Research on Friction and Wear Performance of Plasma Sprayed WC/Ni Coating

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Abstract. In this paper, atmosphere plasma spray (APS) is used to prepare WC/Ni coating on 1Cr18Ni9Ti stainless steel to enhance the wear resistance of materials of the axial-flow fan. The phase composition and microstructure of the spraying coating were analyzed, and the tribological properties of the coating were investigated through the ball-disk point contact sliding dry friction test. The results show that the spray powder is melting and spreading well by using nickel coated tungsten carbide powder as the spray powder combined with APS technology. The as-sprayed WC/Ni coating has a dense structure, slight oxidation. The hard phase tungsten carbide is evenly distributed and the interface of the bonding phase nickel is well combined with tungsten carbide. The microhardness of the coating cross-section can reach 655±90HV0.3. In the point contact wear test with high contact stress, tungsten carbide particles are pinned to the friction surface, which greatly improves the resistance to abrasive wear. The coating wear rate is only 2.42×10⁻⁶mm³·N⁻¹·m⁻¹, and the anti-wear of the coating is about 136 times that of Inconel718 alloy under the same friction condition. The dry friction and wear mechanism of the WC/Ni coating are manifested as surface fatigue scale peeling. The large pieces of tungsten carbide particles are prevented from being pulled out and peeled because of the crushing of tungsten carbide particles and the bonding effect of nickel. And the anti-wear of the coating has not deteriorated due to fatigue during the high friction cycle.

1. Introduction
In China’s current power structure, commercial coal-based thermal power generation accounts for nearly 60% of the annual total power generation[1]. The safe and stable operation of coal-fired power generation equipment plays an important role in guaranteeing industrial production[2]. The axial fans are widely used as the auxiliary equipment of the boilers to adapt the large-capacity demand of coal-fired power generation boilers. The fan blades and impellers, during its operation, will bear the erosion and wear of dust, hard particles, etc., resulting in a serious decline in efficiency, and induce cracks or even breakage of the blades, endangering the safety and long-term stable operation of the boilers. In order to eliminate the wear of the fan, the dust removal equipment is installed at the entrance of the fan. However, that can’t completely solve the friction and wear problems of the fan. To fundamentally solve this problem, it is necessary to improve the wear resistance of the fan material.

Using surface engineering technology to prepare highly wear-resistant coatings on the surface of metal substrates is an effective means to solve the wear behavior of coal-fired power generation devices[3]. Electroplating the hard chromium has been used for decades to improve the wear resistance of metal substrates. Nevertheless, the process of electroplating produces strong carcinogenic chromic acid mist and a large amount of highly polluting waste liquid. With the increasing requirements for
environmental protection and sustainable development, the development of a new wear-resistance technology to replace hard chromium electroplating has become a research hotspot in engineering applications. TiN, Cr$_2$O$_3$, TiAlN and other films prepared by physical vapor deposition process (magnetron sputtering, multi-arc ion plating, etc.) exhibit excellent wear resistance. However, the engineering application of large-area preparation is limited, because the deposition process relies on a vacuum chamber and the thickness of the films deposited by such methods are very thinner, which makes the surface accuracy of the substrate will be higher requirements. The thermal spraying process has the characteristics of good substrate applicability, wide range of coating materials, and efficient automated production by using the industrial robots. Among them, thermal spraying WC-Co, NiCr-Cr$_7$C$_3$ and other cermet coatings have the advantages of high hardness and wear resistance of ceramics and excellent plasticity of metal. They have been widely used in harsh working conditions such as aero engines and ground gas turbines. At present, HVOF is often used to prepare these cermet coatings.

This process puts forward higher requirements on the sprayed powder, such as small range of particle size, high sphericity, and excellent fluidity, which undoubtedly increases the production cost of the coating in other fields. Compared with HVOF, Atmosphere plasma spray (APS) has the advantages of lower requirements for the sprayed powder, and the metal component molten and spread well due to the higher flame temperature, thereby, which provide better adhesion performance to the hard wear-resistant phase.

In summary, the paper uses atmosphere plasma spraying and nickel-coated tungsten carbide powder as the raw material to prepare the coatings. The tribological properties of the coating are investigated by high contact stress ball-disk point contact friction and wear tests, in order to obtain a new type of wear-resistant protective coating suitable for components of coal-fired power generation devices.

2. Experimental method

2.1 Preparation and characterization of the coating

The spray powder is WC12Ni powder (KF-56, BGRIMM Advanced Materials Science and Technology Co., Ltd.), with a particle size range of -325~+140 mesh. The substrate is 1Cr18Ni9Ti stainless steel. Before spraying, the surface of the substrate is roughened by sandblasting with 60 mesh quartz sand and 0.5MPa pressure to improve the coating combination. The surface roughness of the sandblasting substrate is Ra>5μm. The coating is prepared by the Metco 9MC atmosphere plasma spraying system, and Ar and H$_2$ are used as the main and secondary gas for spraying. The substrate is preheated to 200°C by arc starting and no powder feeding. The spraying parameters are: input power 30KW, main air flow rate 55L/min, secondary air flow rate 3L/min, spraying distance 100 mm, powder feeder speed 2.2RPM. X-ray diffraction (XRD, Rigaku Smart Lab 9kW) is used to analyze the phase of the spray coatings. The scanning range is 20-80°, and the scanning speed was 10°/min. The scanning electron microscope(SEM, FEI Verios 460) was used to analyze the surface of the as-sprayed coating and the section of sprayed coating. The HV-1000A (Xi’an Huayin Instrument and Equipment) type microhardness tester was used to test the coating section, the test load was 300g, the retention time was 15s, 10 sets of indentation were measured and the average value of the micro Vickers hardness was obtained.

2.2 Friction and wear test

The MSR-2T (Lanzhou, Zhongke Kaihua) reciprocating friction and wear tester is used for friction test, the coating is used as the lower sample, and the upper sample is sintered Al$_2$O$_3$ ball of Φ3mm. As a control group, Inconel 718 alloy was used for friction and wear tests under the same conditions, and the test conditions are: load 5N, reciprocating amplitude 5 mm, frequency 4Hz, test time 60/120 min. The friction and wear test is carried out in three sets of parallel tests. The microscope (OLYMPUS DSX510) is used to observe the wear scar of the alumina friction pair and measure the cross-sectional area of the coating wear scar, thereby calculating the coating wear volume V and the coating wear rate (R), the calculation formula is:

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R = \frac{V}{SF}
\]
Where \( S \) is the total friction stroke (m) and \( F \) is the test load (N). SEM is used to characterize the coating wear scar morphology, and analyzes the wear mechanism of the WC/Ni coatings sprayed by atmosphere plasma.

3. Results and discussion

Fig. 1a shows the X-ray diffraction pattern of the WC/Ni coating prepared by atmosphere plasma spraying. The XRD pattern shows that the coating phase composition is Ni, \( W_2C \), \( WC_{1-x} \), WC, and no diffraction peaks of oxides are observed. Although the temperature of the plasma spraying flame is extremely high, the inert Ar is used to isolate the oxygen in the air, so the powder oxidation is relatively slight during the spraying process. Due to the limited high temperature stability of WC, it is easy to produce a certain degree of decarburization to form \( WC_{1-x} \) and \( W_2C \) during the spraying process. However, the large particle size range spray powder has a relatively small specific surface area. In addition, the nickel coated on the WC surface alleviates the decarburization of WC to a certain extent. The micro Vickers hardness of the WC/Ni coating cross-section is 655±90HV0.3, and its higher hardness also indicates that the decarburization of WC is slight.

Fig. 1b is the optical micrograph of the polished surface of the WC/Ni coating. After the as-sprayed coating is polished by water sandpaper and polished by diamond abrasive paste, the surface is smooth and flat, showing good plasticity and workability. The microhardness test shows that the gray area in Fig. 1b is the Ni binder phase, and the dark area is the WC hard phase; it can be seen that the two-phase particle interface in the coating is well bonded, and no obvious pores and cracks are observed.

The scanning electron microscope(SEM) images of the surface of as-sprayed and cross-sectional structure of WC/Ni coating are shown in Fig. 2. Fig. 2a shows that the as-sprayed coating is relatively dense. The spray powder particles are melted and accelerated by the plasma flame flow, overlap and lock each other to form a good combination, indicating the good wettability between metallic nickel and carbide. In Fig. 2b, it can be observed that the molten powder particles show a higher degree of spreading, and at the same time, they also show the breaking phenomenon of the molten droplets hitting the substrate at a high speed. Due to the inherent poor temperature resistance of WC, its powder is prepared by solid-phase reaction, and the powder particles are aggregates of WC fine particles. Therefore, during the plasma spraying process, part of the WC particles spreads and deposits into larger size particles; while part of the powder particles dissociate into fine particles when impacted, so they are distributed in a dispersed state. Fig. 2c is the SEM image of the cross-section of the coating, from which it can be observed that the WC/Ni coating is well bonded to the stainless steel substrate. The coating presents a layered structure with good interlayer bonding, but there are also certain pores inside the coating, and it can be found out from Fig. 2d that the pores mainly exist inside the carbide particles. With reference to Fig. 2b, the spreading particles have certain shrinkage holes, and there are also certain gaps between the particles. Due to the rapid condensation during the spreading of the particles, such shrinkage holes and gaps cannot be completely filled during subsequent particle spreading, and then forming pores.
Fig. 2. SEM images of WC/Ni coatings at (a), (b) as-sprayed surface and (c), (d) polished cross-section

Fig. 3 is the SEM images of the WC/Ni coating and the Inconel718 alloy under the same dry friction conditions. According to Herzt contact stress theory, the contact stress between Inconel718 alloy (E≈190GPa, μ=0.3) and Φ3mm alumina ball (E≈300 GPa, μ=0.22) under 5N normal load can exceed 1GPa, therefore, there are obvious furrows in the wear scar of Inconel718 alloy (see Fig. 3c and Fig. 3d), i.e., severe abrasive wear occurs. The hardness of the WC/Ni coating is much higher than that of the Inconel718 alloy, and theoretically its elastic modulus is also higher than the latter, that is, the contact stress is higher under the test conditions; however, as shown in Fig. 3a, the width of the wear scar of the WC/Ni coating is not only significantly narrower, and there are no furrows inside the coating, which indicates that the coating has excellent resistance to abrasive wear. From the high magnification SEM image of the coating wear scar in Fig. 3b, it can be observed that there are WC particles (high image contrast due to low conductivity) in the wear scar protruding on the friction surface. In addition, the hard and brittle WC particles have a certain degree of dissociation. Under the action of high contact stress and friction plowing, metallic nickel yields first and produces plastic deformation, while WC particles form micro-bumps due to higher deformation resistance. At the same time, the extremely high hardness of WC particles makes the coating exhibit excellent wear resistance. Because of the cyclic reciprocating friction force, the WC micro-protrusions on the friction surface of the coating will bear the tangential alternating stress, so the coating wear mechanism appears as the local fatigue scale peeling of the WC particles.

Fig. 3. SEM images of the wear scars of (a), (b) WC/Ni coating; (c), (d) 718 alloy

In order to further investigate the wear resistance of the WC/Ni coating under the condition of higher reciprocating friction cycles, the wear scar of the WC/Ni coating under the same friction contact conditions...
condition for 2 hours was characterized, and the wear scar profile is shown in Fig. 4. In Fig. 4a, it can be observed that the depth of the Inconel718 alloy wear scar (1h) reaches 60μm, while the depth of the coating wear scar after 1h and 2h rubbing were only 1.5μm and 2.1μm, respectively; and for the WC/Ni coating, there is almost no change in the width of the wear scar with the doubling of the friction time, which also shows that the coating has an excellent bearing effect on the special friction surface under dry friction.

![Fig. 4. Profiles of the wear scars of (a) 718 alloy and (b) WC/Ni coating](image)

Fig. 4. Profiles of the wear scars of (a) 718 alloy and (b) WC/Ni coating

Fig. 5 shows the comparison of friction coefficient and wear rate between WC/Ni coating and 718 alloy. Fig. 5a shows that the friction coefficient of Inconel718 alloy has been increasing continuously during the test time, and has a large fluctuation. In contrast, the friction coefficient of the WC/Ni coating is smaller, and the curve changes more smoothly with time, reflecting the better stability of the friction surface of the coating. The volume wear rate of Inconel718 alloy is relatively large, reaching 330.59×10⁻⁶ mm³·N⁻¹·m⁻¹, while the WC/Ni coating under the same conditions is only 2.42×10⁻⁶ mm³·N⁻¹·m⁻¹, therefore, the wear resistance of the coating is 136 times that of Inconel718 alloy. In addition, the volume wear rate of the WC/Ni coating is basically unchanged under the test time of 1h and 2h. It can be inferred that the dissociated scales of the WC particles on the coating surface are mainly surface fatigue behavior, which can be attributed to the inherent layered structure of the plasma spray coatings and the adhesion of metallic nickel to hinder the extension of surface fatigue cracks to the interior of the coating.

![Fig. 5. (a) Friction coefficient and (b) Volume wear rate](image)

Fig. 5. (a) Friction coefficient and (b) Volume wear rate

The Al₂O₃ friction counterpart paired with the WC/Ni coating has obvious volume loss, i.e., a part of the spherical crown is completely removed, and due to the existence of high-hardness WC particles on the friction surface of the coating, there is a certain furrow in the wear scar of the Al₂O₃ friction counterpart.

![Fig. 6. Wear scar morphology of Al₂O₃ friction counterpart paired with WC/Ni coating and Inconel718 alloy](image)
4. Conclusion

Using atmosphere plasma spray and Ni-coated WC powder as a raw material, WC/Ni coatings with a dense structure can be prepared. The study of its microstructure and tribological behavior has drawn the following main conclusions:

The powder particles melt and spread well to form a layered structure of the WC/Ni coating. The WC phase in the coating presents a distribution morphology in which large-sized particles and dispersed particles coexist, and the microhardness of the coating reaches $655 \pm 90 \text{HV0.3}$;

The sliding dry friction wear rate of atmosphere plasma sprayed WC/Ni coating, paired with sintered Al$_2$O$_3$ friction counterpart, is $2.42 \times 10^{-6} \text{mm}^3\text{N}^{-1}\text{m}^{-1}$, and its wear resistance is about 136 times that of Inconel718 alloy under the same conditions; in addition, the friction coefficient of the WC/Ni coating after the running-in period is 0.4, which is significantly lower than that of Inconel718 alloy, and the friction coefficient of the coating has a more stable curve with time;

After high contact stress and friction, the WC particles on the friction surface of the WC/Ni coating form bearing slightly convex peaks, and benefit to the adhesion of metallic nickel, the coating has excellent wear resistance. The main wear mechanism of the WC/Ni coating by APS is the dissociation of hard WC particles and fatigue scale peeling.

Acknowledgments

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