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The effect of Mo content in plasma-sprayed Mo-NiCrBSi coating on the tribological behavior

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ABSTRACT

NiCrBSi is a material popularly used as a hard thermal sprayed coating. The coating performs well as a wear resistant coating under low stress. At higher stress in metal-to-metal sliding wear condition, however, the NiCrBSi starts to experience surface deformation, which will inevitably lead to seizure as the stress increases. In order to improve the tribological properties of the NiCrBSi plasma-sprayed coating, Mo is added to the coating to reduce the friction between the coating and other metal contacting surface, thus, improving its dry sliding wear resistance. In this study, various amounts of Mo were mixed with NiCrBSi at 0, 25, 50, 75 and 100 wt.%. The powders were sprayed using an air plasma spraying technique onto stainless steel samples to form coatings, which were ground to achieve flat surfaces and a thickness of 350–400 µm. The mechanical properties of the coatings were determined. The coating samples were then tested using a reciprocation ball-on-flat tribometer. It was found that as the Mo/NiCrBSi ratio increases, the wear mechanism changes. Coatings containing 75%Mo and 25%NiCrBSi exhibit the highest wear depths corresponding to the cracking of the thin NiCrBSi splats. On the other hand, coatings containing 25%Mo and 75%NiCrBSi possess the lowest wear depths with no surface cracks. The presence of Mo covering the coating surface hinders the metal seizure between NiCrBSi and steel counter surface.

1. Introduction

Wear damage is an expensive problem many industries are facing, whether it is the wear of die faces in metal forming, the wear of rollers in paper industry or the wear of components in automobile. Part of the problem can often be solved using material technologies. Surface engineering in particular, plays a big part in the attempt to minimize wear damage in just about every industry. This work involves a surface coating technique known as plasma spraying. Plasma spraying can produce thick coatings from various materials. Wear resistant coatings generally require high hardness as well as low friction to fight against material deformation and mass loss. With low friction, there is less force acting on the surface of a component, and hence, less energy is dissipated as heat. The heating induced by friction can cause the temperature of the components' surfaces to rise to a detrimental level at which the surfaces start to soften and deform. Seizure of the metal surfaces will then follow which will have an effect of accelerating the wear process. Furthermore, chemical reactions, most commonly oxidation, also take place due to this increasing temperature of the contacting surfaces. When metal oxidation accompanies the wear process, components tend to fail prematurely. Many metals and alloys are of much interest to the tribologists as the materials for the wear resistant coatings, two of which have been the focus of many researchers in recent years due to their beneficial characters. These materials are Mo [1–3] and NiCrBSi [4–6].

Mo is a refractory metal. In its elemental form, it is soft. But during processing at high temperature, for example in plasma spraying, it forms a thin oxide layer, MoO_2 [7]. The oxide layer improves the hardness of the Mo coating. The greater benefit, however, comes from the reduction in the coefficient of friction of the coating surface [8]. In many applications where sliding wear between metal surfaces is a problem, such as synchronizer rings and piston rings [9,10], Mo coating may be the suitable solution. The presence of the MoO_2 on the splat boundaries, however, has an adverse effect of reducing the cohesion strength of the coating, causing the coating to fail by splat delamination [11,12].

The other material is NiCrBSi. Ni and its alloys have been a popular choice for coatings due to their ease of processing and moderate strength and corrosion resistance at high temperature [13,14]. Cr is added to Ni to improve the hardness and corrosion resistance. B and Si are added to lower the melting point and to improve the self-fluxing ability of the material [15,16]. B can also form hard phases with Ni, such as Ni_3B, thus improving the hardness of the coating [17,18]. This material is often used in applications where high hardness and wear resistance are required. When high hardness as well as low friction is needed, it is possible to mix the two materials, Mo and NiCrBSi, and produce a composite coating with two distinct phases.

The objective of this work is to study the wear behaviors of the plasma-sprayed Mo-NiCrBSi coatings having various amounts of Mo and NiCrBSi contents in order to select the combination with the superior dry sliding wear resistance.

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Table 1
Mo and NiCrBSi composition.

	Mo	Ni	Cr	B	Si	Fe	C	Particle size (μm)
Mo	99.4	–	–	–	<0.1	<0.1	<0.2	45–90
NiCrBSi	–	Bal.	15	3.1	4.4	4	0.7	10–53

2. Experimental procedure

2.1. Materials

Sample substrates were prepared from stainless steel AISI 304 sheet, cut into 250 × 600 × 5 mm test pieces. Two thermal spray powders were used in the present study. These are pure Mo (Amperit 105.2) and NiCrBSi (JK7660 JETKOTE). Their compositions are provided in Table 1. The starting coating powders were premixed from Mo and NiCrBSi powders using a dry milling technique. In the blends, the powders stayed as separate particles with no large agglomerations occurring. The powders were blended in different proportions of Mo/NiCrBSi to create 5 powder blends which are 100/0, 75/25, 50/50, 25/75 and 0/100. The powders were then subjected to plasma spraying.

2.2. Plasma spraying process

In this experiment, grit blasting, using alumina grit of average size 740 μm, was employed as a means to clean and to roughen the substrate surfaces. This surface preparation step is essential in order to promote high coating adhesion. The surface roughness of the grit blasted samples was approximately 5–6 μm Ra. All five samples were then plasma sprayed to achieve the coating thickness of greater than 400 μm, using Metco 3MBII plasma gun fitted with a 532B nozzle and a 3M210 powder injector. The powder injector was positioned externally at 90° to the plasma jet axis. The spraying parameters are shown in Table 2.

2.3. Microstructural analysis and mechanical testing

The as-sprayed coatings were cross-sectioned in order to obtain the microstructure using a scanning electron microscope. The porosity was measured using an Image Pro Plus program. Pull-off tensile testing was used to study the adhesion of the coatings. Vickers microhardness measurements using 300 g load and 15 second dwell time and Brinell hardness measurements fitted with 5 mm diameter steel ball using 187.5 kg and 15 second dwell time were also carried out.

2.4. Wear test

Another group of as-sprayed samples was polished on the top planar surfaces to achieve the surface roughness of less than 0.5 μm Ra and the remaining coating thickness of 350–400 μm. Wear tests, using a reciprocating ball-on-flat setup on a micro tribometer UMT-2 (CETR UMT), were then performed. Through-hardened high carbon steel balls (AISI 52100) of 6.3 mm diameter and hardness of 60-64 Rockwell C were used as contact tips. The wear test parameters are shown in Table 3.

Table 2
Plasma spraying parameters.

Powder	Plasma spraying parameters				
	A	Ar flow (LPM)	H_2 flow (LPM)	Powder feed rate (g/min)	Spray distance (mm)
Mo	400	47.2	7.1	70	100
Mo/NiCrBSi 75/25	500	47.2	7.1	50	100
Mo/NiCrBSi 50/50	500	47.2	7.1	50	100
Mo/NiCrBSi 25/75	500	47.2	7.1	50	100
NiCrBSi	400	47.2	7.1	50	100

Table 3
Test parameters for reciprocating ball-on-flat tests.

Test parameter	
Ball radius	6.3 mm
Normal force	25.0 N
Stroke length	10.0 mm
Oscillating frequency	5.0 Hz
Test duration	1000 s
Ambient temperature	25 ± 3 °C
Lubrication	None

3. Results and discussion

3.1. Coating microstructures and mechanical properties

The thickness of the as-sprayed coatings and the remaining thickness after grinding are shown in Table 4.

After spraying, the cross-sectioning revealed the microstructures as shown in Fig. 1. All samples show typical lamellar structures of plasma-sprayed coatings where the sprayed powder particles deformed and solidified when they impinged on the substrate surface to form splats. The splats piled up during spraying to gain the coating thickness.

Mo has a very high melting point of 2623 °C. The Mo powder in the plasma jet transformed to the molten state with a low degree of melting due to its high melting point together with the coarseness of the starting powder. Hence, when the Mo solidified on the substrate, a low degree of deformation occurred, resulting in high porosity, see Fig. 1(a). Glancing angle XRD analysis on the surface of the as-sprayed Mo coating shows that a small amount of MoO_2 has formed on the coating during spraying, see Fig. 2. The presence of MoO_2 can help improve the dry sliding condition of the coating. The Mo is known for its self-bonding property, which means that it can form chemical bonds with many metals and alloys, including to itself. Therefore, Mo can bond strongly with the iron-based substrate, thus promoting high adhesion strength. Large pores, however, are found in the coating as well as at the coating/substrate interface, resulting in the weakening of the interfacial strength, see Fig. 1(a).

NiCrBSi with its melting temperature of approximately 1025 °C, on the other hand, can melt easily in the plasma jet. This, together with the fact that the material is a self-fluxing alloy, means that the spraying droplets can easily deform to the contour of the underlying substrate. The resulting coating shows a structure with good integrity, see Fig. 1(e). There are some small pores present. No extensive oxidation occurred during spraying.

Due to the self-bonding property of Mo, when it was mixed with NiCrBSi, it can adhere well to the foreign phase. Micrographs of Mo/NiCrBSi 75/25, Mo/NiCrBSi 50/50 and Mo/NiCrBSi 25/75 samples are shown in Fig. 1(b), (c) and (d), respectively. The light coloured phase is Mo and the dark coloured phase is NiCrBSi. There is no separation between the splats of different phases. Some porosity is still present in sample Mo/NiCrBSi 75/25 and Mo/NiCrBSi 50/50 due to the low deformation of Mo. The presence of NiCrBSi, however, can help lower

Table 4
Coating thickness of test samples.

	Coating thickness (μm)	
	As-sprayed[a]	After grinding[b]
Mo	≥460	360–400
Mo/NiCrBSi 75/25	≥450	350–400
Mo/NiCrBSi 50/50	≥450	350–390
Mo/NiCrBSi 25/75	≥480	370–410
NiCrBSi	≥480	370–420

[a] Measured using a micrometer.
[b] Measured directly from sample cross-sections. The values indicated are from 3 specimens per each group and are varied within one specimen due to the rough interfaces.