Effect of WC content on the friction and wear properties of Ni-WC coatings on 6082-T6 aluminum alloy

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Abstract

The Ni-WC coatings were prepared on the surface of 6082-T6 aluminum alloy by plasma spraying. The effect of WC content on the microstructure, mechanical properties and wear performance of the coatings was investigated. The wear mechanism was discussed according to the wear surface morphology and phase composition. The results show that with the increase of the WC content, the microhardness of Ni-WC coatings increases and the bond strength first increases and then decreases sharply. The Ni-20WC coating shows the highest bond strength. The friction coefficient decreases with increasing the WC content, while the wear rate first reduces and then increases as the WC content rises. The wear mechanism of Ni-WC coatings is a mixture of adhesive wear and oxidation wear. With WC content increasing from 10 wt% to 20 wt%, the friction coefficient and wear rate reduce mainly due to the formation of the continuous oxide film on the wear surface. When the WC content reaches to 30 wt%, the severe oxidation and the defects of the coating such as some microcracks and holes, lead to the increase of the wear rate.

1. Introduction

Aluminum alloys are widely used in aerospace, automobile, light railway traffic and other fields due to its advantages of light weight, high specific strength, good plasticity, easy processing and excellent atmospheric corrosion resistance [1–5]. However, the applications of aluminum alloys are restricted due to the disadvantages of the low hardness and poor wear resistance. Therefore, it is very important to improve the surface hardness and wear resistance of aluminum alloys [6–9].

The spraying techniques, which have been widely used in many products design, is a new kind of technology for hardening and protecting parts surface [10–17]. The cermet composite coating combines high hardness and strength of ceramic and excellent thermal conductivity and plasticity of metal because of the presence of the hard particles (i.e., Al2O3, WC) in the metal matrix [18–20]. Many reports proposed that the powder properties, spraying parameters and coating morphology have a significant impact on the tribology performance of the coating [21–25]. Li et al. [26] studied the wear resistance of epoxy/Al2O3 coating on TC18 titanium alloy by air spraying process. They found that the specific wear rates of the epoxy/Al2O3 coating were declined sharply and the wear resistance was improved due to the addition of Al2O3. Shipway et al. [27] prepared WC-Co coating by high velocity oxy-fuel (HVOF) thermal spraying. The results demonstrated that sintered hardmetals with WC particles in the nanoscale range offer improved properties over their conventional counterparts. Alidokht et al. [28] investigated the effect of WC morphology on dry sliding wear behavior of cold-sprayed Ni/WC composite coatings. They supposed that the size, morphology and distribution of the WC particles in the coatings affected the stability of the mechanically mixed layers, the third body flows, and wear resistance.
Up to now, the Ni-WC composites have been shown to be effective at reducing wear. Unfortunately, there are few researches on the wear resistance of Ni-WC coating on the surface of aluminum alloys. Thus, in the present study, the Ni-WC coatings with different WC content were prepared on the surface of 6082-T6 aluminum alloy by plasma spraying. The effect of WC content on the microstructure, mechanical properties and wear performance of the coatings was investigated. The results can give insights into the wear mechanism of the coatings and lay theoretical/experimental bases for practical application of aluminum alloys.

2. Experimental procedure

The Ni-10 wt.% WC, Ni-20 wt% WC, Ni-30 wt% WC powders which contain submicro-WC and micro-Ni (Shanghai yunfu Nanotechnology Co. Ltd, China) was used in this study. The average WC grain size was about 2 μm and the grain size of Ni was 40–60 μm, as shown in figure 1. The 6082-T6 aluminum alloy with the dimension of Φ30 × 7 mm was used as the substrate. Before spraying, the substrates were treated by roughening, then the Ni-WC coatings with different WC content were sprayed onto the substrate by ZB-80K air plasma spraying system. In order to improve the strength of coating, Ni-20Al coating as the priming coating was sprayed onto the substrate before the Ni-WC coating. The spraying parameters were listed in Table 1.

The phases of the powders and coatings were analyzed by D8-ADVANCE x-ray diffractometer (XRD) with monochromated CuKα radiation over a range of 2θ from 30° to 80°. The microstructure of cross-section of coatings were investigated by a JSM-5610LV scanning electron microscope (SEM). The elemental compositions of coating and the wear surface were investigated by energy dispersive spectroscopy (EDS).

Microhardness was measured using HVS-1000A Vickers indenter with 50 g load and 15 s holding time on the as-polished regions. An average microhardness value was determined based on 5 indentation measurements. The bonding strength of coatings was measured by AG-I250KN electronic universal testing machine. The tensile rate was 0.1 mm min⁻¹. Before tension, the spraying sample and the counter-part was jointed by E-7 gum, then put it into the electric heating furnace at 120 °C for 3 h to be fully cured. The 45 steel was used as the counter-part with the dimension of Φ30 × 50 mm.

Ball-on-disk test was carried out in a QG-700 tribometer to investigate the friction and wear properties of coatings. The room of experiments was controlled at a constant temperature of 25 °C. The sliding loads and
velocity were set to 7 N and 400 r min\(^{-1}\), respectively. The sliding time was 15 min. The GCr15 balls with a diameter of 6.3 mm were used as the counter body. Each test for the spraying coatings was repeated three times. The friction coefficient was automatically collected by the master computer program connected with the QG-700 tribometer and the wear volume loss, wear scar depth and width of worn specimen were measured via a Nanofocus AG 3D surface profiler.

3. Results and discussion

3.1. XRD analysis

Figure 2 presents the XRD pattern of the Ni-WC powders and the Ni-WC coatings respectively. The Ni-WC powders contain WC and Ni phases. While for the Ni-WC coatings, except Ni and WC phases, some NiO phases are formed which is due to the oxidation of Ni phases during the spraying under the high temperature. Meanwhile, from figure 2 it can be found that compared with the Ni-WC powders, the intensity of the diffraction peak of WC phase reduces for the Ni-WC coatings. It’s speculated that this is caused by the formation of amorphous phase or nanocrystalline after the spraying [29].

3.2. Cross section morphology of coatings

Figure 3 shows the SEM cross-sectional morphology of Ni-WC coatings. All the samples contain aluminum alloy substrate, Ni-Al priming coating and Ni-WC coating. For Ni-10WC coating, the thickness of the Ni-Al priming coating and the Ni-WC coating are nearly 120 \(\mu m\) and 750 \(\mu m\), respectively. The values are around 245 \(\mu m\) and 480 \(\mu m\) when WC content is 20 wt%. With further increasing WC content to 30 wt%, the thickness of the Ni-Al coating and Ni-WC coating are about 140 \(\mu m\) and 420 \(\mu m\), respectively. Meanwhile, when the WC content is 10 wt% and 20 wt%, the coating presents a dense structure and there is no obvious bubbles or holes (figures 3(a), (b)). However, many microcracks and pores can be found in Ni-30WC coating (figure 3(c)), indicating the decrease of the density of the coating. Meanwhile, from figure 3, a large number of irregular WC phases are distributed evenly in the coating. The number of WC phases increases with the increase of the WC content.

3.3. Mechanical properties of coatings

The microhardness and bond strength of Ni-WC coatings are shown in figure 4. From figure 4(a), it can be found that the microhardness of the Ni-WC coatings is much higher than that of the aluminum alloy substrate. As the WC content increases, the microhardness further increases. The value of Ni-30WC coating is about 698.2 HV, which is increased by 745% than that of the aluminum alloy substrate (82.6 HV). The high hardness of the Ni-WC coating may be due to the hardening effect caused by the submicro-sized WC particles. Yang [30] reported that the high hardness of the WC-(nano-WC-Co) coating are attributed to the hardening effect from the micro- and nano-sized WC particles distributing in Co phase. Figure 4(b) shows the bond strength of Ni-WC
coatings. With the increase of WC content, the bond strength increases. But when the WC content increases to 30 wt%, the value decreases sharply. This is mainly because when the WC content is high, there is a large difference in the thermal expansion coefficient, and the pinch effect occurs during the rapid cooling in the spraying process. As a result, the microcracks and holes form (figure 3(c)) and the bond strength of the coating reduces.

3.4. Friction and wear property of coatings

Figure 5 shows the SEM morphology of wear tracks of the Ni-WC coatings. The compositions of the positions in figure 5 are analyzed by EDX, and the results are listed in table 2. The wear of Ni-WC coating is mainly due to the combined effect of adhesive wear and oxidation wear. During dry sliding friction, the hard asperities of the
coating surface produce plastic deformation under great pressure. With the extension of the friction time, the temperature of the wear surface increases, and the contact surface causes of adhesion. The adhesion point will tear and break off under the action of shear stress. At the same time, under the high temperature, the material contact surface is easy to oxidize to form the oxide film. Under the action of cyclic friction, the oxide film is generated and destroyed constantly, resulting in oxidation wear. From figure 5(a), the Ni-10WC coating has a serious wear and lots of exfoliation pits are forming. This is mainly due to the low hardness and strength of the coating with 10 wt% WC. Meanwhile, in the dark grey area (position A) the content of oxygen is high, indicating the formation of some oxides during the wear test. With the WC content increasing to 20 wt% (figure 5(b)), the dark grey area (position B) enlarges and a continuous oxide film are formed on the wear surface. As shown in figure 5(c), when further increases the WC content to 30 wt%, the dark grey area further increases (position C), which means the coating is oxygenated severely. Meanwhile, some cracks are observed in Ni-30WC coating (figure 5(c)).

Figure 6 shows the friction coefficient curves of the Ni-WC coatings. The friction coefficient reduces with the increase of the WC content. When the content of WC is 10 wt%, the average friction coefficient is 0.78. It falls continually from 0.62 to 0.54 with increasing the WC content from 20 wt% to 30 wt%. This is related to the microhardness of the Ni-WC coating. The lower the WC content, the smaller the microhardness is, the larger the contact area of the coating and the counter body is, the greater the friction and the higher the friction coefficient is. As a result, the friction coefficient of the coating reduces with the increase of WC content. Meanwhile, the oxidation film produced by the high temperature during the friction process, leads to the
Figure 6. The friction coefficient curves of the Ni-WC coatings.

Figure 7. 3D surface topography and 2D cross-sectional surface profile of the wear tracks of the coatings: (a) and (b) Ni-10WC, (c) and (d) Ni-20WC, (e) and (f) Ni-30WC.
decrease of the friction coefficient. This is proved by SEM and EDS results of figure 5 and table 2, respectively. Besides, from figures 4(a) and 6, as the WC content increases from 20 wt% to 30 wt.%, the microhardness improves greatly, while the average friction coefficient reduces slowly. This is mainly because when the WC content is high (30 wt.%), the bond strength of the coating decreases due to the occurrence of the defects, such as the microcracks and holes (figure 3(c)), which results in a decline of the resistance to microcutting force.

Figure 7 presents the 3D topography and line profile of the wear tracks of Ni-WC coatings. It can be found that the bottom of the wear scar profile of the Ni-20WC and Ni-30 WC coatings is flat, while the Ni-10WC coating sharpens significantly. The width and depth of wear scar of Ni-10WC coating are 1.257 mm and 0.061 mm (figure 7(b)). As the WC content increases to 20 wt%, the width and depth of wear scar reduce to 0.823 mm and 0.024 mm (figure 7(d)). When further increases the WC content to 30 wt%, the values are 1.066 mm and 0.037 mm (figure 7(f)). This indicates that the Ni-10WC coating is worn seriously, while the wear of Ni-20WC and Ni-30WC coating reduces obviously and the wear of Ni-30WC coating is larger than that of Ni-20WC coating.

The wear rate is obtained by calculating the volume loss of the coatings measured from the 3D topography of the wear track, and the results are plotted in figure 8. As the WC content increases, the wear rate first decreases dramatically and then rises slightly. The wear rate of Ni-10WC coating is $4.52 \times 10^{-3} \text{mm}^3 \text{m}^{-1}$. It reduces to $2.88 \times 10^{-3} \text{mm}^3 \text{m}^{-1}$ when the WC content is 20 wt% due to the formation of a continuous oxide film (figure 5). The value slightly rises to $3.01 \times 10^{-3} \text{mm}^3 \text{m}^{-1}$ when further increases WC content to 30 wt%, which can be explained by the brittleness of the oxide film. This is also proved by Mi et al. [29]. They stated that some cracks and fatigue delamination are observed on the worn surface, suggesting that the oxide film is brittle, resulting in the failure of the coating and increasing the wear rate.

4. Conclusions

(1) The Ni-WC coating presents high hardness and with the increase of the WC content, the microhardness increases. The bond strength increases as the WC content increases. But when the WC content increases to 30 wt%, the value decreases sharply. The Ni-20WC coating shows the highest bond strength.

(2) The friction coefficient decreases as WC content increases. The wear rate first reduces and then rises, the minimum value of $2.88 \times 10^{-3} \text{mm}^3 \text{m}^{-1}$ when the WC content is 20 wt%.

(3) The Ni-20WC coating has the highest wear resistance followed by the Ni-30WC coating, and the Ni-10WC coating has the lowest wear resistance. The wear of Ni-WC coatings is mainly due to the combined effect of adhesive wear and oxidation wear. With WC content increasing from 10 wt% to 20 wt%, the average friction coefficient and wear rate reduce due to the formation of the continuous oxide film on the wear surface.
surface. When the WC content reaches to 30 wt%, the surface oxidation and defects of the coating such as some microcracks and holes, lead to the increase of the wear rate.

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