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Effect of W dissolution in NiCrBSi–WC and NiBSi–WC arc sprayed coatings on wear behaviors

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ABSTRACT

This work concerns the arc-sprayed NiCrBSi–WC and NiBSi–WC coatings produced from cored-wires. Porosity and WC/W_2C contents were determined from the as-sprayed coatings. It was suggested that the dissolution of W into the Ni-rich matrix, which was more pronounced in NiBSi–WC coating and resulting in the thermal expansion coefficient of the matrix to reduce, caused this coating to have lower thermal stress from fabrication. This resulted in a lower amount of WC/W_2C detachment in NiBSi–WC coating. The dissolution of W however has an adverse effect of reducing the WC/W_2C contents in the coating, which reduces its hardness. Wear testing revealed that, even though the NiCrBSi–WC coating contained higher WC/W_2C content than the NiBSi–WC coating due to lower W dissolution, its performance was inferior to the latter. In the dry sliding wear test, the problem of WC/W_2C detachment on the contacting surface became exacerbated in the NiCrBSi–WC coating, leaving craters on the wear surface. In the three-body abrasive wear test, there was much less WC/W_2C detachment. However the NiBSi–WC coating continued to out-perform the NiCrBSi–WC coating, suggesting that the higher W dissolution into the Ni-rich matrix has a major role in increasing the abrasive resistance of the coating.

1. Introduction

Carbide-reinforced NiCrBSi and NiBSi as metal matrix composites (MMCs) have been used in many applications such as oil drilling equipments, agricultural machineries, piston rings, rollers in steel making and wire drawing rolls, in order to combat mechanical degradations such as sliding wear, abrasive wear and rolling contact fatigue [1–5]. WC is one of the most commonly used hard reinforced particles due to its high hardness and toughness and its ability to be wetted easily by many molten metals [6–8], hence producing a well bonded MMC.

Electric arc spraying (EAS), also known as metallization, is a thermal spraying technique used in depositing a thick metallic coating from wire form. It is a simple and cost-effective process and is popularly employed in surface refurbishments and maintenance sectors. The principle of EAS involves two electrically conductive wires fed into a common arc point, creating a temperature of up to the melting temperature of the wire material at which melting occurs. The molten material is continuously atomized and the droplets are accelerated toward the substrate by a compressed air jet [9]. As well as a solid metallic wire, cored wires where non-conductive powders are contained inside a metallic tube can also be used.

Material properties that govern its wear performance, apart from its intrinsic properties such as friction coefficient, hardness and fracture toughness, also include external factors such as lubrication, temperature, environment and the material compatibility with the counter surfaces. In the case of carbide-reinforced NiCrBSi and NiBSi coatings, factors such as coating adhesion strength to the substrate, type of carbides, and carbide content [10,11] also play a major role in enhancing the wear resistance of a component. These mentioned properties have a strong relationship to the microstructure of the material.

Previous work has found that W can dissolve into the NiCrBSi–WC and NiBSi–WC EAS coatings during spraying, forming solid-solutions of NiCrW and NiW at room temperature. As a consequence, the carbide contents were lowered in both coatings [12]. These occurrences undoubtedly affect the physical and mechanical properties of the coatings, and in particular, the tribological properties where the coating's main applications lie.

The objective of this work is to study the effect of the W dissolution in NiCrBSi–WC and NiBSi–WC coatings produced via the EAS process on the physical and mechanical properties of the coatings.

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2. Experimental procedure

2.1. Materials

Stainless steel 304 coupons of dimension $5 \times 25.4 \times 60$ mm^3 and $10 \times 10 \times 5$ mm^3 were used as substrates for sliding wear test specimens and abrasive wear test specimens, respectively. All substrate specimens were grit blasted using 740 μm Al_2O_3 in order to achieve the surface roughness of 8–10 μm Ra. The high surface roughness is essential to ensure adequate bonding of the coatings. The degree of surface roughness required depends on the coating material, the process and the service condition of the coating. The minimum roughness of 8 μm Ra was chosen according to an industrial practice of producing an arc sprayed wear-resistant coating of less than 300 μm thickness. Higher degree of the substrate roughness will result in higher bonding strength of the coating but will also increase the roughness of the finished coating. The specimens were then ultrasonically cleaned and dried, and were ready for the EAS coating process. Two groups of coating samples were produced using EAS from 2 types of cored wire. The wire compositions are shown in Table 1.

2.2. Electric arc spraying (EAS)

The specimens were spray-coated using Sulzer Metco SmartArc to achieve a coating thickness of 250–300 μm. For wear applications, thicker coating is generally more desirable to allow for a longer lifetime. However the maximum coating thickness is partly controlled by the loss of the outer surface roughness as the coating builds up and also the reduction in its bond strength as the coating becomes thicker. Hence the 250–300 μm thickness was chosen as a moderate thickness that still allow for a usable wear-resistant coating. The optimized spraying parameters and the sprayed materials for two groups of sample, *a* and *b*, are shown in Table 2. The optimization was done by varying the spray distance and the arc voltage, which subsequently controls the arc current and the wire feed rate. The chosen condition produced a coating with the lowest percentages of porosity and oxide content.

2.3. Physical properties

The samples were cross-sectioned and polished to reveal the coating microstructures. JEOL JSM5410 scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDS) were used to characterize the structures and phase compositions of the coatings. The percentage of cracks and porosities of the coatings were determined using image analysis [13] (Image Pro Plus version 5.1) on optical images of the coating cross sections. Hardness testing in kg/mm^2 using Vickers microhardness at 0.4 kg loading and Brinell hardness at 187.5 kg loading were also utilized. An averaged Vickers hardness number was obtained from 30 indentations across the polished cross-section of the coating in order to represent the heterogeneous nature of the coating. An averaged Brinell hardness number was obtained from 10 indentations on the polished surface of the coating to represent the effective hardness of the coated specimen.

Due to the gradual variation of chemical composition in coating splats as a result of W dissolution [12], a clear distinction does not occur between WC and the Ni-rich phases. In this work, etching was therefore employed in order to identify the carbide phases. The chemical mixture was 1:1 of 70% conc. HNO_3:H_2O by volume. The polished planar and cross-section samples were exposed to the mixture for up to 5 min at 75 °C. Splats exhibiting no sign of corrosion attack were determined as carbides. Image analysis was then used to measure their area percentages.

Table 1
Chemical composition of sprayed wires.

Cored wire	Metallic elements (totaled to 50 wt%)					Fused WC/W_2C 50 wt%
	Ni	Cr	B	Si	C	
a	Bal.	10–12	1.7–2.0	4–5	0.4	+100%
b	Bal.	–	1.7–2.0	4–5	0.4	+100%

Fused tungsten carbide consists of 78–80% W_2C and 20–22%WC by weight. WC/W_2C particle size is 100 ± 40 μm.

Table 2
Optimized spraying parameters.

Sample	*a*	*b*
Cored wire	*a*	*b*
Air pressure (kN/m^2)	345	
Arc voltage (V)	32–35	
Arc current (A)	150	
Feed rate (kg/s)	0.0028	
Spray distance (mm)	127	

2.4. Tribological testing

2.4.1. Dry sliding wear

The as-sprayed samples were polished in the planar direction to achieve the surface roughness of 0.7 μm Ra. Linear reciprocating ball-on-flat dry sliding wear tests were performed on Micro Tribometer UMT 2 test machine (Bruker Instrument, USA). The test setup and parameters adhered to ASTM G 133-95 procedure A using 25 N normal force, 10 mm stroke length, 5 Hz oscillating frequency and 1000 s test duration in an unlubricated condition at room temperature [14]. The pin tip radius of 4.76 mm however was not adopted. Instead a through-hardened high carbon steel ball (AISI 52100) of 6.3 mm diameter and hardness of 60–64 Rockwell C was used as the contacting spherical surface. Three tests were conducted for each group of specimen. The wear damages were reported as wear depths of the specimens. In order to obtain the wear depth value, the tested specimen was cross-sectioned and examined through an optical microscope. The lowest point on the wear track was taken as the wear depth.

2.4.2. Abrasive wear

The as-sprayed samples were polished to 0.7 μm Ra in the planar direction. A wheel grinder was employed for the abrasive test, using a wheel speed of 30 rpm. The specimens were under a 20 N load and moved in the opposite direction to the wheel at 60 rpm. The grinding wheel was padded with a polishing cloth. A continuous feed of 5 μm alumina suspension (Buehler Micropolish II Deagglomerated) was set at 2 ml/min. Three tests were conducted for each group of specimen. Weight changes of the specimens were used to evaluate the abrasive wear performance.

3. Results and discussion

3.1. Coating microstructures

Cross sections of the coatings were revealed using the back-scattered SEM, see Fig. 1. Both coatings display good integrity. No large cracks were observed. There are however some small globular pores and intergranular pores observed in coatings *a* and *b*. In both samples, WC/W_2C (light colored phase) scatters throughout the Ni-rich matrix (dark colored phase). The Ni-rich phase varies significantly in its chemical composition, and hence