

# Al RICH HARD COATINGS ON Al ALLOY BY LOW PRESSURE PLASMA SPRAYING

K. Nakata and M. Ushiroda

*In order to improve the wear resistance of an Al alloy surface, a low pressure plasma spray coating has been applied to make a hard coating. An A6063 alloy was used as the substrate, with coatings of rapidly solidified powders of the alloys Al-50Si, Al-17Si-15Fe, and Al-50Fe. Dense layers with high hardness of 200–240 and 450–530 HV were obtained with Al-50Si and Al-17Si-15Fe powders, respectively. The abrasive wear resistance of these coatings improved by two and three times respectively on that of A6063. A much higher hardness of 700–850 HV was obtained with Al-50Fe powder, but porosity and cracking*

*occurred in the layer. These defects prevented an improvement of the abrasive wear resistance of the coatings compared to those of Al-50Si and Al-17Si-15Fe powders.*

*The authors are at the Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka 567, Japan. Contribution to the 10th International Conference on Surface Modification Technologies held in Singapore on 2–4 September 1996.*

© 1997 The Institute of Materials.

## INTRODUCTION

Surface hardening of Al alloys has recently been under investigation as a means of improving wear properties so that steel parts can be exchanged for Al parts thus achieving weight savings in many kinds of products, for example machine and automobile parts. Recent Japanese activities<sup>1–11</sup> in this area are reviewed in Ref. 12, according to which surface hardening processes of Al alloys are classified into two groups: surface melting and alloying; and coating. The former enables the formation of a thick (millimetres) hardened layer by using a fusion process with a high energy density heat source such as a plasma arc, laser beam, or electron beam. However, surface finishing of an alloyed layer is unavoidable. On the contrary, the coating process gives a lesser heating effect on a substrate than the alloying process and in most cases does not necessitate surface finishing of the coating layer. Among coating processes, spray coating has a high potential to form a hard layer on an Al alloy surface in a layer of several hundred micrometres with high deposition rate. However, there are few studies<sup>13–16</sup> on the hard coating of Al alloy substrates by spraying with Al base coating materials.

In this study Al rich highly alloyed powders, made by atomising into water, were used to form a coating layer. The effects of spraying conditions and the compositions of powders on the structure, hardness, and wear resistance of the coated layer are discussed, and the effect of substrate surface treatment on adhesive properties of the coated layer is also evaluated.

## EXPERIMENTAL DETAILS

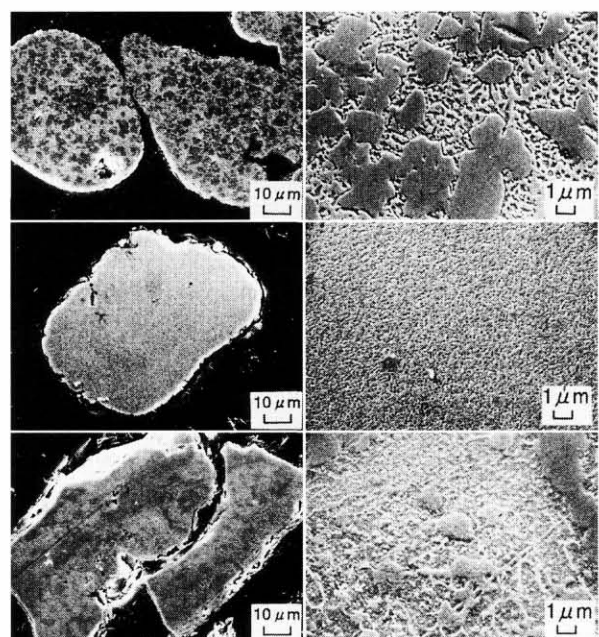
### Materials

An A6063 (Al-0.55Mg-0.45Si) alloy plate of dimensions 50 × 60 mm and thickness 6 mm was used as the substrate. Three Al alloy powders having different structures were used to form hard coatings. Figure 1 shows the microstructures of these powders. Al-50Si powder has a simple hypereutectic structure showing hard primary Si particles dispersed in the Al alloy matrix. Al-17Si-15Fe powder has a similar structure, but the matrix dispersoid is changed to fine intermetallic compounds, although these were

not identified by X-ray diffraction, as shown in Fig. 2. Al-50Fe powder consists of hard intermetallic compounds only. These powders were made with a rapid solidification method by atomising a molten alloy into running water.<sup>17</sup> Powder size was about 80 µm (mean dia.) with a size distribution from 53 to 105 µm.

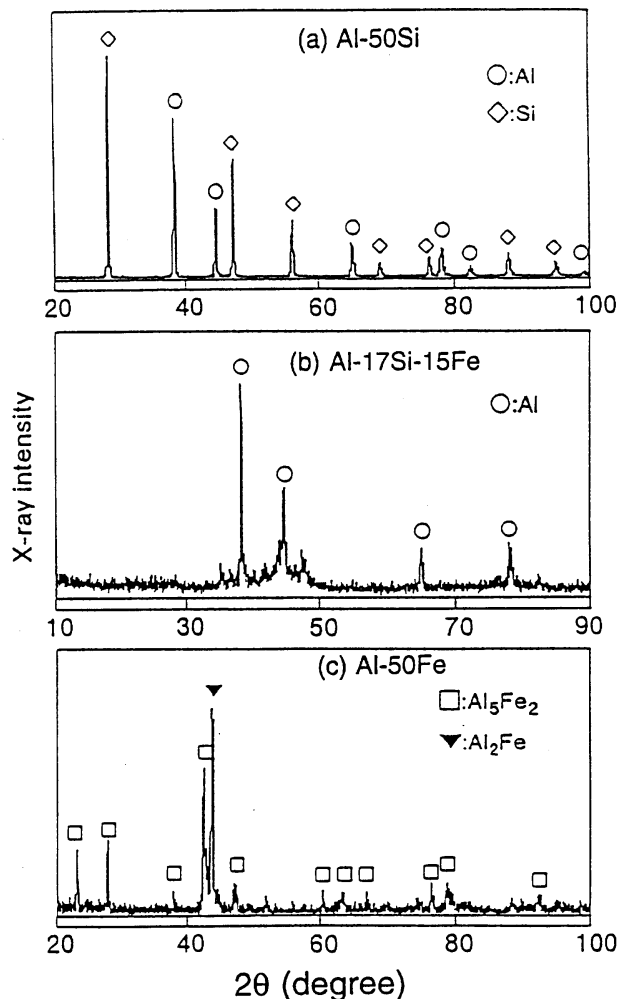
### Methods

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 flowrates of 47 L min<sup>-1</sup> of Ar and 7 L min<sup>-1</sup> of H<sub>2</sub>. Chamber pressure was varied from 0.7 × 10<sup>4</sup> to 4.0 × 10<sup>4</sup> Pa at a constant plasma power of 32.4 kW (600 A and 54 V). Powder feedrate was 20 mL min<sup>-1</sup> with Ar as the carrier gas, and spraying distance was 250 mm. These parameters were kept



a Al-50Si; b Al-17Si-15Fe; c Al-50Fe

1 Scanning electron micrographs of Al alloy powder microstructures

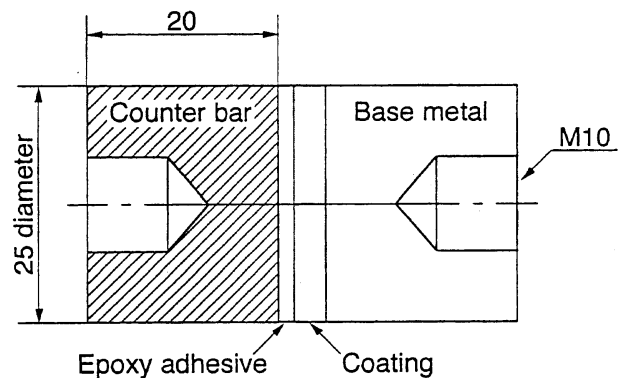


2 X-ray diffraction patterns for Al alloy powders

constant. Before spraying, the substrate surface was blasted with  $\text{Al}_2\text{O}_3$  powders of 710–850  $\mu\text{m}$  by compressed air abrasive blasting equipment to ensure surface cleaning. Blasting pressure was varied up to 0.7 MPa to examine the effect of blasting on adhesion strength of the spray coatings.

With these spray conditions a coating of 150–200  $\mu\text{m}$  thickness was applied. The structure of the coatings was studied by SEM 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 coatings was evaluated with a Suga type abrasive wear tester, which abrades the coating surface with a 320 grit SiC sandpaper as a counter disc by a shuttle movement with a stroke of 13 mm and a total wear distance of 2.6 m at a load of 9.8 N. The wear volume of an abraded track was measured to evaluate abrasive wear resistance.

Coating to substrate adhesion strength was measured by a tensile test using a specimen as shown in Fig. 3. 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 coating and substrate with a constant crosshead speed of 0.5 mm  $\text{min}^{-1}$ . After the tensile test, the fracture surface was evaluated by SEM to determine the fracture position.



3 Schematic illustration of specimen for tensile test to evaluate coating adhesion strength

## RESULTS AND DISCUSSION

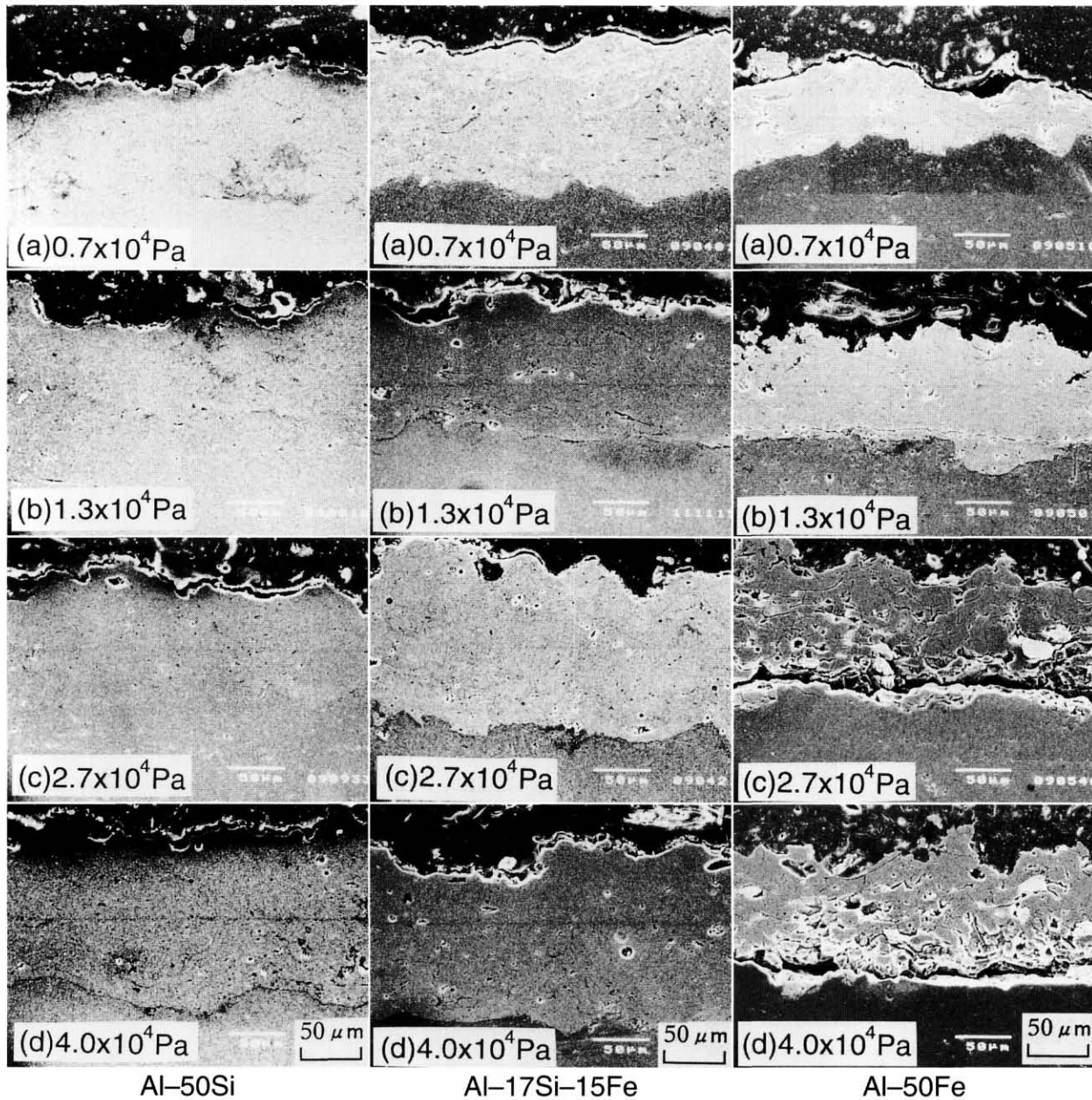
### Structure

Figure 4 shows the structures of cross-sections of the spray coatings at different spraying pressures. A dense and defect free coating could be obtained for Al–50Si and Al–17Si–15Fe coatings, though porosity appeared in Al–17Si–15Fe coatings and slightly increased with increasing spraying pressure. On the contrary, significant porosity and cracking were formed in the Al–50Fe coatings and at their interface with the substrate, irrespective of the spraying pressure, and these defects were inclined to increase with increasing spraying pressure. Figure 5 shows high magnification photos of the structures of the cross-sections of coatings produced at  $2.7 \times 10^4$  Pa. In Al–50Si coatings, primary Si particles with large grain size of about 5–10  $\mu\text{m}$  and very fine grain size in the submicrometre to micrometre range were observed; the proportion of large Si particles increased with decreasing spraying pressure. In Al–17Si–15Fe coatings no second phase was obvious, and in Al–50Fe coatings large cracks along the interface and many fine cracks in the coatings appeared. These results indicate that the integrity of the coatings depends more on powder composition than on spraying pressure. Al–50Fe powder has a high melting point (about 1453 K) and is brittle; Al–50Si and Al–17Si–15Fe powders have lower melting points (about 1313 and 1173 K)<sup>18</sup> and are not so brittle.

Figure 6 shows typical X-ray diffraction patterns obtained from the surfaces of coatings made at  $2.7 \times 10^4$  Pa. These patterns were almost the same as those of the starting powders, though peaks of intermetallic compounds appeared in Al–17Si–15Fe coatings. Al–50Si and Al–17Si–15Fe coatings have the same type of structure, with Si in the Al–50Si coating and  $\text{Al}_3\text{Fe}$  and Al–Si–Fe system intermetallic compounds in the Al–17Si–15Fe coating dispersed in the Al alloy matrix. By contrast, in Al–50Fe coatings no peak of Al was observed; only the intermetallic compounds  $\text{Al}_2\text{Fe}$  and  $\text{Al}_5\text{Fe}_2$  were detected.

### Hardness

Figure 7 shows the hardness distribution in the coating cross-sections. Uniform hardness distribution was obtained in Al–50Si and Al–17Si–15Fe coatings; their hardnesses reached about 240 and 530 HV, respectively, which were much higher than that of the substrate Al alloy (50 HV). It seems that these



4 Scanning electron micrographs of cross-sectional microstructures at various spraying pressures

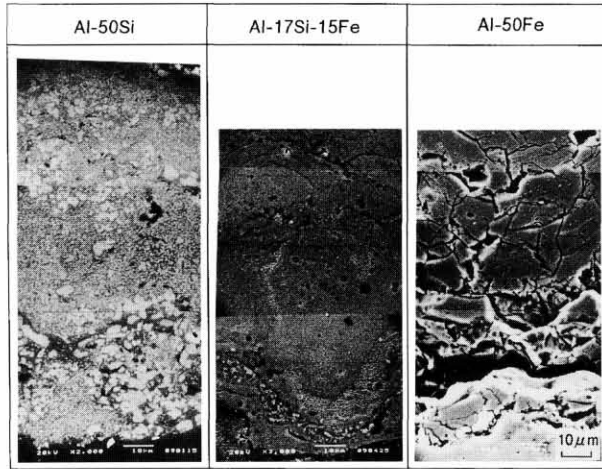
hardness increases result from dispersion strengthening by fine primary Si particles or intermetallic compounds. Al-50Fe coatings showed much higher hardness, 700–850 HV, which corresponds roughly to that of iron aluminide, though an irregular hardness distribution was measured, resulting from the porosity and cracking.

Figure 8 shows the relationship between spraying pressure and coating hardness. The influence of spraying pressure on the hardness of coatings was small, excepting the lowest spraying pressure ( $0.7 \times 10^4$  Pa), at which hardness was lower. Higher pressures produced almost constant values of hardness. The plasma flame elongates exponentially with the decrease in spraying pressure, and at  $0.7 \times 10^4$  Pa it came into contact with the substrate, thus preventing rapid solidification and cooling of the coatings owing to overheating by the plasma flame. Therefore, in the dispersion strengthening type coatings (Al-50Si and Al-17Si-15Fe) a decrease in hardness appeared.

Al-50Fe coatings, however, showed little dependence of hardness on spraying pressure, because they consist of intermetallic compounds themselves. The decrease in scatter in hardness values in Al-50Fe coatings is explained by the less extensive cracking and porosity at lower spraying pressures (Fig. 6).

#### Wear resistance

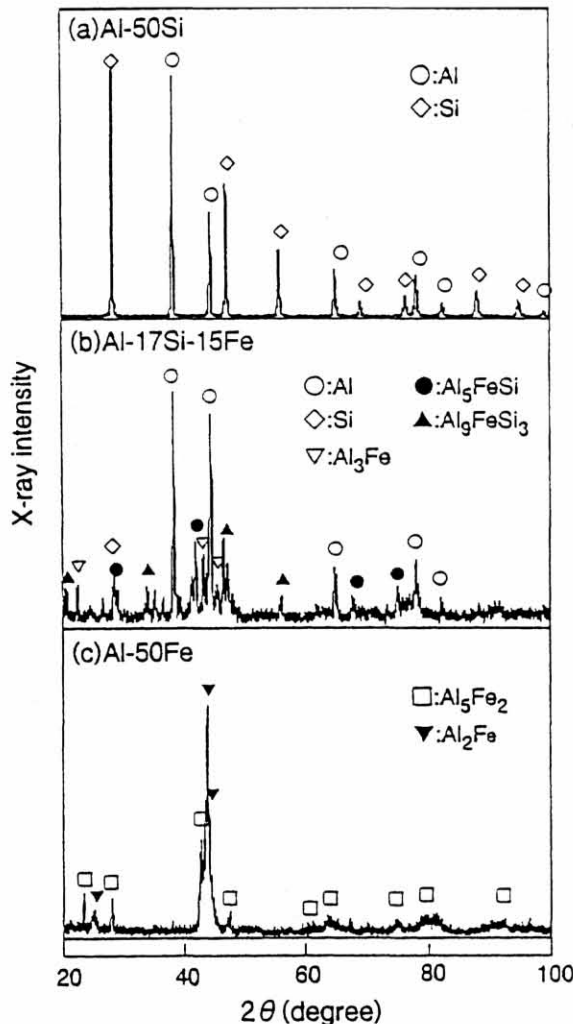
Figure 9 shows Suga type abrasive wear test results. Relative wear losses  $W_R$  give the ratios of the wear volume for each coating to that of the substrate. Values of  $W_R$  for Al-50Si and Al-17Si-15Fe coatings decreased abruptly to half and one third of the substrate values as the hardness increased, but  $W_R$  of Al-50Fe coatings did not decrease to the same extent with hardness because of the brittleness of the iron aluminide coatings, containing much porosity and cracking. This means that the combination of integrity and hardness of coatings is very important in improving wear resistance.



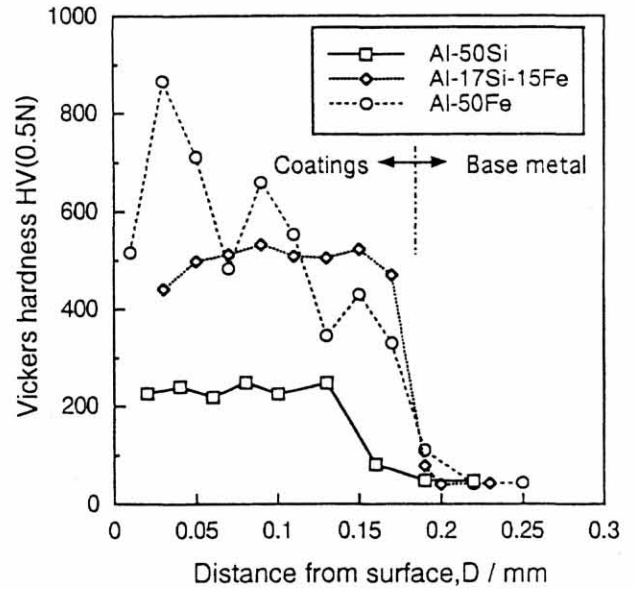
5 High magnification SEM micrographs of cross-sectional coating microstructures:  $2.7 \times 10^4$  Pa spraying pressure

**Adhesion strength**

Figure 10 shows the effect of blasting pressure on the substrate adhesion strength of coatings at a spraying pressure of  $2.7 \times 10^4$  Pa. Fracture mode (related to fracture position) is classified into three types as shown in the inset. Mode A corresponds to an excellent adhesion strength as the fracture position is in the epoxy resin adhesive at the interface between

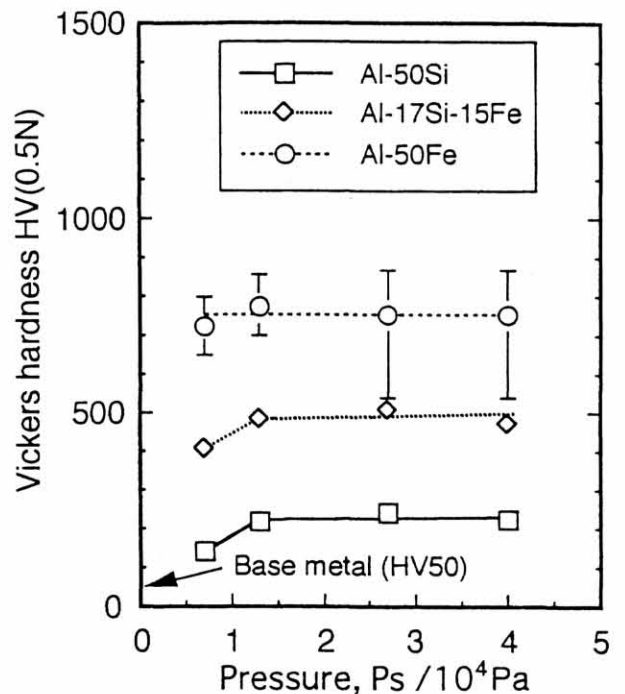


6 X-ray diffraction patterns for spray coatings

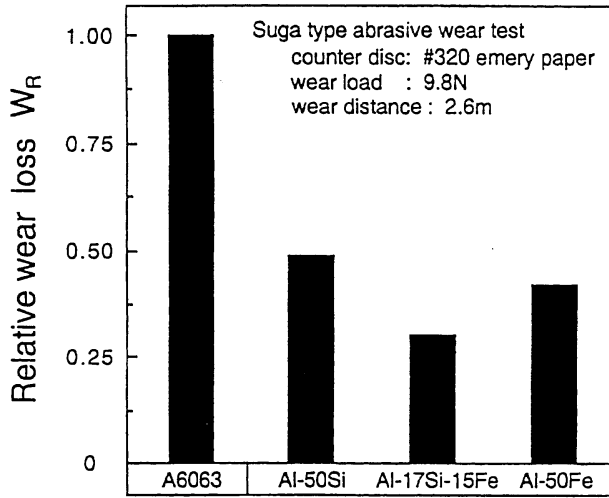


7 Hardness distributions in coating cross-sections

counter bar and the coating. Mode B shows poor adhesion strength as the fracture position is at the interface between coating and substrate. Without blasting treatment, the adhesion strength was nil, but this increased with increasing blasting pressure. This confirms the necessity of blasting treatment to ensure good adhesion of coating to substrate. Al-50Si coatings had higher adhesion strength than Al-17Si-15Fe coatings and the fracture mode changed from mode B to mode C at blasting pressures above 0.4 MPa, though Al-17Si-15Fe coatings showed mode B irrespective of the blasting pressure. Al-50Fe coatings were not tested. It is well known that blasting treatment increases substrate surface roughness (as shown in Fig. 11) and increases adhesion strength by an anchoring effect as well as the surface cleaning effect.



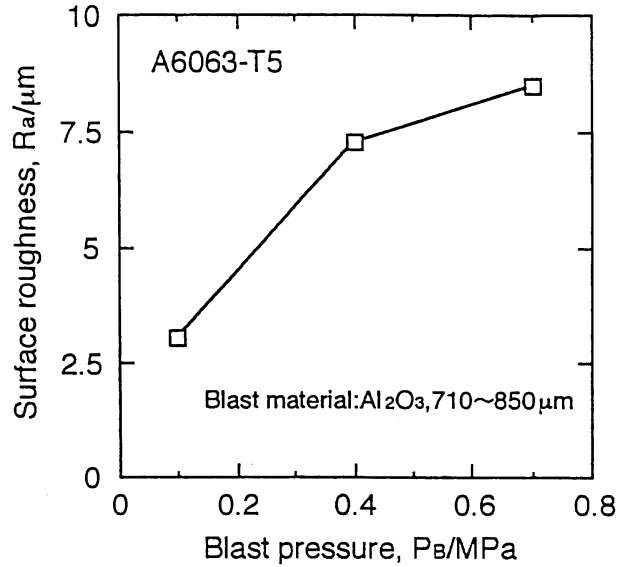
8 Variation of coating hardness with spraying pressure



9 Abrasive wear test results comparing coatings with substrate

**CONCLUSIONS**

Spray coatings with high hardness and wear resistance can be obtained on an Al alloy substrate by low pressure plasma spraying using Al rich highly alloyed powders. Their structure should consist of fine dispersoids such as Si or intermetallic compounds, in an Al alloy matrix, in order to avoid porosity and cracking. By using Al-50Si and Al-17Si-15Fe powders, coatings with 200-240 and 450-530 HV hardness respectively and improved abrasive wear resistance were obtained.



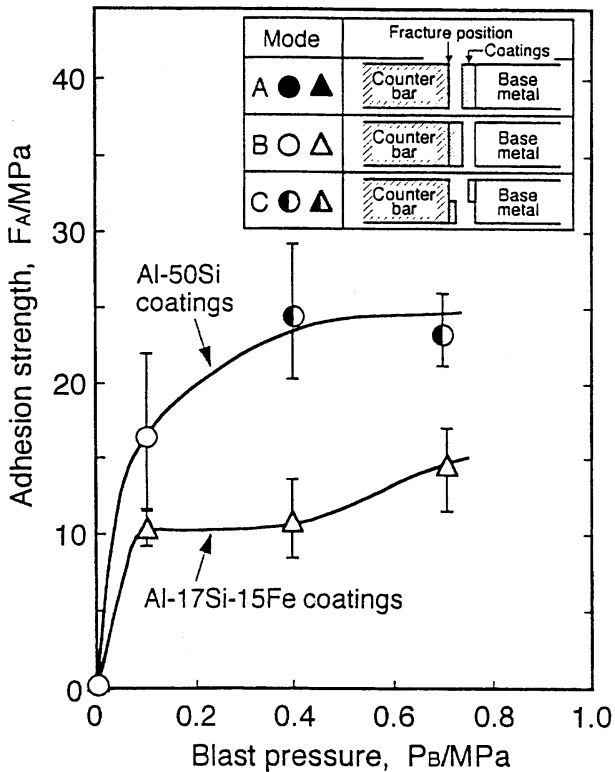
11 Variation of substrate surface roughness with blasting pressure

**ACKNOWLEDGEMENT**

The authors would like to express their thanks to Kubota Corporation, Casting R&D Department for supplying the Al alloy powders.

**REFERENCES**

1. F. MATSUDA and K. NAKATA: Proc. 2nd Int. Conf. on Power Beam Technology, Stratford-upon-Avon, UK, Sept. 1990, The Welding Institute, 297-306.
2. S. SHIMIZU, K. NAGAI, F. MATSUDA, and K. NAKATA: *J. Jpn Inst. Light Met.*, 1990, **40**, (10), 761-767.
3. F. MATSUDA, K. NAKATA, S. D. PARK, and T. HASIMOTO: *J. High Temp. Soc. Jpn*, 1993, **19**, (4), 168-178.
4. S. HARADA, T. UEYAMA, D. ZHOU, K. KUDO, and K. NAKATA: *J. Light Met. Weld. Constr.*, 1993, **31**, (10), 455-461.
5. K. NAKATA, T. HASHIMOTO, and F. MATSUDA: Proc. 1st Int. Conf. on Processing Materials for Properties, Hawaii, HI, USA, Nov. 1993, 1089-1092.
6. H. TACHIKAWA and T. ARAI: *J. Surf. Finish. Soc. Jpn*, 1993, **44**, (4), 320-325.
7. S. TOMIDA, K. NAKATA, and F. MATSUDA: *J. Jpn Inst. Light Met.*, 1994, **44**, (5), 263-268.
8. S. YOSHIE and E. HIRAISHI: *J. Light Met. Weld. Constr.*, 1994, **32**, (9), 409-415.
9. Y. KANBE, Y. NAKADA, S. KURIHARA, H. KOIKE, and T. MIYAKE: *Q. J. Jpn Weld. Soc.*, 1994, **12**, (1), 82-88.
10. S. TOMIDA, K. NAKATA, T. MUKAIYAMA, and F. MATSUDA: *Q. J. Jpn Weld. Soc.*, 1994, **12**, (2), 295-300.
11. Y. TAKAHASHI and M. TANAKA: *J. Light Met. Weld. Constr.*, 1995, **33**, (3), 101-110.
12. F. MATSUDA, K. NAKATA, and S. TOMIDA: in 'Thick surface hardening technology of aluminum alloy', (ed. JRCM); 1995, Tokyo, Japan, Nikkan Kogyo Shimbun.
13. E. LUGSCHEIDER *et al.*: Proc. 7th Nat. Thermal Spray Conf., Boston, MA, USA, June 1994, ASM International, 79-83.
14. K. YUSHCHENOKO *et al.*: Proc. Int. Thermal Spray Conf., Kobe, Japan, March 1995, High Temperature Society of Japan, 803-807.
15. A. LLYUSCHENKO *et al.*: Proc. 8th Thermal Spray Conf., Houston, TX, USA, Sept. 1995, ASM International, 317-320.
16. D. J. VARACALLER *et al.*: Proc. 8th Thermal Spray Conf., Houston, TX, USA, Sept. 1995, ASM International, 373-380.
17. I. OHNAKA: *J. Jpn Inst. Light Met.*, 1989, **39**, (7), 514-523.
18. T. B. MASSALSKI: 'Binary alloy phase diagrams', 2nd edn, Vol. 1; 1990, Materials Park, OH, ASM International.



10 Variation of coating to substrate adhesion strength with compressed air blasting pressure

*In print again!*



# NON-METALLIC INCLUSIONS IN STEEL

**Roland Kiessling**  
with the collaboration of  
**Nils Lange**

*contents*

- Part I** Inclusions belonging to the pseudo-ternary system  
 $\text{MnO-SiO}_2\text{-Al}_2\text{O}_3$  and related systems
- Part II** Inclusions belonging to the systems  $\text{MgO-SiO}_2\text{-Al}_2\text{O}_3$ ,  
 $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3$  and related oxide systems. Sulphide inclusions
- Part III** The origin and behaviour of inclusions and their  
influence on the properties of steels
- Part IV** Supplement to parts I-III including literature survey 1968-1976

**Book 194 ISBN 0 904357 18 X 215mm x 138mm**  
**European Union £50 / Members £40**  
**Non-European Union \$100 / Members \$80**  
**p&p European Union £5.00 / Non-EU \$10.00 per order**

Orders to: The Accounts Department, The Institute of Materials,  
1 Carlton House Terrace, London SW1Y 5DB  
Tel: +44 (0) 171 839 4071 Fax: +44 (0) 171 839 2078

N. American orders to: Ashgate Publishing Co., Old Post Road, Brookfield,  
VT 05036, USA Tel: 802 276 3162 Fax: 802 276 3837

Cards accepted: Visa MasterCard American Express