

# Wear resistance of plasma sprayed Al–Si binary alloy coatings on A6063 Al alloy substrate

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## Abstract

To improve the wear resistance of the aluminum (Al) alloy low pressure, plasma spraying was employed to form a hyper eutectic Al–Si binary alloy coating on A6063 aluminum alloy substrate by using tentatively made powders with different Si contents from 20 to 70 mass%. Dense coatings with approximately 200  $\mu\text{m}$  in thickness were made on a substrate for each powder and no cracking and peeling occurred in the coatings. Hardness of the coatings increased with increasing Si content and reached approximately 570 HV at approximately 70 mass% Si. Wear resistance of the coatings evaluated by ball-on-disc wear test increased with increasing Si content to one third of that of the substrate at more than 50 mass% Si. Friction coefficient of the coating was approximately 0.4 at more than approximately 30 mass% Si and lower than that of the substrate, approximately 0.6. Estimated bond strength of the coating is at least approximately 20 MPa or higher irrespective of Si content. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Plasma spraying; Aluminum alloy substrate; Aluminum–silicon alloy coating; Hardness; Wear; Adhesion

## 1. Introduction

Aluminium (Al) alloy is one of the key materials of weight-saving the industrial products, especially in automobile and railroad car industries. In order to apply Al alloys to the machine parts used at the wear condition, improving wear resistance is imperative because of lower wear resistance of Al alloy to that of steel material. However, there is no convenient technology for anti-wear surface treatment of Al alloys such as carburizing and/or quenching for steels with a low cost and capability of mass production. Therefore, to improve the wear resistance of Al alloy, many kinds of surface modification processes have been tried and some of them are applied in practice [1]. Among coating processes, thermal spraying is the superior one, capable of coating a thick layer with approximately several hundred micron meters in short operating time,

thus is widely used in industrial products of steel materials. Until now, the application of thermal spray coating to Al alloy substrate is limited. Recently, however, research in this area has progressively increased [2–18]. As coating materials, metallic, cermet and ceramic materials were used, but there is little research on the combination of the coating material of Al alloy and the substrate of Al alloy [7–10,13,17]. Aluminum-base metal matrix composite with SiC, TiC,  $\text{Al}_2\text{O}_3$  [7,9,10,17] and polyimide [8] as reinforcement, was applied as the coating material. In our previous report [13], the authors have briefly showed the possibility of coating a wear resistant Al alloy layer by using highly alloyed Al powders with Si and/or Fe. In this work, as a coating material we focused Al–Si hyper eutectic alloys with different Si contents up to approximately 70 mass% and evaluated the effect of Si content on the properties of the coatings, mainly wear resistance and adhesion strength to the Al alloy substrate by using the low pressure plasma spraying process.

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Table 1  
Chemical compositions of materials used

Alloy designation		Chemical composition (mass%)	
		Si	Mg
Substrate	A6063	0.45	0.55
	Al-20Si	18.8	–
	Al-30Si	29.1	–
	Al-40Si	37.5	–
Powder	Al-50Si	45.5	–
	Al-60Si	58.8	–
	Al-70Si	69.0	–

## 2. Experimental details

### 2.1. Materials used

An A6063 (Al-0.55 mass% Mg-0.45 mass% Si) alloy plate of dimensions  $50 \times 60$  mm and thickness 6 mm was used as the substrate. Al–Si hyper eutectic alloy powders containing different Si contents from approximately 20 to 70 mass% were used as a coating material, which were tentatively made with a rapid solidification method by atomizing a molten alloy into running water [19]. Powder size was approximately 80  $\mu\text{m}$  in mean diameter with a size distribution from 53 to 105  $\mu\text{m}$ . Composition of these powders are shown in Table 1.

Fig. 1 shows scanning electron microscope (SEM) microstructures of the cross-section of powders, which

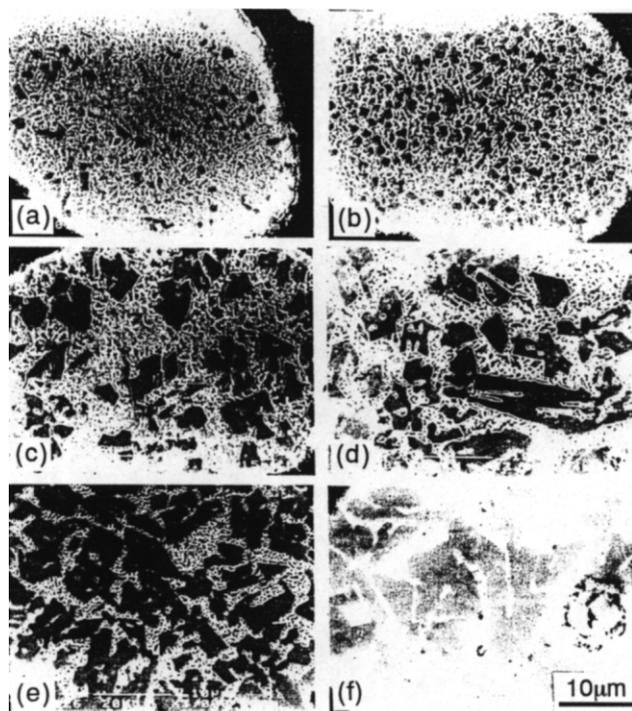


Fig. 1. SEM microstructures of the powders on the cross-section, (a) Al-20Si, (b) Al-30Si, (c) Al-40Si, (d) Al-50Si, (e) Al-60Si and (f) Al-70Si.

consist of primary Si particles and surrounding  $\alpha$  Al + Si eutectic structure. Fine and uniform distribution of primary Si particles with 1–2  $\mu\text{m}$  in diameter was formed at approximately 20–30 mass% Si by rapid solidification. Volume fraction and particle size of primary Si particles increased as increasing Si content. Coarse primary Si particles with plate-like or rod-like shapes with 20–30  $\mu\text{m}$  in length began to appear at approximately 50 mass% Si and became dominant at more than approximately 60 mass% Si.

### 2.2. Methods

Low pressure plasma spraying in a vacuum chamber was employed to prevent oxidation of the powder during spraying. An Ar–H<sub>2</sub> gas mixture was used as a plasma gas, with flow rates of 47 l/min of Ar and 7 l/min of H<sub>2</sub> at a plasma power of 32.4 kW (600 A and 54 V) under a chamber pressure of 27 kPa. Powder feed rate was 20 ml/min with Ar as the carrier gas and spraying distance was 250 mm. These conditions were selected from the result of our previous work [13]. Before spraying, the substrate surface was blasted with Al<sub>2</sub>O<sub>3</sub> powders of 710–850  $\mu\text{m}$  by compressed air abrasive blasting equipment at blasting pressure of 0.7 MPa to ensure surface cleaning. With this spray condition, a spray coating of 150–200  $\mu\text{m}$  thickness was formed. The structure of the coating was studied by SEM with EDX and X-ray diffraction analysis. Hardness measurement with a 0.5 N load was performed on the spray coating cross-section. The wear resistance of the coating was evaluated with a ball-on-disc type sliding wear tester. The test was done at the condition in air without lubricant by using Al<sub>2</sub>O<sub>3</sub> ceramic counter ball of 6.35 mm in diameter with a total sliding distance of 100 m at a sliding speed of 150 mm/s and a load of 10 N. The wear resistance was evaluated with the depth of a wear track measured with a non-contact profile meter.

The bond strength of the spray coating to the substrate was measured by a tensile test using the specimen as shown in Fig. 2. Spray coatings were deposited on the surface of a cross-section of a cylinder substrate, 25 mm in diameter and its surface was then joined to a counter specimen by epoxy resin adhesive. Tensile testing was done perpendicular to the interface between the coating layer and the substrate with a constant crosshead speed of 0.5 mm/min. After the tensile test, the fracture position was determined by SEM observation on the fracture surface.

## 3. Results and discussions

### 3.1. Structure

Optical photos of the microstructures of spray coat-

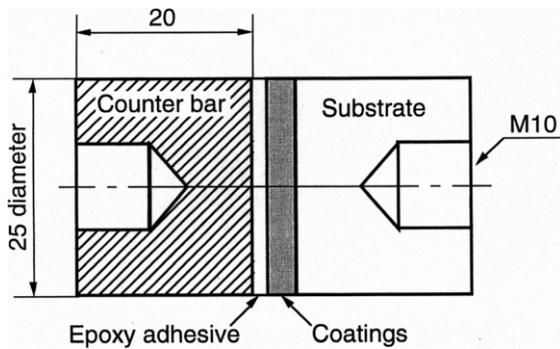


Fig. 2. Tensile test specimen for measuring bond strength of spray coating.

ings in cross-section are shown in Fig. 3a,b,c for Al-30Si, -50Si and -70Si, respectively. All the coatings formed are dense without large porosity, and there is no cracking in the coatings or in the interface between coatings and the substrate. The structure of the coating consist macroscopically of two regions, one is a matrix of the coatings and the other is an island-like or banded structure observed with bright tone in the relatively dark matrix structure. In the matrix of spray coatings, fine primary Si particles are uniformly distributed irrespective of Si content. Their particle sizes are sub-micron to several micron even at approximately 70 mass% Si. They are much smaller than those in the original powders in comparison with Fig. 1. This seems to be due to the effect of rapid solidification at the collision of fully-melted powders on the coating surface. In contrast, relatively large Si particles are even observed obviously as an island-like or banded structure and their shapes and sizes are quite similar to those of primary Si particles in each original powder. This suggests that the powders with relatively large size were not fully melted in plasma flame and partially melted powders formed these typical structures due to their insufficient deformation on the coating surface at the collision. Increasing Si content tends to inhibit the deformation of deposited powders and good bonding

between them due to coarse plate- or rod-like primary Si as clearly seen in Fig. 3c.

### 3.2. Hardness

Hardness profiles in the coating cross-sections are shown in Fig. 4. Uniform hardness distribution was obtained in each coating, though small irregular in data was observed in Al-70Si. The hardness of each coating was much higher than that of the substrate Al alloy, 50 HV. The mean hardness of each coating increased monotonically with increasing Si content as shown in Fig. 5 and reached 570 HV in maximum at approximately 70 mass% Si. It seems that hardness increase results from dispersion strengthening by hard primary Si particles, of which hardness is approximately 870–1350 HV [20].

### 3.3. Wear resistance

Fig. 6 shows typical wear tracks on the coatings and surface appearance of counter  $\text{Al}_2\text{O}_3$  balls showing some adhesions on their surfaces after ball-on-disc test. These photos show clearly the effect of spray coatings on increasing wear resistance. The substrate shows severe damage by wear test and much adhesion on the surface of counter ball. On the contrary, spray coatings show much less wear on their surface and less adhesion to the counter ball. Thus, the friction coefficient of the coating measured during wear test decreased to approximately 0.4 at more than approximately 30 mass% Si, which is lower than that of the substrate, approximately 0.6 as shown in Fig. 7.

Fig. 8 shows the effect of Si content of the coatings on the wear depth of wear track measured by a non-contact profile meter. As Si content increased, wear depth decreased sharply up to approximately 40 mass% Si and almost saturated to one third of that of the substrate at more than 50 mass% Si, but slightly decreased at approximately 70 mass% Si due to the brittleness of coarse primary Si particles. A similar

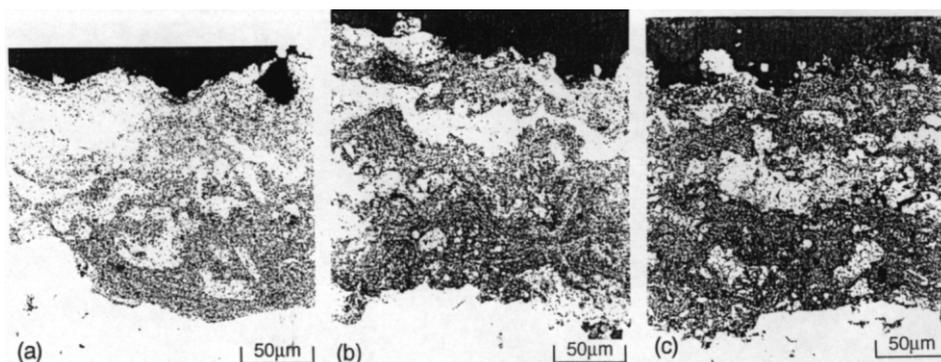


Fig. 3. Optical photos of microstructures of spray coatings on the cross-section, (a) Al-30Si, (b) Al-50Si and (c) Al-70Si.

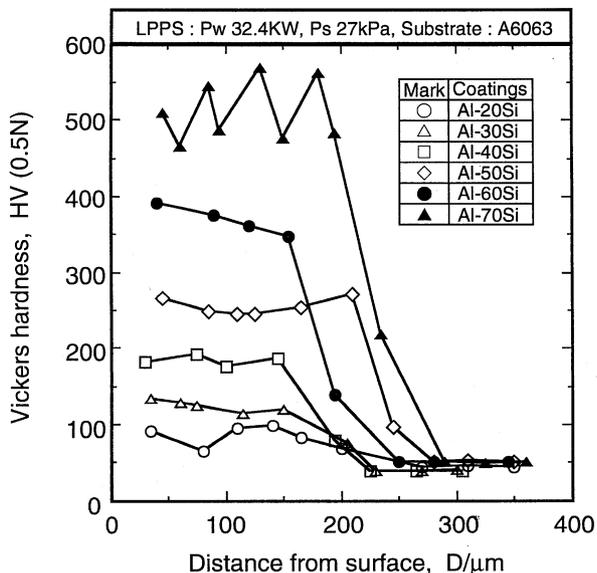


Fig. 4. Hardness profiles in the coating cross-sections.

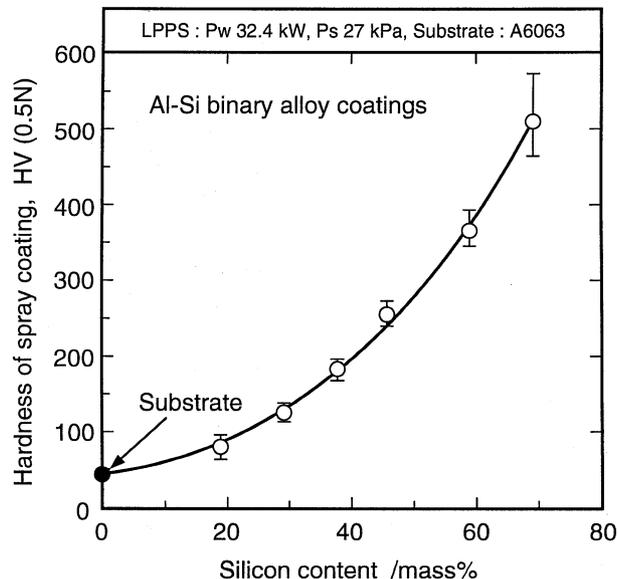


Fig. 5. Effect of Si content on hardness of the coating.

relationship is obtained between the wear depth and hardness of the coatings as shown in Fig. 9. Wear depth decreased linearly as increasing hardness and saturated at more than approximately 200 HV of the coatings.

3.4. Bond strength

According to our previous study [13], blasting pressure affects the bond strength at Al<sub>2</sub>O<sub>3</sub> blasting of the substrate surface before thermal spraying. To ensure good bond strength, 0.7 MPa was adopted as blasting pressure. The bond strength of each coating to the substrate ranged from 20 to 30 MPa irrespective of Si content, but in most cases, the fracture occurred at the adhesive itself between a counter bar and the coatings. Only one specimen showed the fracture between the

coating and the substrate, which indicated 31 MPa. Therefore, this suggests that the bond strength of these coatings to the Al alloy substrate is at least approximately 20 MPa or higher, which reaches the same level measured at plasma spraying of steel coating on Al alloy substrate [15].

4. Conclusions

To improve the wear resistance of the Al alloy substrate low pressure plasma spraying was employed to form a hyper eutectic Al–Si binary alloy coating on A6063 Al alloy substrate by using tentatively made

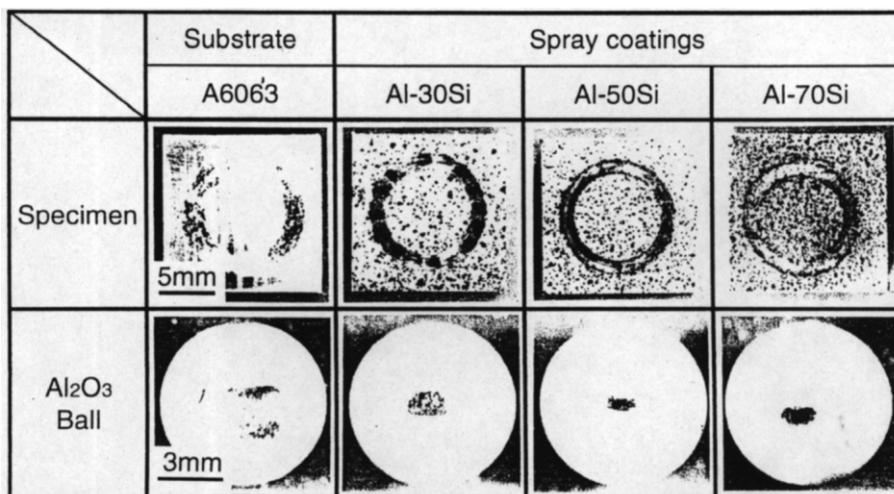


Fig. 6. Typical wear track on the coating and surface appearance of Al<sub>2</sub>O<sub>3</sub> counter ball after ball-on-disc test.

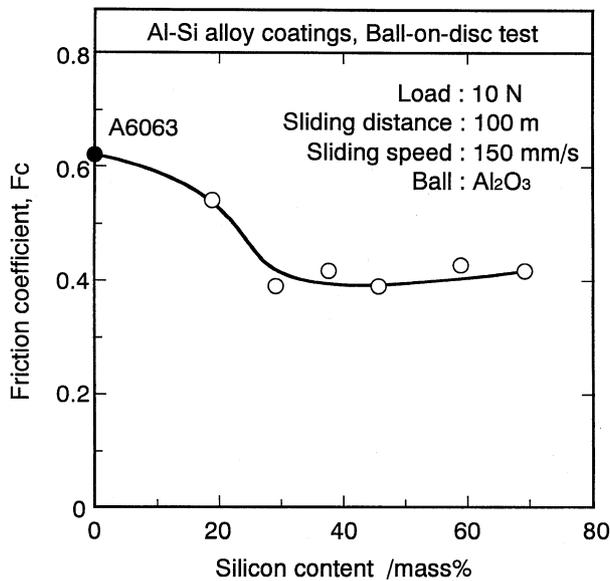


Fig. 7. Effect of Si content on Friction coefficient of the coating evaluated by ball-on-disc test.

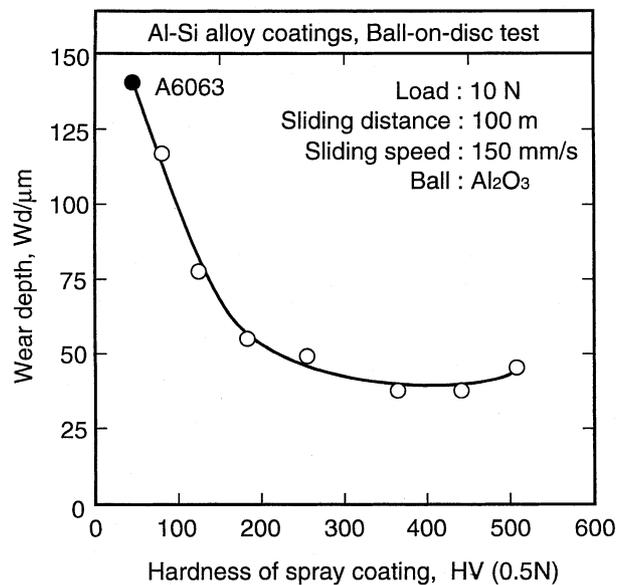


Fig. 9. Relation between wear depth of wear track and hardness of the coating.

powders with different Si contents from 20 to 70 mass%. The main conclusions obtained are as follow:

1. All the coatings formed are dense without large porosity, and there is no cracking and peeling neither in the coatings nor in the interface between coatings and the substrate.
2. The coatings consist of a matrix with uniformly distributed fine primary Si particles irrespective of Si content, which are much smaller than those in the original powders and their particle sizes reach sub-micron to several micron even at approxi-

mately 70 mass% Si. Island-like or banded structure also observed in the matrix with relatively large Si particles are quite similar to those of primary Si particles in each original powder due to incomplete fusion in the plasma flame.

3. Hardness of the coatings increased monotonically with increasing Si content and reached approximately 600 HV at 70 mass% Si due to increasing volume fraction of hard primary Si particles.
4. Wear resistance of the coatings evaluated by the wear track depth increased with increasing Si content sharply up to approximately 40 mass% Si and almost saturated to one third of that of the substrate at more than 50 mass% Si. Friction coefficient of the coating decreased to approximately 0.4 at more than approximately 30 mass% Si and lower than that of the substrate, approximately 0.6.
5. Estimated bond strength of the coating is at least approximately 20 MPa or higher irrespective of Si content.

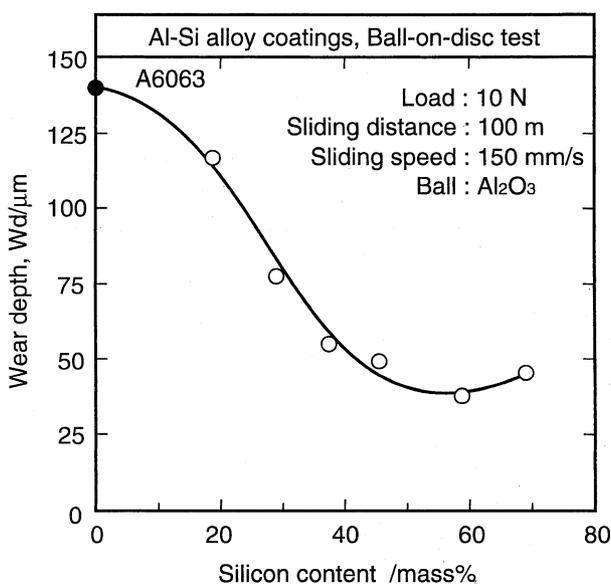


Fig. 8. Effect of Si content on wear depth of wear track evaluated by ball-on-disc test.

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