Microstructure and Wear Properties of Plasma-Sprayed Aluminum–Silicon–Polyester Coatings

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ABSTRACT: Powder coatings, which are made by plasma-spraying processes, are being used in industrial applications because of their wear resistance, chemical resistance, and high impact strength even at low service temperatures. These factors increase the importance of plastic and plastic-based coatings in industrial applications. In this study, an aluminum–silicon–polyester-based composite coating was applied by plasma-spraying processes with and without an intermediate bond coat (Ni–Al). The effects of the coating thickness, intermediate bond coat, and processes parameters on the microstructure and wear properties of the coating were studied experimentally. The wear properties of the coatings were determined according to ball-on-disk procedure. The microstructures of the coating were examined by optical microscopy and scanning electron microscopy. The results indicated that the plasma-spraying current and thickness had a strong influence on the wear resistance and microstructural properties of the aluminum–silicon–polyester coating. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 100: 3609–3614, 2006

Key words: coatings; morphology; structure-property relations

INTRODUCTION

Surface engineering is an economical method for the production of materials, tools, and machine parts with required surface properties, such as bond strength, wear resistance, and corrosion and chemical resistance. The purpose of surface technology, including thermal spraying, is to produce functionally effective surfaces.[1–3]

A surface coating with protective layers also improves the surface properties and protects them from environmental and chemical factors. The properties of a coating, mostly the bond strength and wear resistance, are directly related to the properties of the material compositions and coating parameters.[3,4] Protective polymers and polymer-based composite coatings are being increasingly used in industry because of their unique combination of wear resistance, bond strength, corrosion resistance, erosion resistance, optical, magnetic, and electric–electronic properties, and biological, thermal-attack, and tribological properties. These properties of coatings are very important in surface-engineering applications.[3–7]

The adhesion between a coating and a substrate is an important factor for surface properties. The properties of a coating strongly depend on the chemical composition, spraying parameters, and topography of the substrate surface. To obtain very high resistance against wear, an intermediate bond coat must be used to eliminate stress between the substrate and coating.[1,3,5] Also, substrates must be cleaned by chemicals, and sand blasting improves the adhesion of coatings. Resistance to corrosion, a low density, and high impact resistance even at low service temperatures have increased the importance of polymer and polymer-composite coatings in engineering applications. Therefore, different materials, such as metals, ceramics, and polymer powders, can be used as coating materials by thermal spraying, including plasma-spraying (PS) processes. The PS process has been developed for a high degree of sophistication for metallic and ceramic coatings in industrial applications, but little information has been published about plastic coating applications in the literature. An important factor for using powders in coating applications with the PS process is low-cost, noncritical applications. The filler, additives, and fibers in the powders also increase the properties of the coating without affecting the spray-coating process. The resistance to corrosion, bond strength, and wear resistance of the coating are its main advantages. Also, flexible process parameters allow the use of the material and components in a wide range of industrial applications.[3–9]

TABLE I
Characteristics and Compositions of the Powders

	Powder type	
Property	Ni–Al (bond-coat powder)	Al–Si–polyester (top-coat powder)
Powder dimension range (μm)	44–125	15–50
Chemical composition (%)	95 Ni, 5 Al	48 Al, 12 Si, 40 polyester
Density (g/cm^3)	3.14	2.3
Powder dimension morphology	Spherical	Complex

This experimental study examines in more detail the properties of aluminum–silicon–polyester (Al–Si–polyester)-based coatings. The wear and morphological properties have been studied as functions of the coating thickness and spraying current. Because of its properties, Al–Si–polyester coatings have been suggested for surface-coating applications. Experimental results have shown that the PS current and coating thickness have a quite strong influence on the wear resistance and microstructural properties of coatings.

EXPERIMENTAL

Materials

Two kinds of powders were used in this study. Ni–Al was used as an intermediate bond-layer coat. Al–Si–polyester powder was used as a top coat. Both powders were supplied by Metco (Winterthur, Switzerland). The polyester powder particles had the proper morphology, and the aluminum and silicon particles had a complex morphology. These morphologies had an important role during the coating process in specifying the homogeneity of the coating. The characteristics and compositions of the powders are listed in Table I. The surface morphologies of the Ni–Al bonding coat and Al–Si–polyester powder were researched with optical microscopy and scanning electron micros-

copy (SEM), respectively. The powder surface morphologies are shown in Figure 1(a,b).

Coating process and sample preparation

The coatings were carried out with an automatic controlled PS machine (9 MB, Metco). The substrates were cleaned with the solvent trichloroethylene (Merck, Gernsheim, Germany) before the Ni–Al and Al–Si–polyester-based composite coating. After the cleaning process, the substrates were roughened with 30-μm alumina powder for better bond strength between the substrate and coating. The roughened surfaces were heated up to 100–150°C. After the heating process was completed, the coating operation was performed on the prepared substrates (SAE 1035 steel) with an angle to the substrate surface of approximately 60° with and without the Ni–Al bond coat. The substrate was controlled by an air jet during the PS process bonding the layer-coat and top-layer coatings. The Ni–Al bond-coat process was carried out with constant parameters (70 V and 500 A). The thickness of the bond coat was approximately 0.1 mm. The process parameters that were used during the Al–Si–polyester powder coating are listed in Table II. The Al–Si–polyester-coated surfaces were air-cooled at the indoor temperature after the coating process was completed.
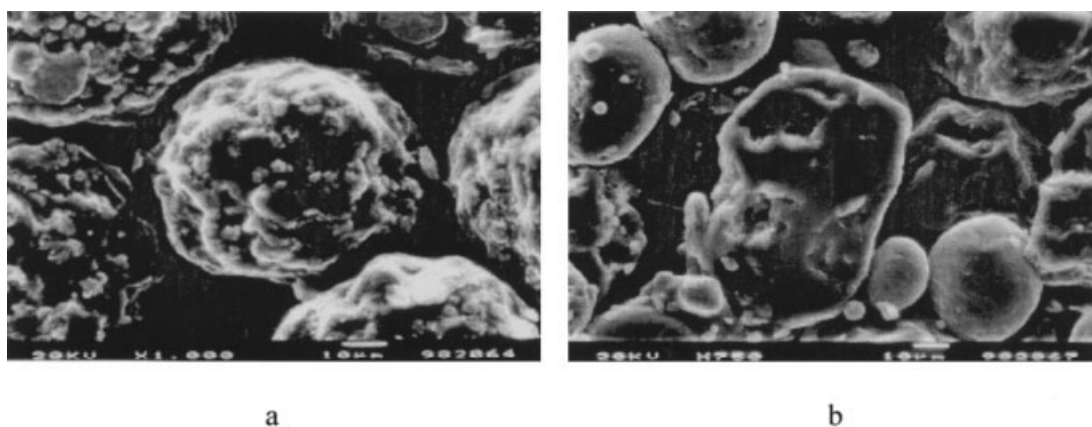
Figure 1 SEM micrographs of (a) Ni–Al (bond-coat powder) and Al–Si–polyester (top-coat powder).[3]

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Hydrogen flow rate (L/min)	8
Injector angle	60°
Plasma type	Ar + H$_2$
Substrate	SAE 1035 steel
Plasma current (A)	450, 500, 550
Arc voltage (V)	60, 70
Nozzle diameter (mm)	6
Nozzle distance (mm)	50–90
Powder feed rate (g/min)	30
Coating thickness (mm)	0.5–1–1.5–2
Argon flow rate (L/min)	80
Plasma-gun type	METCO 9 MB
Plasma-gun type	Ar + H$_2$
Carrier gas flow ratio (argon, L/min)	4.5
Nozzle and electrode	W cathode, Cu anode

Measurements

Wear-resistance tests were carried out on a ball-on-disk wear test machine at room temperature under dry conditions according to the ball-on-disk procedure.[10] As the counterpart, a steel ball with a 5-mm diameter was used. The force on the ball was 3, 5, or 7 N, and the total wearing distance was 20 m. Wear-resistance tests were carried out with cylindrical samples with a diameter of 25 mm and a length of 2 mm. The specimens were then subjected to wear tests (20 m) on a ball-on-disk test apparatus. The coating surfaces after the coating were cleaned with the solvent trichloroethylene for each test, and the load was applied against the samples by a weight-loading system. The specimen surfaces were cleaned with trichloroethylene after the wear tests. Every weight was determined on a precision balance with an accuracy of ±0.0001 g, and then the weight loss was calculated. For each specimen, the tests were carried out two times, and their averages were taken for evaluation. The variation of the wear resistance of the Al–Si–polyester coating is presented in Figure 2. The eroded surfaces and morphologies were characterized by light microscopy (Prior, Leica, Wetzlar, Germany) and SEM (model JSM 840, JEOL, Tokyo, Japan). The results of the evaluation of the coating surfaces for the polymer-based coatings with and without a bond-layer coat are presented in Figures 3–5. Before the SEM investigation was conducted, the samples were coated with gold to a thickness of 30 Å. The SEM investigation was performed at 20 kV after the samples were coated with gold for conductivity.

RESULTS AND DISCUSSION

The wear resistance is extremely important for the coating process. The wear resistances of Al–Si–polyester coatings measured with the ball-on-disk test[10] are shown in Figure 2(a–c). The wear values were low

at the beginning of the wear ball-on-disk test and then rose gradually. The wear-resistance values also strongly depended on the PS current and coating thickness. The plasma current is a significant parameter that can influence the porosity level of a coating material.[3,8,9] A high wear resistance (low material loss) was obtained at 500 A of plasma current with a bond coat [Fig. 2(b)]. This may be due to strong mechanical adhesion of the substrate, bond coat, and top coat. When the coating thickness increased, the mechanical adhesion that influenced the wear resistance de-
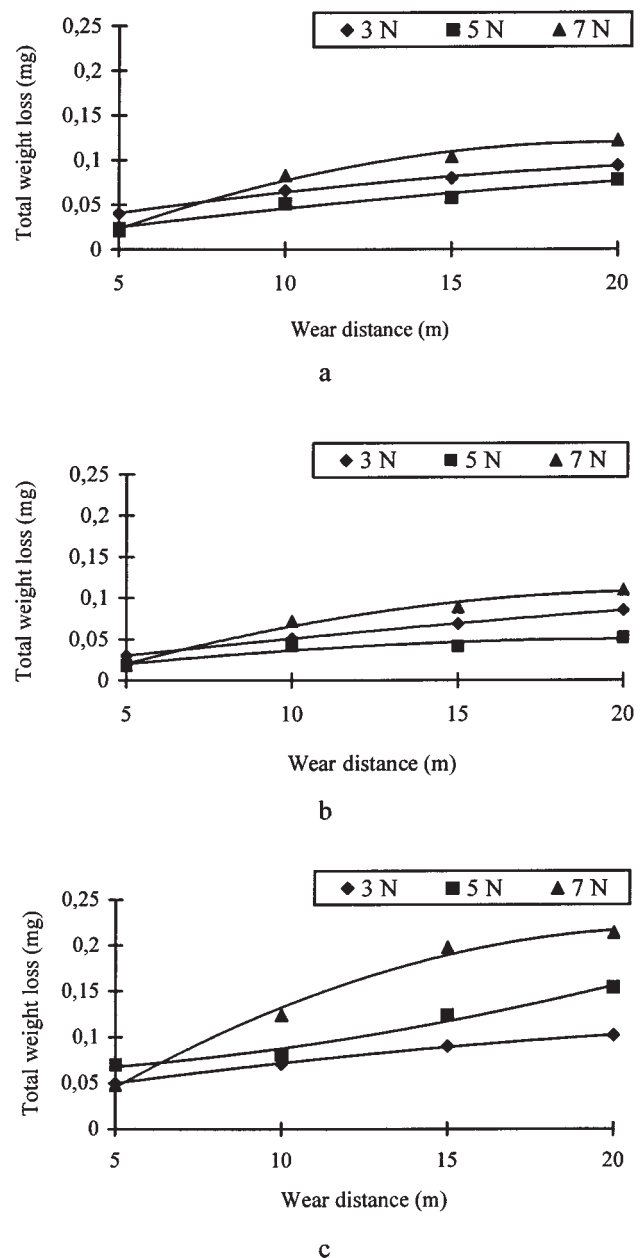

Figure 2 Variation of the wear resistance of Al–Si–polyester coatings (thickness = 1.5 mm): (a) $I = 450$, (b) $I = 500$, and (c) $I = 550$.
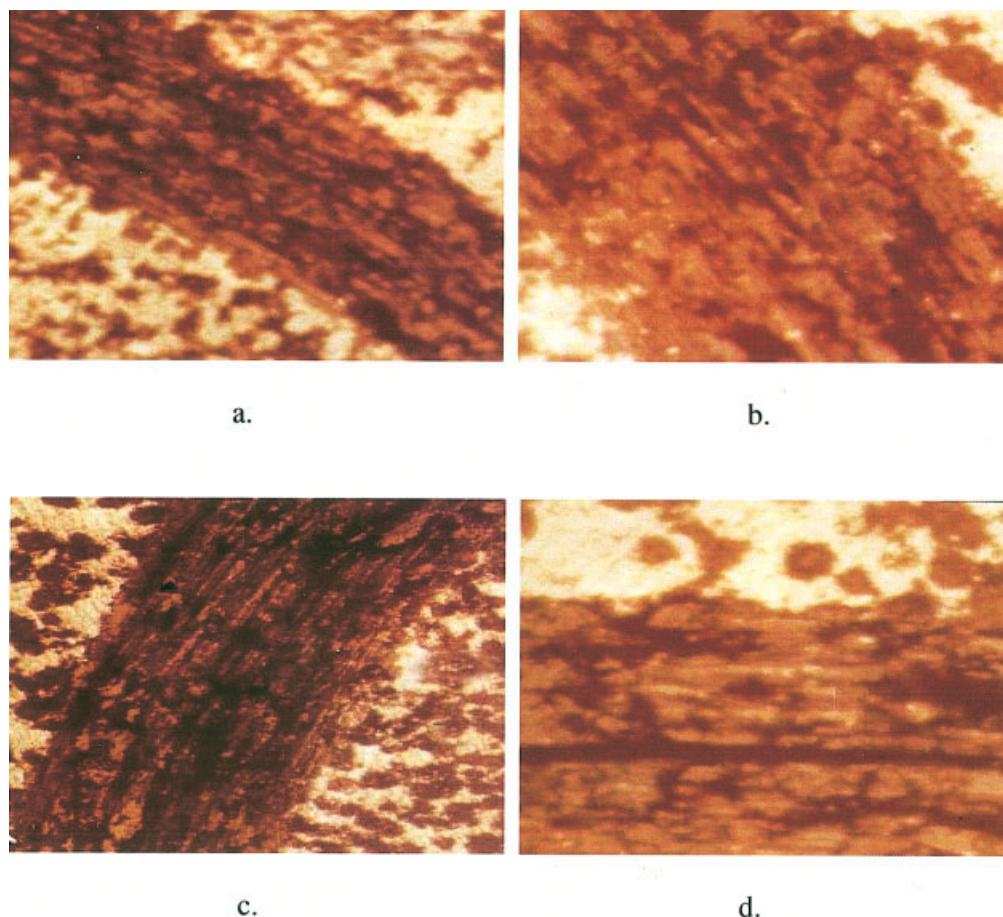
Figure 3 Wear track surface morphologies of Al–Si–polyester: (a) with a Ni–Al bond coat (wear tracks; coating thickness = 1.5 mm, I = 500 A), (b) without a Ni–Al bond coat (wear tracks; coating thickness = 1.5 mm, I = 500 A), (c) with a Ni–Al bond coat (wear tracks; coating thickness = 2 mm, I = 500 A), and (d) without a Ni–Al bond coat (wear tracks; coating thickness = 2 mm, I = 500 A). [Color figure can be viewed in the online issue, which is available at www.interscience. wiley.com.]

creased because of stress and shrinkage between the substrate surface and coating. This may be due to an exothermic reaction between the coating. Ni–Al also could reduce cracks in the coating structure because of slow cooling. The wear resistance of the coatings without the Ni–Al coat were low because of weak mechan-
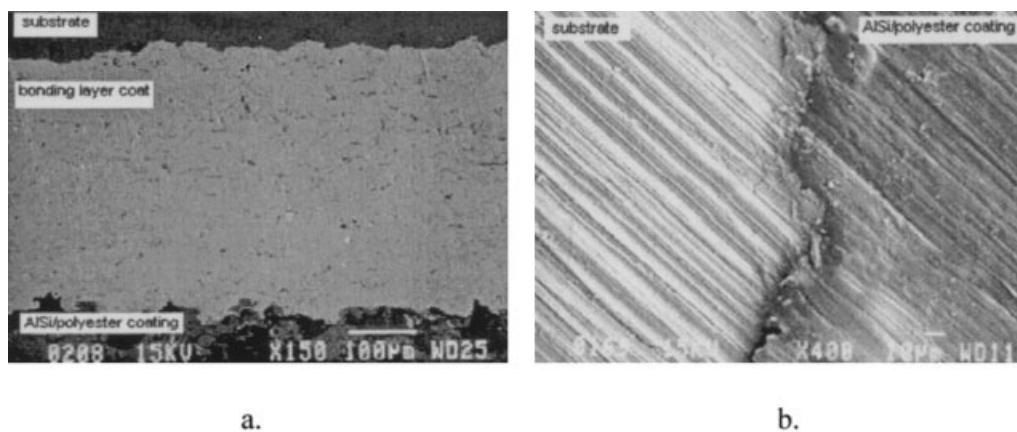
Figure 4 Cross sections of Ni–Al and Al–Si–polyester coatings: (a) with a bond coat (coating thickness = 1.5 mm, I = 500 A) and (b) without a bond coat (coating thickness = 1.5 mm, I = 500 A).[3]
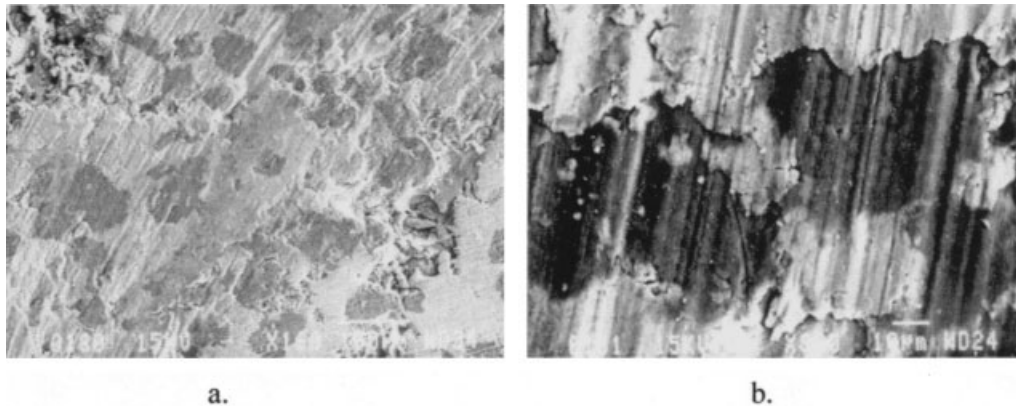
Figure 5 SEM morphologies and cross sections of Ni–Al and Al–Si–polyester coating: (a) with a bond coat (worn surface; coating thickness = 1.5 mm, I = 500 A) and (b) without a bond coat (worn surface; coating thickness = 1.5 mm, I = 500 A).

ical adhesion between the coating layers. To ensure good wear resistance (low material loss), the Ni–Al coat absolutely had to be used in this type of coating. Ni–Al not only reduced the stress and shrinkage but also prevented some porous microcracks. Microcrack that occurred because of fast cooling reduced mechanical adhesion, include wear resistance. Experimental studies showed that when the coating thickness was greater than 1.5 mm, the wear resistance decreased (high weight loss). Good results were obtained when a coating thickness of 1.5 mm and a current of 500 A were used [Fig. 2(b)]. The experimental results indicated that the wear resistance of the Al–Si–polyester coating strongly depended on the PS current. With the 450- and 550-A plasma current, the coating wear values were high [Fig. 2(a,c)]. A low material loss was obtained when the spraying current was 500 A. This was believed to be due to few or no microcracks. It was very important to control the coating spraying parameters, which corresponded to the mechanical properties, including the wear resistance and coating performance. Strong mechanical adhesion was important for the wear resistance of the coating. The experimental results showed that good wear resistance (low material loss) could be obtained, depending on strong mechanical adhesion between the substrates and coating layers.

The microstructural properties were examined by optical microscopy and SEM. Figure 3(a–d) shows views of the wear tracks formed on the Al–Si–polyester coating by light microscopy. The wear tracks of the coating [Fig. 3(a)] with a bond coat were narrow and not deep (coating thickness = 1.5 mm). The wear tracks of the coating [Fig. 3(b)] without a bond coat were large and deep (coating thickness = 1.5 mm). The wear tracks of the coating [Fig. 3(c); thickness = 2 mm] with a bond-coat layer were larger and deeper than the wear tracks of the 1.5-mm coating [Fig. 3(a)]. However, the coating produced without a bond coat showed larger wear tracks and a deeper area [Fig.

3(d); coating thickness = 2 mm]. The increasing coating thickness reduced the wear resistance because of stress that was applied to the coating.[3] Good wear results were ensured with a 500-A PS current. For the 450- and 550-A PS current coatings; the wear resistances did not strongly depend on the bond layer and exhibited the importance of the thickness of the polyester-based coating. This may be due to few or no microcracks and increasing plastic deformation with increasing thickness. Also, increasing the thickness caused inefficient adhesion between the coating layers.

Figures 4(a,b) and 5(a,b) show the wear tracks and cross sections of the Al–Si–polyester by SEM. High wear resistance (low material loss) was obtained with a bond coat during the experimental study. An increase in the coating thickness caused weak mechanical adhesion between the metal specimen and layers of the coating. The bonding that influenced the mechanical properties, including the wear resistance, depended on the bond coat. Therefore, strong mechanical bonding could be obtained between the metal specimen and coating [see the bond-coat-viewing cross section in Fig. 4(a,b) of the Al–Si–polyester]. Without a bond coat, because of fast cooling, the mechanical properties, including the wear resistance, decreased. The bond strength with a bond coat was much higher [Fig. 4(a)] than that of the coating not containing the Ni–Al bond coat [Fig. 4(b)]. Fast cooling makes a brittle structure break off faster and makes a cracked, porous structure.[3] Therefore, the microstructure of the coatings was important. The elasticity of the coating structure decreased because of stress and shrinkage inside the coating. The bond coat ensured thermal expansion equilibrium, which provided strong mechanical bonding properties. Consequently, the increase in the mechanical properties, including the wear resistance, was relatively clear. Stress and pores could cause a nonhomogeneous structure in the Al–Si–polyester coating. The high wear resistance of

the coating indicated the importance of the Ni–Al bond coat. Because Ni–Al stabilized thermal expansion, it eliminated stress.[3,4,8,9]

Experimental studies during this work showed that the coatings with and without Ni–Al contained microcracks. However, it is believed that the coating with the Ni–Al coat had fewer microcracks than the coating without Ni–Al. The coating thickness increased porosity in the structure that exhibited weak mechanical adhesion [Fig. 4(b)]. The coatings with Ni–Al had increased high wear resistance [less weight loss in Fig. 2(b)]. To obtain high wear resistance, Ni–Al had to be used in this type of coating. The spraying distance between the nozzle and substrate material also affected the wear resistance of the coating. When the spraying distance increased (from the nozzle to the substrate) during particle transfer, it is thought that melting occurred. The porosity of the coating with Ni–Al was much less than that of the coating without Ni–Al. This was thought to be due to not many cracks. When Ni–Al was used, microcrack observations decreased during SEM observation [Fig. 5(a)]. Cracks were observed much more in the Al–Si–polyester coating without Ni–Al [Fig. 5(b)].

CONCLUSIONS

The effects of PS parameters on the wear and microstructural properties of Al–Si–polyester-based coatings with and without an intermediate bond coat (Ni–Al) were investigated. The following conclusions were drawn from this experimental study. The PS current and thickness of the coating played an important role in the wear resistance. The presence of the Ni–Al coat increased the wear resistance of the coating. The Ni–Al coat decreased the microcracks and porosity of the coating. A plasma current of 500 A ensured high resistance to wear with the Ni–Al coat. The wear resistance decreased (high material loss) without the Ni–Al bond coat. This experimental work also indicated that the Ni–Al bond coat was very effective at reducing microcracks and was a good addition for this type of coating in terms of high bond strength.

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