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Microstructure and Properties of Thermal Sprayed WC-CrC-Ni Coatings

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Hard chrome plating has excellent resistance to corrosion and wear, but the hexavalent chromium associated with the plating process has serious environmental and health concerns. One of the alternative candidates to replace hard chrome plating is thermal sprayed tungsten carbide coating. In this paper, three different WC-CrC-Ni commercial powders were thermal sprayed to deposit coatings onto stainless steel substrates. The powder morphology and coating microstructure were examined. The coating properties, including hardness, adhesion force, deposition efficiency and wear resistance, were tested. It was found that even though the three powders have the same composition, their coating performances are slightly different. Despite the minor differences, the thermal sprayed WC-CrC-Ni coating is a hard and wear-resistant material, which can replace hard chrome plating on applications in the steel industry.

Keywords: Tungsten carbide, Thermal spray, WC-CrC-Ni, Wear

1. INTRODUCTION

Hard chrome plating is widely used on steel rolls in a continuous galvanizing line due to its good anti-wear properties and corrosion resistance. However, the hexavalent chromium associated with the chrome plating process is known to have detrimental effects on the environment and human health(1). Research into a replacement for hard chrome plating has been widely carried out(2,3). Although there is not a technology which can really replace hard chrome plating both economically and functionally, there are a few alternative candidates. Thermal sprayed tungsten carbide coating is one of them.

Thermal spraying is a widely used industrial process for applying protective coatings to material surfaces. It is a process that involves the deposition of molten or semi-molten droplets of powder onto a substrate to form a coating(4). Tungsten carbide and chromium carbide-based coatings are frequently used in various industrial fields such as the steel industry and aerospace industry to improve the resistance to sliding, abrasive and erosive wear(5-7). For example, the sliding wear rates of thermal sprayed WC/17Co or WC/10Co4Cr against many different types of materials is much less for both the coatings and mating materials than for hard chrome(2).

WC-Co is the most common thermal sprayed tungsten carbide coating. It is composed of hard WC particles introduced into the tough metallic matrix produced during a liquid phase sintering process(8). It exhibits very good wear resistance. However, its corrosion resistance is not as good as its wear resistance. When using Ni instead of Co as the binder material or alloying CrC into the binder phase, the corrosion resistance was reported to be increased(8). This paper investigates the properties of WC-CrC-Ni thermal sprayed coatings which were deposited using three commercial powder feedstocks.

2. EXPERIMENTAL METHOD

Commercial thermal spray powders purchased from three different companies were used in this study. These powders have the same composition as WC-20CrC-7Ni. Table 1 lists the details of the powders.

The powders were sprayed by a JP-8000 gun (AMT-AG) to form coatings on SUS 316 substrates. The spray parameters are listed in Table 2. The parameters of oxygen flux, kerosene flux and spray distance were recommended by each powder manufacturer. The substrates have three different types. One is a plate with the dimensions of 25.4mm x 25.4mm x 8mm, which was used for metallographic observation and for wear tests. Another is a plate with the dimensions of 100mm x 200mm x 8mm which was used to measure the deposition efficiency. The third is a 40mm long bar

Table 1 Details of the thermal spray powders

Sample name	Powder name	Manufacturer	Apparent density	Powder size
W1	W2007J	Fujimi	4.02 g/cm^3	15-45μm
W2	Woka 3702	Sulzer Metco	4.67 g/cm^3	15-45μm
W3	Amperit 551.074	H.C. Starck	4.1 g/cm^3	15-45μm

Table 2 Spray parameters

Symbol	W1	W2	W3
O_2 flux (nlpm)	832	900	792
Kerosene flux (l/h)	19.2	24.1	22.7
Carrier gas (N_2) flux (nlpm)	6.0	6.0	8.0
Powder rate (g/min)	90	90	90
Barrel length (in)	6	6	6
Spray distance (mm)	380	300	380

with a diameter of 25mm, which was used for adhesion tests.

SEM was used to examine the powders and coating cross-sections. Photoshop was used to quantify the coating porosity. Cross-sectional microhardness measurements were performed by means of Vickers indentation (Matsuzawa MXT50) at a load of 300g for 15secs. Ten indents were made along the mid-plane of a polished transverse section and the mean hardness was obtained from the separate readings.

The adhesion test followed ASTM C633 standards. The coating was deposited on a section of a bar. This section was joined to a non-coated bar with 3M Scotch-Weld Epoxy Adhesive 2214 Regular. They were cured at a temperature of 150°C for 1hour before the test. The adhesion force of the coating was determined by the tension test performed on an MTS Sintech 10/GL machine.

Deposition efficiency was calculated by the following equation:

$$\text{Deposition Efficiency} = \frac{\text{Weight of deposited coating}}{\text{Weight of consumed powder}} \times 100\%$$

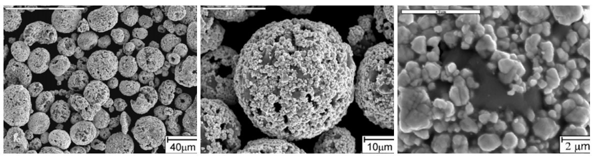
A larger substrate was used in order to cover the calculated sprayed powders onto it. The substrate was weighed before thermal spraying and after 10 passes spraying.

The wear properties of the coatings were evaluated by using a ball-on-disk type wear tester (Universal Nano/Micro Materials Tester). Two different kinds of balls were used: one was made of tungsten carbide; the other was made of stainless steel. Coating samples were polished by a #80 diamond polish pad and were sandblasted to reach a roughness of Ra 2.5μm. Tangential wear velocity was 0.3m/s. The load was 10 N. Total distance was 1080m. The weight loss for each sample and each ball was then measured.

3. RESULTS AND DISCUSSION

3.1 Powder Morphology

Figures 1~3 show the morphologies of the three tungsten carbide thermal spray powders. From the different magnifications, the powder size and structure can be seen clearly. In general, each powder has a very similar size distribution, 15~45μm. The W1 powder is more spherical than the others. At high magnification, tungsten carbide particles can be seen on each powder clearly. The size of the tungsten carbide particles is around 1μm.



× 200 × 1000 × 5000

Fig.1. Morphology of W1 powder.

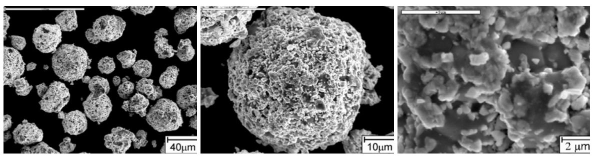


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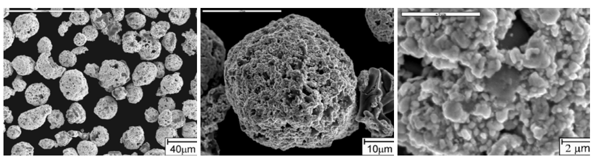
Fig.2. Morphology of W2 powder.



× 200 × 1000 × 5000

Fig.3. Morphology of W3 powder.

3.2 Coating Microstructure

Figures 4~6 show the microstructure of the coatings and their EDS analyses. Due to having the same composition, each coating has a similar microstructure. There are white and black particles in the coatings. From EDS analyses, it is shown that the small white particles are tungsten carbide while the large black particles are chromium carbide. Both particles are hard materials and were uniformly distributed in the coatings.

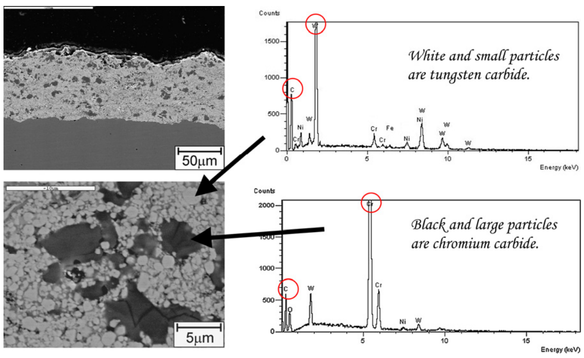


Fig.4. Microstructure and EDS analysis of W1 coating.

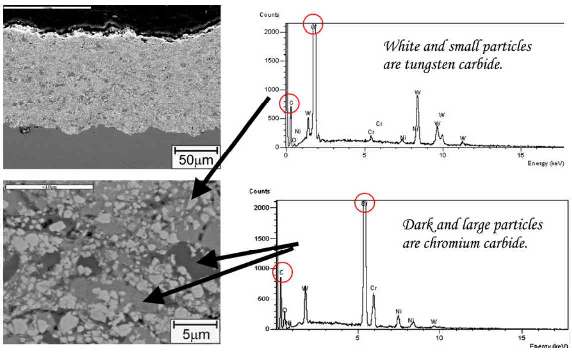


Fig.5. Microstructure and EDS analysis of W2 coating.

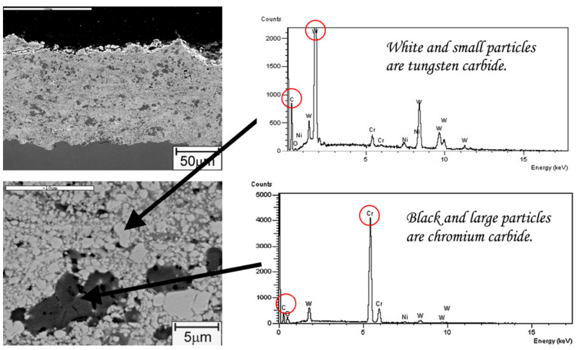


Fig.6. Microstructure and EDS analysis of W3 coating.

3.3 Microhardness

As mentioned earlier, both tungsten carbide and chromium carbide are hard materials. As a result, as coatings they exhibit a very high hardness. Figure 7 illustrates the microhardness of these coatings. W1 is a little below HV 900, while W2 and W3 are above HV 950.

It is interesting that W1 has a lower hardness than W2 and W3, even though they have the same composition. It should be noted that the coating properties might be affected by the spray parameters. In this study, all the powders were sprayed with one parameter, which was provided by the powder vendors. It is possible to increase the hardness of the W1 coating by tuning its spray parameter. Nevertheless, it is sure that WC-CrC-Ni coating exhibits a very high hardness.

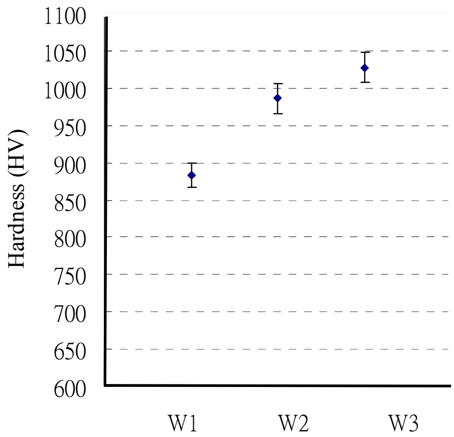


Fig.7. Microhardness of W1, W2 and W3 coatings.

3.4 Adhesion Test

Four specimens were prepared for each coating. The testing results are shown in Fig.8. A tension force between 48 and 63MPa was measured for each specimen. When examining any fractured surfaces, it was found that the fracture occurred on the adhesive portion. This indicates that the measured tension force is mainly the strength of the adhesive. In other words, the adhesion force of the coating should be higher than the strength of the adhesive. From the results, the measured highest strength of the adhesive for each coating is above 60MPa. It can be reasonably assumed that the adhesion force for each coating is higher than 60MPa.

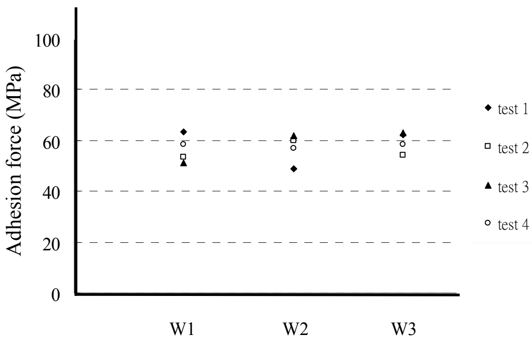


Fig.8. Adhesion force of W1, W2 and W3 coatings.

3.5 Deposition Efficiency

The deposition efficiency of spraying each coating is shown in Fig.9. The W1 coating has the highest deposition efficiency while W2 has the lowest. Generally speaking, round powder can flow smoothly. From the powder morphologies, the W1 powder exhibited a good roundness which indicates that this powder could be applied smoothly during the spraying resulting in a high deposition efficiency. However, the roundness of the W2 powder is better than that of the W3 powder, but was shown to have a lower deposition efficiency. Therefore there must be other factors influencing the deposition efficiency.

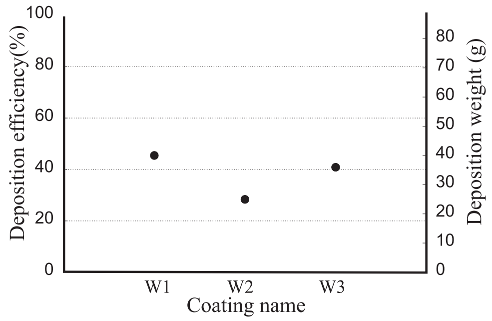


Fig.9. Deposition efficiency for W1, W2 and W3 coatings.

One possibility is the density of the powder. In order to melt all the powder thoroughly within the limited time during thermal spraying, the powder is usually designed to be porous. From the powder certificates provided by the vendors, the apparent densities for the W1, W2 and W3 powders are 4.02, 4.67, and 4.1g/cm^3 respectively. The W2 powder is denser than the others. This powder might have a higher chance of not melting properly. An unmelted powder is likely to bounce back when it hits the substrate. As a result, the deposition efficiency is decreased. The low deposition efficiency of the W2 coating could be the result of its not melting properly.

3.6 Wear Test

A stainless steel ball was first used on the ball-on-disk tests. The weight losses for both the coating and the ball are shown in Fig.10. This shows that the weight loss for each coating is very small. On the contrary, the weight loss for each ball is a lot higher since tungsten carbide is a harder material than stainless steel. As the difference in the wear properties of the coatings is not shown by a steel ball, a ball made of a harder material should be considered.

A tungsten carbide ball was chosen to replace the stainless steel ball for the second ball-on-disk tests, and the results are shown in Fig.11. The wear properties

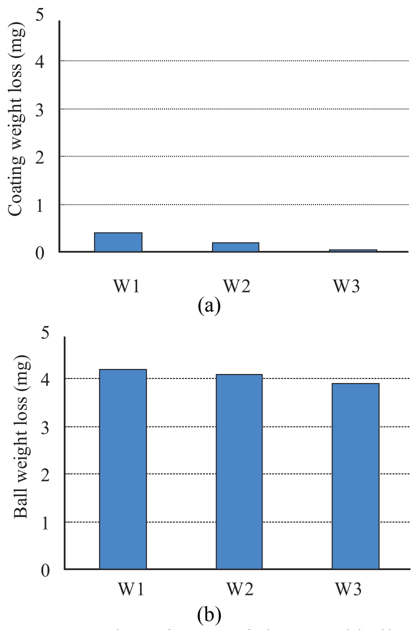


Fig.10. Wear test by using a stainless steel ball.
(a) Weight loss of the coating; (b) Weight loss of the ball.

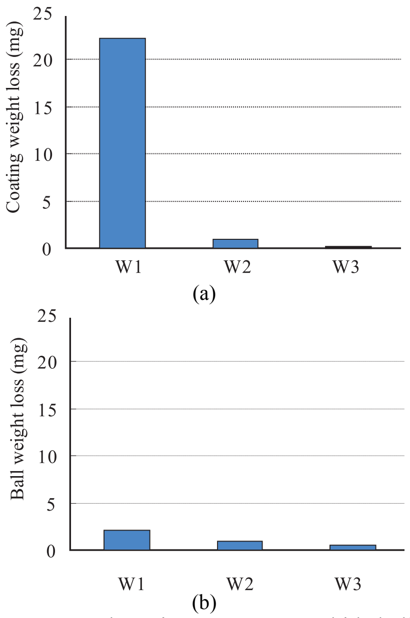


Fig.11. Wear test by using a tungsten carbide ball.
(a) Weight loss of the coating; (b)Weight loss of the ball.

of the coatings can now be distinguished from the coating weight losses. The W1 coating shows a high weight loss after the test which indicates a poor wear resistance. The W2 and W3 coatings exhibit a good wear resistance. It is interesting that all three coatings were sprayed from powders with the same composition, but resulted in different wear properties. Examination of the wear traces by SEM was executed to try to unveil any possible reasons.

Figures 12-14 show the SEM images of the wear traces for each coating. Each figure includes: (a) a cross-section with the wear trace indicated by an arrow; (b) the surface morphology of the wear trace; and (c) the wear trace at high magnification. A clear wear trace can be seen from Fig.12(a) which is consistent with the high weight loss of the W1 coating. From Fig. 12(b) and 12(c), it can be seen that a large amount of material has fallen out from the surface of the wear trace. This could be due to the weak strength of the coating. When the molten droplets were deposited on the substrate during thermal spraying, somehow the bonding between each droplet was not strong enough. With the loading during the wear test, the grains near the surface easily fall out.

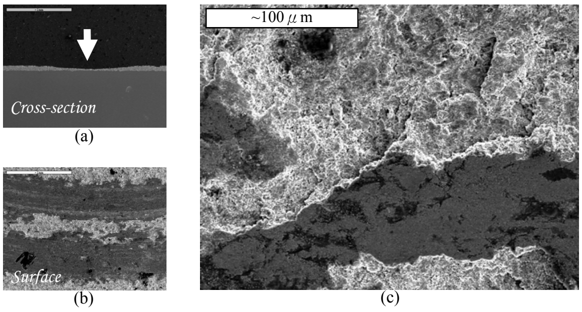


Fig.12. Wear trace of W1 coating. (a) Cross-section; (b) Wear trace surface at low magnification; and (c) Wear trace surface at high magnification.

Figures 13 and 14 are the wear traces of the W2 and W3 coatings. The weight losses for these two coatings are very low which is reflected by the shallow wear traces. The wear traces were too shallow to be observed from the cross-sections. When examining the surface morphologies of their wear traces, flakes of oxide were found. It is possible that the coating material underwent a high temperature condition when performing the wear test and was oxidized. These oxide flakes became brittle and were detached from the surface due to the repeated loading force.

4. CONCLUSIONS

Three different WC-CrC-Ni commercial powders, W1, W2 and W3, were thermal sprayed to deposit coatings and their properties were tested. The following conclusions are made:

(1) Small WC particles and large CrC particles were normally distributed in a thermal sprayed WC-CrC-Ni coating.

(2) W1 powder is more spherical than the others. It is assumed to have better fluidity which is reflected by a higher deposition efficiency.

(3) W2 powder is denser than the others according to their apparent densities. Its low deposition efficiency could be due to more non-molten droplets bouncing off the substrate during thermal spraying.

(4) The hardness of the W1 coating is lower than the others. Its low hardness is reflected by a high wear loss. The W2 and W3 coatings have better wear resistances than W1.

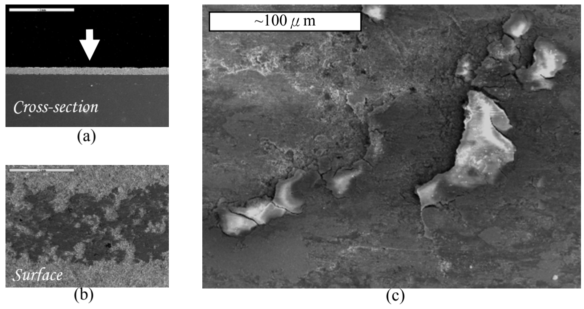


Fig.13. Wear trace of W2 coating. (a)Cross-section; (b) Wear trace surface at low magnification; and (c)Wear trace surface at high magnification.

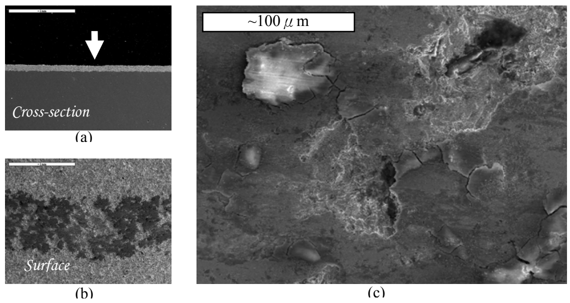


Fig.14. Wear trace of W3 coating. (a)Cross-section; (b) Wear trace surface at low magnification; and (c)Wear trace surface at high magnification..

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