Erosion and Wear Resistance of Cr$_3$C$_2$-NiCr Composite Ceramic Coating for Gun Barrel

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Abstract. A Cr$_3$C$_2$-NiCr coating was prepared on the PCrNi3MoVA steel via HVOF for the further use in gun barrel to reduce the wear and erosion of the PCrNi3MoVA steel. The microstructure and interfacial bonding state of the coating were analyzed by scanning electron microscopy (SEM). The erosion resistance of the coating was tested by high-speed hot airflow generated by a modified pressure-vented vessel. The high temperature friction coefficient and high temperature wear resistance of Cr$_3$C$_2$-NiCr coating and PCrNi3MoVA steel substrate were compared by high temperature friction and wear test. Results show that the Cr$_3$C$_2$-NiCr coating combines well with PCrNi3MoVA steel without cracking and shedding. The coating does not fall off under high-speed airflow erosion yet with an oxidation of the surface. The high temperature wear resistance of Cr$_3$C$_2$-NiCr coating is significantly better than that of PCrNi3MoVA steel substrate.

1. Introduction

As an important combat force in modern warfare, artillery is widely used by the armed forces in the world. With the gradual development of high-pressure guns, the erosion of the gun barrel by the high-temperature and high-pressure gunpowder gas and the wear of the projectile on the inner wall of the barrel have become increasingly prominent, which lead to a significant reduction in body length [1]. With the rapid development of new materials technology, the use of high-performance protective materials and appropriate technical means to protect the gun tube is of great significance for extending the service life of the barrel.

Materials for gun tube protection generally require high wear, erosion and impact resistance and good chemical stability. Over the years, scholars have conducted extensive research and exploration on various new types of gun barrel protection materials. It mainly includes refractory metals and their alloys such as Ta, Mo, Cr, W, Re, etc. [2-6], as well as ceramics and cermet such as diamond or CBN, Si$_3$N$_4$, SiC, Al$_2$O$_3$, ZrO$_2$, SiAlON and WC-Co [7-12]. Ceramic materials generally have excellent high temperature stability and wear resistance, but the impact resistance is poor, while metal materials generally have good ductility, but high temperature performance and wear resistance are much less than ceramics. In theory, if the performance advantages of these two materials complement each other, it will better meet the performance requirements of the gun tube material.

Cr$_3$C$_2$-NiCr is a kind of cermet that combines the ductility of NiCr alloy with the wear resistance of Cr$_3$C$_2$ ceramics, which is an ideal metal surface protection material. In this paper, the Cr$_3$C$_2$-NiCr
coating was sprayed on the surface of PCrNi3MoVA steel by high velocity oxygen fuel (HVOF) technology. The high temperature erosion was tested by a modified pressure-vented vessel and the high temperature wear resistance of the coating were studied by high temperature friction and wear test.

2. Materials and methods

2.1. Materials
The composition of the 75Cr3C2-25NiCr powder selected for the test is shown in Table 1. The substrate material was PCrNi3MoVA steel. Substrate samples having dimensions of 150 mm x 100 mm x 6 mm and φ 40 mm x 40 mm were prepared separately. The substrate surface was polished separately to remove oil and impurities. The Cr3C2-NiCr coating was prepared on the PCrNi3MoVA steel substrate by Praxair's JP5000 HVOF equipment. The preparation process is shown in Table 2.

Table 1. The basic parameters of the powder.

| Powder          | Element composition (wt%) | Particle size (μm) |
|-----------------|----------------------------|--------------------|
| 75Cr3C2-25NiCr  | Cr 70 Ni 21 C 9 / / / Co | 15~45              |

Table 2. The spraying process parameters of Cr3C2-NiCr.

| Spray Gun | Spraying thickness (mm) | Fuel flow (L/min) | Oxygen flow (L/min) | Powder gas flow (L/min) | Spraying distance (mm) | Gun speed (mm/min) | Feeding rate (g/min) |
|-----------|-------------------------|-------------------|---------------------|-------------------------|------------------------|-------------------|---------------------|
| JP-5000   | 0.3                     | 430               | 835                 | 2.5                     | 360                    | 500               | 50                  |

2.2. Microstructure observation and coating representation
The prepared Cr3C2-NiCr coating was cleaned and polished. The surface and the cross-section of the coating were observed by scanning electron microscopy (SEM), and the interface state of the coating was analyzed.

2.3. High-temperature friction-wear test
Cr3C2-NiCr coating and PCrNi3MoVA steel were subjected to high temperature friction-wear tests using a ball-type high-temperature friction and wear tester to evaluate their high-temperature wear resistance. The test machine has a 6mm-diameter steel ball with a frictional linear velocity of 25 cm/s, testing load of 10 N, 4.3 mm from the center of rotation of the sample. The test environment temperature was 500 °C and the friction distance was 450 m. The surface morphology of the two samples was measured by Lext laser confocal scanning microscopy, and the wear of the samples was measured by surface topography.

2.4. High-temperature erosion test
The sample was subjected to the erosion test using an improved pressure-vented vessel designed by the research team. The device can simulate the high temperature and high pressure internal environment when the gun fires. In this experiment, nitrocellulose propellant was used with a single charge of 2.5 g. The volume of the combustion chamber is 6mL, the explosive temperature is 2500-2800 K, and the heat flow excitation time is 5~10ms in a single detonation. The peak pressure is close to 400 MPa, which is basically consistent with the internal ballistic characteristics of the high pressure gun. Under this condition, the prepared Cr3C2-NiCr coating samples were subjected to a 30-round consecutive erosion test with single firing interval of 5 min. The samples were taken out after the test,
3. Results and Discussion

3.1. Microstructure of the Cr$_3$C$_2$-NiCr coating
The SEM photographs of the interface and coating structure of Cr$_3$C$_2$-NiCr coating prepared by HVOF are shown in Figure 1 and Figure 2. It can be seen from Figure 1 that the Cr$_3$C$_2$-NiCr coating has a distinct layered structure, and the coating has no obvious cracks and defects. The coating is tightly bonded to the substrate, the interface is clear, and there is no obvious transition zone. Some of the bonding surfaces have certain defects due to the surface roughness of the substrate, and the bonding mode is mechanical bonding. The EDS analysis is carried out in Figure 2 which shows the light color region is NiCr phase while the dark region is Cr$_3$C$_2$ hard phase. It can also be seen from Figure 2 that Cr$_3$C$_2$ hard phase is flat layered, and the carbide hard phase is distributed in a polygonal shape in a molten or semi-molten state. The hard phase and the alloy are staggered to form a typical "hard phase + soft matrix" wear-resistant structure [13].

![Figure 1. SEM of Cr$_3$C$_2$-NiCr coating interface.](image1)

![Figure 2. SEM of Cr$_3$C$_2$-NiCr coating structure.](image2)

3.2. Friction coefficient and wear mechanism of Cr$_3$C$_2$-NiCr coating
The high temperature friction coefficient of the Cr$_3$C$_2$-NiCr coating and PCrNi3MoVA steel is shown in Figure 3 and Figure 4. It can be seen from Figure 3 that the high temperature friction coefficient of
PCrNi3MoVA steel does not depend on the friction distance and is basically stable at 0.524, with the standard deviation of 0.021. It can be seen from Figure 4 that the high temperature friction coefficient of the Cr3C2-NiCr coating is positively correlated with the friction distance. When the friction distance reaches 360m, the friction coefficient reaches the maximum value. At this time, the friction coefficient is close to that of PCrNi3MoVA steel, and then the high temperature friction coefficient begins to gradually decline and tend to stabilize. The initial value of the high temperature friction coefficient is 0.242, the average value is 0.435, and the standard deviation of the friction coefficient is 0.051. It shows that the high temperature friction coefficient of Cr3C2-NiCr coating is lower than that of PCrNi3MoVA steel under the same high temperature and load conditions.

The surface morphology of the wear zone of Cr3C2-NiCr coating and the wear zone of PCrNi3MoVA steel by laser confocal scanning microscopy are respectively shown in Figure 5 and Figure 6. The surface topography of the wear zone is shown in the left side of the figure, and the sectional view of the measurement position is shown in the right side. It can be seen from the figure that the cross-sectional area of the wear zone of PCrNi3MoVA steel is relatively uniform, which is because the structural composition of PCrNi3MoVA steel is uniform and the wear mechanism is mainly fatigue wear. After measurement, the wear scar cross-section area of PCrNi3MoVA steel is $S = 15134.138\mu m^2$, and the total wear amount is $V = 2\pi rS \approx 0.4mm^3$. 

![Figure 3. Friction coefficient in high temperature of Cr3C2-NiCr coating.](image)

![Figure 4. Friction coefficient in high temperature of PCrNi3MoVA steel.](image)
The cross-sectional area of the wear scar of Cr$_3$C$_2$-NiCr coating is not uniform, because Cr$_3$C$_2$-NiCr is a composite structure composed of NiCr alloy and Cr$_3$C$_2$ ceramic. The wear resistance of Cr$_3$C$_2$ ceramic is better than that of NiCr alloy. Due to the shear stress and the wear of NiCr alloy, the Cr$_3$C$_2$ particles on the surface are peeled off during the friction process. The peeling-off Cr$_3$C$_2$ particles continue to slide on the surface under the action of load which causes deeper and larger scratches in the low hardness alloy. It is indicated in the SEM morphology of Cr$_3$C$_2$-NiCr coating structure that the distribution of Cr$_3$C$_2$-NiCr coatings and the particle size are not uniform. Therefore, the cross-sectional areas of Cr$_3$C$_2$-NiCr coating have large variety, and the average wear area needs to be calculated. It is determined that the minimum wear scar cross-sectional area is $S_1 = 3055.572 \mu m^2$, the maximum is $S_2 = 4387.091 \mu m^2$, and the average value of the wear scar cross-sectional area is $S = 37210.332 \mu m^2$. The wear scar radius is $r = 4.3 mm$, and the wear amount is $V = 2\pi rS = 0.1 mm^3$.

It can be seen from the numerical value of the wear amount that the wear of PCrNi3MoVA steel is about 4 times as much as that of Cr$_3$C$_2$-NiCr coating at 500 °C. Therefore, the use of Cr$_3$C$_2$-NiCr coating significantly improves the high temperature wear resistance of PCrNi3MoVA substrate.

![Figure 5. Wear area of Cr$_3$C$_2$-NiCr coating.](image)

![Figure 6. Wear area of PCrNi3MoVA steel.](image)

![Figure 7. SEM of the eroded coating surface.](image)
3.3. The erosion resistance of the Cr$_3$C$_2$-NiCr coating

The erosion test results of the Cr$_3$C$_2$-NiCr coating are shown in Figure 7. It can be seen from Figure 7 that a small amount of microcracks and a large amount of white substance appear on the surface of the eroded Cr$_3$C$_2$-NiCr coating. EDS results indicate that the white material has a higher oxygen content. Studies have shown that the Cr element on the surface of Cr$_3$C$_2$-NiCr coating will combine with oxygen to form Cr$_2$O$_3$ [14]. Theoretically, the generated Cr$_2$O$_3$ will cover the surface of the coating and block the oxidation reaction. However, in gun tube, high temperature oxidation will occur along with the friction process of the projectile on the inner wall, so the generated oxide layer will be destroyed along with the movement of the projectile, so that the high temperature propellant gas will continuously react with the coating, so the oxidation reaction is likely to occur continuously along with the actual launch process, eroding the surface of the coating.

![Figure 8. SEM of the crack on the surface.](image)

It is shown in Figure 8 that the cracks are passing through both the white oxides and the black matrix, which indicates that the crack did not occur in a single phase or at the interface of two phases, but the entire surface of the coating. It can be inferred that there is no stress concentration caused by differences in phase performance during the erosion process. Two phases act as a whole when cracking occurs during thermal shock.

4. Conclusions

In this paper, the Cr$_3$C$_2$-NiCr coating was prepared on the PCrNi3MoVA steel substrate by HVOF technology. The thermal erosion resistance and high temperature wear resistance of the coating were tested. The following conclusions were obtained:

1. The combination of Cr$_3$C$_2$-NiCr coating and PCrNi3MoVA steel substrate is mechanically combined. The Cr$_3$C$_2$-NiCr coating has obvious layered structure, with no obvious cracks and defects.

2. Under high temperature, the friction coefficient of Cr$_3$C$_2$-NiCr coating is lower than that of PCrNi3MoVA steel. Under the same conditions, the wear amount is only one quarter of that of PCrNi3MoVA steel, and its wear resistance is better than that of PCrNi3MoVA steel.

3. Local oxidation occurs on the surface of Cr$_3$C$_2$-NiCr coating under high-speed propellant flow erosion, and micro cracks are generated, which is unfavorable for gun tube protection.

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