%. According to XRD analysis result, it can be concluded that the white and block phase was tungsten carbide ($\text{WC} + \text{W}_2\text{C}$). During the fabrication process of the coating, the molten pool rapidly solidified with tungsten carbide and the substrate as the core, which resulted in the formation of dendrite phases. According to the EDS and XRD results, the dendrite phase was confirmed to be Cr_{23}C_6 with an approximate composition of 42Cr–50C–2Fe–6W (at%), matrix phase of the coating was confirmed to be $\gamma\text{-Ni}$ with a composition of 58Ni–21C–11Fe–6Si–4Cr (at%).

The cross-section morphologies of the coating were shown in Fig. 3. The SEM image of the coating/substrate transition zone was shown as a smooth bright layer about $1 \mu\text{m}$ in width and dendrites vertical to the interface between the coating and the substrate (Fig. 3(b)). The smooth bright layer had a composition of approximately 60Fe–27C–11Ni–2Cr (at%), and it was identified as Ni-rich Fe-based solid solution phase. Figure 4 showed the results of EDS line analysis from the coating to the substrate at the interface location. It can be seen that the content of element Fe gradually increased from the coating to the substrate, while the content of element Ni and Cr markedly decreased at the interface. These showed that during the period of cladding Ni/WC powders on NAK80 steel, Fe element in the steel substrate diffused to the coating near the interface and there was a chemical metallurgical bonding between the coating and the steel substrate.

The microstructure at the interface between the coating and the substrate was relevant with the temperature on the substrate surface during the coating formation. During laser

Fig. 1 XRD patterns of the laser cladding Ni/WC composite coating.

Fig. 2 Surface morphologies of the laser cladding coating.

Fig. 3 Cross-section morphologies of the laser clad Ni/WC composite coating on substrate of NAK80 mold steel: (a) Low magnification SEM image; (b) High magnification SEM image.

Fig. 4 EDS line analysis from the coating to the substrate at the interface location.

cladding Ni/WC on NAK80 steel, the temperature on the substrate surface was very high (nearly reaching the melting point of the substrate). Fe element in the substrate diffused to the coating. When the molten powder solidifying, Fe–Ni

solid solution phases formed from γ -Fe and γ -Ni at the interface between the coating and the substrate, then the solid solution phases grew at the interface by the diffusion of element Ni from the molten Ni/WC alloy, and the Ni-rich

Fe-based solid solution phases formed at the interface. As solid-liquid interface moving to the coating, temperature gradient would be reduced and cooling speed would be increased. It resulted in emitting and enriching of the solutes on the front edge of solidified alloy and forming of the dendrites vertical to the interface.

3.2 The microhardness and tribology property analysis

The microhardness profile along the depth direction of the laser clad coating was shown in Fig. 5. It was apparent that there was an intergradation of hardness at the interface between the coating and substrate, which was beneficial for enhancing the adhesion of the coating to substrate. The hardness was in the range of HV 700–HV 900 in the coating zone, even exceeding HV 1200 in WC region, and in the range of HV 350–HV 400 in the substrate. The average hardness of the coating was about HV 800, it was approximately two times that (about HV 400) of NAK80 steel substrate. The hardness of the coating was higher than that of NAK80 steel substrate, because the molten pool rapidly solidified during laser cladding which resulted in fine grain strengthening. Moreover, the elements Cr, Mo can form

solid solution with γ -Ni which resulted in solid solution strengthening. At last, the hard phases WC, W_2C , $Cr_{23}C_6$ dispersed in γ -Ni substrate which resulted in dispersion reinforcement.

In order to evaluate the wear resistance of the coating on NAK80 steel substrate, the tribology properties of the coating sample and NAK80 steel sample were tested by the ball-on-disc metallic dry sliding wear tester respectively. The results showed that the bonding between the coating and the substrate remained undamaged after the test and there was no flaking of the coating from the substrate under the test condition.

Wear scar 3D topographies of the coating and NAK80 steel substrate were shown in Fig. 6. As can be seen from Fig. 6, wear scar width and depth of NAK80 steel substrate were higher than those of the coating sample. Wear volume and wear rate of the wear scars were calculated by the formula (1) and (2), the results were shown in Table 3. It showed that the wear volume and wear rate of the coating sample were far less than those of NAK80 steel sample. It can be concluded that wear rate of NAK80 steel was reduced about 99.6 percent after laser cladding treatment and its wear behavior was improved noticeably by the coating.

Figure 7 showed the worn surface morphologies of the coating and NAK80 steel after a dry sliding wear test at the applied test load of 0.33 kg. Under the sliding wear conditions, since the hardness of NAK80 steel (about HV 400) was lower than that of the AISI 52100 bearing steel ball (about HV 600), it was easy for the hard asperities on the surface of the AISI 52100 bearing steel ball to penetrate into the contact surface of NAK80 steel,¹⁴⁾ which resulted in plowing grooves and plastic deformation on the worn surface of NAK80 steel (see Fig. 7(a)). The AISI 52100 bearing steel ball with higher hardness than that of NAK80 steel had the better abilities of plastic deformation and abrasive wear resistance than those of NAK80 steel. In addition, detaching debris were also found on the worn surface of NAK80 steel (see Fig. 7(a)). EDS analysis result

Fig. 5 Microhardness profile of the laser clad Ni/WC composite coating.

Fig. 6 3D topographies of wear scars for two friction samples: (a) NAK80 substrate; (b) Ni/WC composite coating.

Table 3 Wear volume and wear rate of friction samples.

Sample	Average width of wear scar b/mm	Average depth of wear scar h/mm	Wear volume V_w/mm^3	Wear rate $K/(mm^3 \cdot N^{-1} \cdot m^{-1})$
NAK80 steel substrate	0.482	9.45×10^{-3}	8.863×10^{-3}	12.982×10^{-6}
The laser clad Ni/WC coating	0.162	1.04×10^{-3}	0.037×10^{-3}	0.054×10^{-6}

Note: $r = 2$ mm; $P = 3.234$ N; $S = 211.115$ m.

Fig. 7 SEM morphologies of worn surfaces: (a) NAK80 steel; (b) and (c) Ni/WC composite coating.

showed that the wear debris were mainly composed of Fe element, and a small amount of C, Mn, Ni, Cu and Al elements (94.15Fe–0.11C–1.32Mn–2.57Ni–0.98Cu–0.87Al, mass%), which were primarily detached from NAK80 steel. The above-mentioned evidences indicated that the main wear mechanism of NAK80 steel under the sliding wear conditions was abrasion wear and adhesion wear. The mixture of abrasion wear and adhesive wear accelerated the wear amount of NAK80 steel.^{14–17)}

As shown in Figs. 7(b) and 7(c), there only existed light scratches on the worn surface of the coating. Due to hard phase WC, W₂C and Cr₂₃C₆ being dispersed in the coating (Fig. 2), the surface hardness was improved significantly, so the ability of plastic deformation and adhesive wear resistance of the coating was enhanced noticeably compared to NAK80 steel. During the grinding with the AISI 52100 bearing steel ball, the bonding phase γ -Ni in the coating was worn away first due to hardness of γ -Ni far lower than that of hard phases WC, W₂C and Cr₂₃C₆. Once the hard phases WC, W₂C and Cr₂₃C₆ were exposed to the worn surface, the loss of the coating would decline, which resulted in a favorable abrasive wear resistance. However, the mating steel ball suffered from greater abrasive wear by the coating, due to whose surface hardness lower than that of the coating. So the main wear mechanism of the coating was abrasive wear accompanied with light micro-cutting. It can also be concluded that wear resistance of NAK80 steel was improved significantly by the laser clad Ni/WC composite coating.

The compositions in different regions on the worn surface of the coating (Figs. 7(b) and 7(c)) were shown in Table 4. From the SEM morphologies and EDS analysis results, it was known that region A was mainly composed of WC, whose wear resistance was the best. Region B and D were mainly composed of Ni-based alloy and element W, light scratches can be found on their surface, their wear resistance was only

Table 4 Composition distribution on worn surface of the Ni/WC composite coating on substrate of NAK80 steel (at%).

Composition	C	Si	Cr	Fe	Ni	W
A	62.63	—	—	—	—	37.37
B	33.82	1.54	33.98	6.86	18.29	5.51
C	45.88	3.05	3.65	11.07	35.92	0.44
D	15.85	3.06	27.59	16.18	34.06	3.27
E	17.23	—	49.05	21.92	11.80	—

Note: A, B, C, D, E marked in Fig. 7.

a little poorer than that in region A. During laser cladding, partial WC was melted and decomposed, decomposed element W could dissolve into dendrite Cr₂₃C₆ and γ -Ni which resulted in solid solution strengthening. Because element W did not dissolve into Ni-based alloy in region E, its surface wear mark was deeper than that in region A, B and D, so its wear resistance was relatively weaker. Region C was the region of γ -Ni matrix phase, its wear resistance was the weakest. It was concluded that wear resistance in the region of Ni-based alloy with element W was higher than that in the region without element W in the Ni/WC composite coating, partially melted WC dissolving into Ni-based alloy was beneficial for enhancing the bonding capacity between WC and Ni-based alloy. But excessive melting of WC would decrease the effect of WC on disperse reinforcement and grain refining strengthening of the coating, which resulted in decreasing wear resistance of the coating. So the suitable technology should be chosen correctly, and the melting degree of WC should be controlled during laser cladding Ni/WC composite coating. The technology about laser cladding Ni/WC composite coating on NAK80 mold steel substrate needed further study.

4. Conclusions

(1) Ni/WC composite coating was successfully fabricated on NAK80 mold steel by laser cladding process. There was a chemical metallurgical bonding between coating and steel substrate under the experimental condition. The coating mainly consisted of WC, W_2C , $Cr_{23}C_6$, NiCr, CrB_2 and γ -Ni etc. Dendrite phases $Cr_{23}C_6$ and hard phases WC, W_2C were dispersed in the coating, which enhanced the hardness of the coating surface significantly. The average hardness of the coating was approximately two times that of the original NAK80 mold steel. The coating improved the wear resistance of NAK80 steel surface significantly under room-temperature dry sliding wear test conditions.

(2) The main wear mechanism of the coating was abrasive wear accompanied with light micro-cutting, while the main wear mechanism of the original NAK80 mold steel was the mixture of abrasion wear and adhesive wear. Dense and nearly cracks free was beneficial to improve wear resistance of Ni/WC composite coating.

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