The effect of impingement angle on erosion wear characteristics of HVOF sprayed WC-Ni and WC-Cr$_3$C$_2$-Ni cermet composite coatings

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Abstract

The present study investigated the erosion wear behavior of WC-Ni and WC-Cr$_3$C$_2$-Ni cermet coatings deposited by high velocity oxy-fuel (HVOF) spray process on the substrate of 1Cr18Ni9Ti stainless steel. Microstructures and morphologies of the coatings were examined using SEM images, and x-ray diffractometer was used to analyze the phase composition of the powder and the coatings. The erosion test was carried out using home-made jet rig. In order to better fit the research background of this study, the erodent used for erosion was taken from the Yellow River, China. The coating is well combined with the substrate; and WC-Cr$_3$C$_2$-Ni coating consists of WC, Cr$_3$C$_2$ and Ni phases, WC-Ni coating consists of WC, W$_2$C and Ni phases. Some mechanical properties of the two coatings were compared, WC-Cr$_3$C$_2$-Ni coatings have higher hardness to be compared with WC-Ni ones due to a lower binder content; and the elasticity modulus and nano-hardness values of the WC-Cr$_3$C$_2$-Ni coating are higher than that of the WC-Ni coating. The relationship between the wear performance of the coatings and impingement angle was obtained; and the erosion resistance of the coatings was analyzed. It was observed that WC-Cr$_3$C$_2$-Ni cermet coating exhibits higher erosion resistance under all testing conditions as compared with the WC-Ni cermet coating and 1Cr18Ni9Ti stainless steel. The results show that the erosion mechanism at low angle is mainly cutting, while erosion pits dominate at high angle for the coatings, moreover, plastic deformation could be observed in the case of the binder depletion and cracking found place. and the erosion mechanisms of the 1Cr18Ni9Ti stainless steel are mainly cutting and plastic deformation at low angle and high angle, respectively.

1. Introduction

Erosion wear is one of the most common and unavoidable problems of mechanical components in marine propeller blades, dredger pumps, turbine blades and other hydraulic machinery [1–3]. The Yellow River is one of the two major rivers in China, which the sediment content is very high. Hydraulic machinery working in the Yellow River is inevitably eroded by sediment. Traditionally, these components are fabricated of stainless steel [1, 2], when sand grains impact the surface of the flow components, the strong deformation work drives the material to deform or crack off, and consequently caused the wear of the material [4], naturally then, the efficiency and service life of hydraulic machinery are reduced [2, 5, 6], which causing significant economic losses. Therefore, it is necessary to coat the components with coatings which exhibit excellent wear resistance. To date, a lot of research, which fabricated cermet coating with thermal spraying process have been done by many investigators. High velocity oxy-fuel (HVOF) spraying is the one of the best thermal spraying technologies, the main advantages of HVOF thermal spraying compared with other thermal spraying technologies such as flame spraying, atmospheric plasma spraying and arc spraying [7] are its high velocity of spraying particles and lower thermal temperature during the spraying process, the spraying particles in high velocity can form the coating with high density and high bonding strength; lower temperature contributes to decreasing the degree of oxidative decarbonization during the HVOF spraying [8–14].
Tungsten carbide (WC) based composite coating has high hardness and good wettability with metal phase. At present, WC based composite coatings have been widely investigated [15–19]. According to the bonding phase, WC based composited coatings are mainly divided into WC-Co [15, 20–23], WC-Ni [24–26] and WC-CoCr [1, 27–31]. Lalit et al [32] evaluated the effects of the different WC grain sizes on slurry erosion behavior of WC-CoCr cermet coatings, the test result was observed that WC-CoCr cermet coatings deposited with fine WC grain shows the greater erosion resistance as compared with conventional cermet coatings, and the damage caused by erosion started with chipping, cracking and pullout of WC grain from CoCr binder phase. Yung et al [33] investigated the effects of titanium carbide/zirconium carbide on the erosion resistance of WC-Ni hard metal. TiC can produce platelet grain structure meant for strengthening leading to enhanced abrasion resistance, and ZrC can inhibit the coarsening and abnormal growth of WC grains with the increasing of hardness; the result shows that the addition of TiC can improve the erosion resistance of the specimen, but ZrC does not provide any benefit of wear resistance in this study. Similarly, Cr$_3$C$_2$ can improve the wear resistance of the coating because of its ability to inhibit grain growth [34], however, there are few studies on the effects of Cr$_3$C$_2$ on the erosion resistance of WC-Ni coating.

Naturally then, the objective of this research is to study the influence of Cr$_3$C$_2$ to the overall performance of the coating, and study the phase composition and microstructure of the coatings. Moreover, the relationship between the wear performance of the coatings and impingement angle was investigated.

### 2. Experimental procedure

#### 2.1. Preparation of the coatings

In this study, two different thermal spray agglomerated powders were used for depositing coatings on 1Cr18Ni9Ti by HVOF spraying process, the spraying process was performed at the rig (Praxair, JP-8000, America). The spraying powders selected were WC-Ni and WC-Cr$_3$C$_2$-Ni cermet composition material, which prepared by spray drying and sintering after mixing WC, Ni and Cr$_3$C$_2$. The component ratio of cermet composite powders has been given in table 1.

These two powders had an agglomerated particles size of $-15/+45 \, \mu m$ for the ease of flow during the thermal spraying, and the morphologies of cermet composite powders obtained by SEM were shown in figure 1. It shows that the shape of the powders is regular and nearly spherical.

Prior to coating deposition, the substrate samples were pre-cleaned in alcohol, dried in hot air, and then grit blasted with 30 mesh Al$_2$O$_3$ to provide a fresh and rough surface for better adhesion. This study based on the pre-experiments, combined with the characteristics of the two kinds of powders, used the optimized spraying...
process parameters to prepare the coating, the detailed parameters of HVOF were given in Table 2. The coatings were deposited by ten passes.

### 2.2. Characterization of the coatings

In this test, the phase structure of the original powder and the coating were measured using the D8-Advanced x-ray diffractometer (BRUKER, Germany), and the step-scan method is used to test XRD, the parameters for XRD analysis were shown in Table 3. Microstructure and microelement content of the coatings were observed by an optical microscopy (OM, Olympus BX51M, Japan) and a scanning electron microscope (SEM, Zeiss GEMINI SIGMA 300, Germany). The porosities of coatings were measured by metallographic microscope combined with DT-2000 analysis software. The mechanical properties of the specimens were characterized by nano-indentation and Vickers hardness tester. The parameters for nanoindentation were given in Table 4. Vickers hardness of the coatings and substrates were measured by penetrometer (HXD-1000TC) combined with MH-VK hardness test and analysis system. The test load is 300 g (2.94 N), the loading time is 15 s. In order to decrease the error, the hardness value was measured at intervals of 100 μm, a total of 10 points were measured and averaged.

### 2.3. Slurry erosion tests

The erosion test was carried out using home-made jet rig shown in Figure 2. The specimen was placed on the loader stage, and then the sample was subjected to erosion by the mortar (water sand mixture) from the spray gun. The dimension of the specimens are 35 mm × 25 mm × 10 mm, grit was used as erodent with the size is 150–300 μm, which taken from the Yellow River, China. The slurry erosion tests were done at three impact angles (30°, 60°, 90°) with the velocity of 10 m s⁻¹, the sediment concentration was 20 kg m⁻³. Prior the erosion test, all samples were ground with SiC abrasive paper (mesh 1500) and then polished with a polishing machine to obtain a smooth surface. Erosion time is 30 min, and prior to the erosion, the specimens were pretreated by erosion, the mass loss was measured by an electronic weighing balance with an accuracy of 0.0001 g. The volume wear amounts of the specimen unit area (cm²) and unit time (h) were calculated, and then the volume wear rate was obtained.

### Table 2. Processing parameters in HVOF spraying.

| Spray parameters          | WC-Ni | WC-CrC2-Ni |
|---------------------------|-------|------------|
| Oxygen flow rate (m³ s⁻¹) | 0.93  | 0.91       |
| Kerosene flow rate (m³ h⁻¹) | 0.023 | 0.023     |
| Carrier gas (N₂) flow rate (m³ min⁻¹) | 0.65 | 0.65       |
| Spray distance (cm)      | 38    | 38         |
| Powder feed rate (g s⁻¹) | 1     | 1          |
| Spray gun speed (mm s⁻¹) | 280   | 280        |

### Table 3. The parameters for XRD analysis.

| Cathode type | Tube voltage/kV | Tube current/MA | Step/° | Scanned area/° | Scanning Speed/°·min⁻¹ |
|--------------|----------------|-----------------|--------|----------------|------------------------|
| Cu           | 40             | 40              | 0.02   | 20–90          | 2                      |

### Table 4. The parameters for nanoindentation.

| Parameters                | Value |
|---------------------------|-------|
| Acquisition Rate (Hz)     | 10.0  |
| Max load (mN)             | 10.00 |
| Loading rate (mN min⁻¹)   | 20.00 |
| Unloading rate (mN min⁻¹) | 20.00 |
| Pause (s)                 | 10.0  |
| Approach distance (nm)    | 2000  |
| Approach speed (nm min⁻¹) | 3000  |
| Retract speed (nm min⁻¹)  | 2000  |
| Fn contact (Mn)           | 0.01  |
3. Result and discussion

3.1. Microstructural analysis of the coatings

The cross-section morphology of WC-Ni coating and XRD pattern of the powders and coatings are shown in figure 3. As can be seen from figure 3(a), the WC-Ni coating is dense, and there are no obvious holes or cracks. The coating is well combined with the substrate. The average thickness of the WC-Ni coating measured in this test is 280 μm. It can be observed from figure 3(b), the SEM micrograph shows that there are only small holes distributing within the coating, which can reveal the good compactness of the coating, and the porosity of the coating is 0.49%.

The cross-section morphology of WC-Cr3C2-Ni coating and XRD pattern of powders and coatings are shown in figure 4. WC-Cr3C2-Ni powder were composited by two kinds of hard phases WC and Cr3C2 and
metal Ni. The coating binds well to the substrate, which can be seen from figure 4(a), and the average thickness of the coating measured in this test is 350 μm, figure 4(b) shows that there are a few microcracks and holes in the coating, the porosity of the coating is 1.68%. It can be revealed from the analysis result combined with the x-ray diffraction (figure 4(d)) of WC-Cr₃C₂-Ni coating, there are WC and Cr₃C₂ hard phases and metal Ni phase in the coating. The light gray area indicated by the arrow in figure 4(c) is the binding phase of Ni.

### 3.2. Mechanical properties of the coatings

In this test, the elasticity modulus, average microhardness values and nano-hardness values of WC-Ni, WC-Cr₃C₂-Ni coating and the average microhardness values of the contrast sample 1Cr18Ni9Ti are shown in table 5.

It can be observed from the table 5 that the average hardness value of the WC-Cr₃C₂-Ni is slightly higher than that of the WC-Ni due to a lower binder content, and the average hardness value both the two coatings is about three times that of 1Cr18Ni9Ti. Moreover, the elasticity modulus and nano-hardness values of the WC-Cr₃C₂-Ni coating are higher than that of the WC-Ni coating. Figure 5 shows the schematic diagram of the indentation load-displacement. It can be seen from figure 5 that under the same load, the residual indentation depth of WC-Cr₃C₂-Ni coating is smaller than that of WC-Ni coating, which indicates that the plastic deformation of WC-Cr₃C₂-Ni coating is smaller and the elastic recovery is better than that of WC-Ni coating. In addition, the plasticity index of the material can be obtained from the load-displacement curve [35], it can be calculated that the plasticity index of WC-Cr₃C₂-Ni coating is lower than that of WC-Ni coating. Higher hardness and lower plasticity index indicate that WC-Cr₃C₂-Ni coating is less prone to fracture than WC-Ni coating during the process of impacting.

![Figure 4. The cross-section morphology of the WC-Cr₃C₂-Ni coating and XRD patterns of powders and coatings: (a), (b) morphology; (c) XRD patterns.](image)

### Table 5. The mechanical properties of the coatings and 1Cr18Ni9Ti.

| Specimen     | Elasticity modulus (GPa) | Average hardness (HV₀.₃) | Nano-hardness (GPa) |
|--------------|--------------------------|--------------------------|---------------------|
| WC-Ni        | 255.06                   | 1105                     | 8.497               |
| WC-Cr₃C₂-Ni | 367.53                   | 1188                     | 16.726              |
| 1Cr18Ni9Ti   | —                        | —                        | —                   |

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3.3. Erosion performance of the coatings

Figure 6 gives the erosion volume loss rate of the two kinds of cermet coatings and contrast specimen 1Cr18Ni9Ti stainless steel under the test condition which sediment concentration is 20 kg m$^{-3}$, at 30°, 60° and 90° impact angles. As it reveals in the Figure 6, the volume loss rate of all three materials is decreasing with the increasing of the angle, and the WC-Cr$_3$C$_2$-Ni coating shows the best erosion resistance at every angle, followed by the WC-Ni coating and 1Cr18Ni9Ti stainless steel. This regular is similar to the conclusion reached by Vahid [36]. Vahid suggested that erosion can be divided into ductile erosion and brittle erosion. At low angle, erosion is mainly brittle erosion, the main mechanisms of erosion are cutting and ploughing, which is related to the hardness of the specimen [37], generally speaking, the higher the hardness, the lower the wear rate. Therefore, at low impact angle of 30°, the volume loss rate of WC-Cr$_3$C$_2$-Ni is the lowest, which is 0.135 mm$^3$·cm$^{-2}$·h$^{-1}$, by contrast, it’s only one-third that of 1Cr18Ni9Ti stainless steel; at the impingement angle of 90°, erosion is mainly ductile erosion, The main mechanism of erosion is the plastic deformation and fatigue damage caused by repeated impact of impingement particles [37], which is related to the elastic modulus and fracture toughness of the specimen [38], so the volume loss rate of 1Cr18Ni9Ti stainless steel is greatly reduced, contrast that at low angle; and because the elastic modulus of 1Cr18Ni9Ti stainless steel is close to that of the WC-Ni coating, the volume loss rate of the two samples is not much different at 90° angle.

The erosion morphologies of WC-Ni coatings at different impact angles under 20 kg m$^{-3}$ sediment concentrations are shown in figure 7, combined with the erosion volume loss rate of WC-Ni coating in figure 6, it is not difficult to see that erosion at a low angle has the largest damage value. As can be seen in figure 7(a), at
angle of 30°, the morphology of the coating exhibits more erosion furrows and hard phase particles crushed by erosion particles, compared with 90° angle of impact, the erosion morphology damage is more serious. Figure 7(b) shows that the coating after impact of 60° angle, on the surface of the coating, not only have furrows produced by impact of particles, but also erosion pits produced by vertical impact; the degree of damage on the coating surface is relatively slight at the impact angle of 90°, without a wide range of damage, compared with that at low angle. As shown in figure 7(c), erosion begins with the bonding phase with lower hardness. Because of the vertical impact, the particles cannot cut the bonding phase, the bonding phase becomes worn out by the low-cycle surface fatigue mechanism, which described by Kulu [39], the loss of the bonding phase leads to subsequent spallation of free-standing carbide particles.

The erosion morphologies of WC-Cr3C2-Ni coatings at different impact angles under 20 kg m⁻³ sediment concentrations are revealed in figure 8. Figure 8(a) reveals the region A is the damage to the coating caused by the impact of particles at 30° angle. The damage morphology mainly includes furrows and erosion pits, and the damage mode is mainly cutting mechanism, accompanied by a small amount of plastic deformation of furrows. In region B (figure 8(a)), the coating with uniform distribution of hard phase WC and Cr3C2 in bonding phase Ni is relatively flat and dense, and no obvious erosion damage traces. Region A (figure 8(b)) refers to the furrows by the cutting action of impact particles at 60°, and region B (figure 8(b)) is the damage caused by the impact of the vertical component of the impact particles, the damage mechanism is similar to the failure mechanism in figure 7(c). The erosion morphology of the coating surface at 90° is shown in figure 8(c), some deeper erosion pits appear on the coating surface, the oval region (figure 8(c)) shows hard phase particles crushed by sand are distributed around the erosion pits, the erosion pits will become deeper with the extension of eroded time. On the whole, contrast to the WC-Ni coating, the WC-Cr3C2-Ni coating shows the greater erosion resistance because of its better mechanical properties.

Figure 9 shows the erosion morphologies of 1Cr18Ni9Ti stainless steel at different impact angles under 20 kg m⁻³ sediment concentrations. Figure 9(a) reveals that quantities of erosion grooves exist on the surface of 1Cr18Ni9Ti stainless steel, the erosion damage caused by the impact of particles is relatively obvious, mounts of deformed lips superimposed on the tail of the grooves. Figure 9(b) shows that the cutting degree of the coating at 60° impact angle significantly weakened, longer plastic deformation grooves significantly reduced, but the depth of grooves obviously increased. The erosion morphology of the specimen at 90° obtained is shown in figure 9(c), plastic deformation occurs on the surface of the specimen due to the impact of high-speed particles and then some convex and concave erosion pits are formed.

As can be seen that the erosion of 1Cr18Ni9Ti is dominated by cutting at low angle, while plastic deformation is dominated at high angle, and WC-Cr3C2-Ni coating shows the best erosion resistance at every angle, followed by WC-Ni coating and 1Cr18Ni9Ti stainless steel.
4. Conclusion

In this study, two cermet composite coatings including WC-Ni and WC-Cr$_3$C$_2$-Ni were prepared by high velocity oxy-fuel (HVOF) spray process, the morphologies, volume loss rate and wear behavior of coatings under various test conditions were investigated. The main conclusions are as follows:

Figure 8. Erosion morphologies of WC-Cr$_3$C$_2$-Ni coatings at different impact angles under 20 kg m$^{-3}$ sediment concentrations: (a) 30°, 2000×; (b) 60°, 2000×; (c) 90°, 2000×.

Figure 9. Erosion morphologies of 1Cr18Ni9Ti at different impact angles under 20 kg m$^{-3}$ sediment concentrations: (a) 30°, 2000×; (b) 60°, 2000×; (c) 90°, 2000×.
1. WC-Cr$_3$C$_2$-Ni coating consists of WC, Cr$_3$C$_2$ and Ni phases; WC-Ni coating consists of WC, W$_2$C and Ni phases. The elasticity modulus of the WC-Cr$_3$C$_2$-Ni coating and WC-Ni coating are 367.53 GPa and 255.06 GPa, respectively; the average microhardness value of the WC-Cr$_3$C$_2$-Ni coating and the WC-Ni coating are 1188 HV$_{0.3}$ and 1105 HV$_{0.3}$, respectively; and the average porosity of the coatings are 1.68% and 0.49%, respectively.

2. The relationship between impingement angle and wear rate was investigated under the conditions of a certain sediment, at 30°, 60° and 90° angle, the sequence of the volume loss rate of the coatings is: WC-Cr$_3$C$_2$-Ni < WC-Ni < 1Cr18Ni9Ti, that is, WC-Cr$_3$C$_2$-Ni coating has the best erosion resistance, and 1Cr18Ni9Ti stainless steel has the worst erosion resistance.

3. The erosion is dominated by cutting at low angle for the coatings and 1Cr18Ni9Ti stainless steel, while erosion pits is dominated at high angle for the coatings, and plastic deformation is dominated at high angle for the 1Cr18Ni9Ti stainless steel.

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