Plasma Spray Joining of Al-Matrix Particulate Reinforced Composites

Composite spray powders are used in an attempt to produce true composite joints

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ABSTRACT. Aluminum matrix composite joints have been produced on both aluminum alloy and metal matrix composite (MMC) substrates using powders containing SiC and Al2O3 particulates. Most of the composite powders were produced by ball milling, but the most effective joints were produced using Osprey composite powders. The results of preliminary joining experiments indicate that the substrate should be preheated to 200°C and a very wide bevel angle should be provided in order to obtain the highest strength joints. Silicon alloy additions to the matrix significantly improved strength but titanium additions had no effect. Heat treatment after spraying significantly improved the bond strength and restored precipitation hardening in the matrix. Significant amounts of Mg were lost from the deposit during spraying while some free silicon was produced by pyrolysis of the SiC powder; hence, further efforts must develop powder compositions that produce the optimum matrix composition in the sprayed deposit. No significant amount of Al4C3 was detected in deposits which contained SiC.

Introduction
Interest in metal matrix composites (MMC) such as SiC/Al and Al2O3/Al (SiC and Al2O3 in a matrix of aluminum, respectively) is currently expanding because of the improved performance offered by these advanced materials. However, the utilization of MMC is presently limited by their poor weldability when using conventional fusion welding processes (Refs. 1, 2). Exposure of the SiC/Al-type composite to temperatures above the liquidus of the aluminum alloy, as typically experienced in welding, results in a severe loss of engineered properties due to the formation of brittle and hygroscopic aluminum-carbon compounds (Refs. 2, 3). Furthermore, conventional fusion welding produces a weld pool that has poor fluidity and that solidifies with large volumes of porosity in both the weld and the heat-affected zone (HAZ) because of the release of hydrogen emanating from the aluminum powder used to fabricate many MMCs. Ahearn, et al. (Ref. 1), clearly demonstrated that vacuum degassing for long periods of time prior to welding did reduce porosity in welds deposited by GTAW, but Al4C3 and Al-Si eutectic were detected in the degassed composites.

Nothing has been reported on the joining of composites by the nontransfer thermal spraying technique. Although this technique has been commonly used for surface coating to improve wear resistance, heat resistance, and corrosion resistance of metals and alloys, it seems that few researchers thought that it would be a successful technique to join these composite materials directly. It may be that excellent weldments of MMC could be obtained by this technique if good adhesive and cohesive bonding of the sprayed deposit were accomplished, for it is believed that few brittle compounds, such as Al4C3, little porosity, and almost no HAZ would form in the joints since the surface of the substrate doesn’t melt during spraying due to the small heat input into the joints. The sprayed deposit properties may be enhanced if a distinct second-phase material, such as ceramic fibers, whiskers, particulates, or monofilaments, is incorporated into the deposit structure (Ref. 4).

This project was designed to develop manufacturing technology of plasma spray joining methods for MMC of both SiC/Al and Al2O3/Al. This may be the first study of the nontransfer plasma spray joining processes utilizing composite spray powders to attempt to produce true composite joints containing unreacted SiC or Al2O3 particulates with properties more closely matching those of the composite base metals. In this study, conventional (unreinforced) 6061

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Alloy base plates were used for simplicity and economy. Two matrix alloys were used with the composite spray powders, namely, Al-Si-Ti alloy and 2014 Al (Al-Cu-Si-Mg) alloy. In the former, Si additions were made 1) to reduce the melting temperature of the Al matrix alloy of the composite powder for ease of fusion during spraying, 2) to reduce the extent of reaction between Al and SiC (Refs. 2, 5, 6) in the sprayed deposit, and 3) to prevent liquid alloy particles from oxidizing. Reactive metal additives, such as Ti, were intended 1) to prevent the formation of Al₄C₃ (by the reaction between SiC and Al) by forming reactive metal carbide protective layers on SiC, which are inert with respect to Al (Ref. 6) and 2) to improve the wettability between SiC and Al (Ref. 6). Yang (Ref. 6) thermodynamically explained the above effect of Si and Ti additions.

Strengthening treatments, such as HIP consolidation and solution/aging heat treatment, were performed on the sprayed joints. Furthermore, a comparison of the effects of ball-milled 2014 Al-SiC powder and Osprey 2014 Al-SiC powder was made.

### Experimental Materials

#### Spray Powders

Table 1 shows the spray powder formulations which were prepared by ball milling or spray deposition. Three types of SiC were used with 5-, 15-, and 40-mm average size, respectively. The Al₂O₃ powder had a 20-mm average size, while the aluminum metal powder was spherical with an average size of 45 to 90 μm.
The substrates used in this study were 1100 Al-O, 6061 Al-T4, 10 vol-% Al2O3/6061 Al, and 20 vol-% SiC/6061 Al-O. Typical tensile properties are shown in Table 2. The thickness of these plates was 3.2 mm (1/8 in.) and the joint bevel angle was large (130 deg, no root opening).

### Experimental Procedure

#### Description of Apparatus

A commercial nontransferred arc spraying system was used. To increase the effectiveness of the deposit rate and the thickness, the plasma gun was mounted vertically and operated from a pneumatically controlled table. To increase the reliability and accuracy of a controlled deposit thickness, the gun was positioned in a stationary location. The vertical axis (Z) was controlled by raising and lowering the table. This is how the depth of field of the gun was controlled. In the joining process, the gun was moved right to left repeatedly on the horizontal axis (X) at translational speeds of 12.5 m/minute during spraying.

#### Preparation of Spray Powders

Most of the composite spray powders were prepared by ball milling Al alloy powder with the SiC or Al2O3 particulate reinforcing phase and any other additive element powders without any additional agents — Fig. 1. To a considerable extent, this formed a homogeneous composite powder wherein the hard phase was dispersed in the soft alloy matrix of the composite. The ball milling conditions are shown in Table 3. When SiC or Al2O3 particulates were incorporated into the composite metal powders, these were added at the start of the milling process. Figures 2 and 3 show SEM photos of the ball-milled Al-12wt-%Si-1.5wt-%Ti-10vol-%SiC (5 mm) powder and the ball-milled 2014 Al-10vol-%SiC (15 mm) powder, respectively, as examples.

Osprey composite SiC powder in a 2014 Al alloy matrix, as well as the ball-milled composite powder, was used in this study. The 2014 Al alloy was melted by induction heating in a crucible. The crucible was pressurized and the metal was ejected through a nozzle into an atomizer. SiC powder was injected into the metal spray. Figure 4 shows SEM photos of the 2014 Al-15vol-%SiC Osprey powder. The SiC particulates are incorporated into the metal powders more deeply and homogeneously than those of ball-milled composite powders.

Figure 5 (Ref. 7) shows the particle size distribution of the Osprey powder. The range between 45 and 150 mm represents where SiC particulates were incorporated into the metal droplets. To separate the unreinforced particles, the Osprey powder measuring between 45 and 150 mm was separated from the finer powders and then used in this study.

#### Determination of Spray Conditions and Spray Joining Processes

#### Grit Blasting

Figure 6 shows a joint specimen and its dimensions. Before joining, the shaded portion to which a sprayed deposit would adhere was roughened by
abrasive grit blasting. This was done to clean the oxides from the surface and provide a rougher surface for better adhesion. Blasting conditions are shown in Table 4.

**Preheating**

To determine the optimum preheating temperature of the substrate, tensile tests of preliminary spray-joined specimens were performed — Fig. 8. Tensile strength was measured by applying a tensile load to the sprayed specimen vertically to the axis of spraying. The reported joint efficiencies were normalized by the formula: Joint Efficiency (%) = 100 X (UTS of the joint)/base plate longitudinal UTS. Figure 7 shows three types of failure after tensile tests. Mode A is an adhesive fusion line failure. Mode C is a cohesive failure wholly in the deposit metal. Mode B is a mixed failure.

As seen in Fig. 8, the tensile strength of joints increased with preheating temperatures up to 200°C. It is generally believed that preheating of the substrate is necessary 1) to eliminate moisture on the surface which prevents molten sprayed metal particles from adhering strongly to the substrate, 2) to prevent hot sprayed deposit from cooling rapidly, and 3) to allow the substrate to expand in order to decrease the relative difference of thermal expansion and contraction in volume between the substrate and the hot sprayed deposit. In this experiment, the tensile strength of joints tended to decrease above 200°C, which was due to excessive oxidation of the substrate during preheating. On the other hand, without preheating, easy spalling of the deposit from the substrate occurred. Wholly cohesive failures were obtained at 200°C.

**Spray Distance**

Figure 9 shows the influence of spray distance on deposit efficiency (DE) and ultimate tensile strength (OTS) of the joints. One of the spray powders was Al and the other was 2014 Al-15vol-%SiC Osprey powder. In the latter case, heat treatment as described in the upcoming section on “Strengthening Treatments of the Joints” was performed after joining. It is seen that bringing the spray gun near to the substrate with a narrow spray track resulted in greater deposit efficiency of deposited materials; however, the strength of the deposit decreased due to less bonding force between the particles or at the deposit-substrate interface. A 95-mm spray distance was chosen in this study as providing the best combination of deposit strength and deposit efficiency.

**Bevel Angle**

The influence of bevel angle (included angle) of the joint on the tensile strength is shown in Fig. 10. The larger the bevel angle, the greater the cohesive strength as well as the adhesive strength. It is believed that the increase of tensile strength with bevel angle resulted from greater impact force of the spray particles and a resulting decrease in pores in each deposit. A 130-deg bevel angle was selected for further work in this study.

**Plasma Spraying Conditions**

Based on the results of the preliminary tests as noted above and the recommended spray conditions (Ref. 8) from the equipment supplier, the plasma spray conditions of this study were determined as described in Table 5. It was found that all the substrates required preheating in order to obtain satisfactory results. The typical preheat time before spraying was 10 minutes.

Using these conditions, plasma spray joining tests using composite spray powders were carried out.

**Strengthening Treatments of the Joints**

To increase the density and to greatly improve the adhesive and cohesive bonding of plasma sprayed deposits, HIP (hot isostatic press) and/or solution/aging heat treatments were carried out after joining. The HIP temperature, time, and pressure were 500°C, 1 hour, and 103.4 MPa (15,000 psi), respectively. The samples were not encapsulated before HIPing.

Heat treatment was added not only to strengthen the joint, but also to resolutionize the substrate because preheating (200°C 10 minutes) prior to joining brought about a 30% decrease in the tensile strength of the substrates. Therefore, the specimens were heat-treated to the T6 condition for 2014 Al (solution treatment: 500°C, 8 h/aging treatment: 500°C 8 hours). Based on the results of the preliminary tests, the recommended HIP conditions were determined as described in Table 5. It was found that all the substrates required HIPing.
Spray Powders with SiC Particulates

A wide variety of composite metal powders formulations for spraying was prepared and used to produce demonstration joints of different materials. Figures 11 and 12 show the influence of Ti content in composite spray powders with SiC particulates (5-mm and 40-mm size) on UTS. Although addition of Ti had almost no effect, adding Si up to 12% had a benefic effect on the tensile properties. The volume fraction of the reinforcement phase and porosity in the sprayed deposits were measured using an image analyzer. The fracture surfaces were examined in a scanning electron microscope.

Figure 14 shows the effect of SiC incorporation efficiency on the tensile strength of the joints. The tensile strength increased with increasing SiC incorporation efficiency. The fracture surface of the deposit was almost as strong as the interface, which was due to the good interlocking of the particles in the deposit.

Evaluation of the Joints

Tensile Tests

Tensile tests of all specimens were performed at room temperature. The tests were conducted in an Instron tensile testing machine at a crosshead speed of 0.02 cm/min (0.008 in./min). All results represent an average of three or more tests. Some of them were etched lightly with Keller's reagent.

Figure 15 shows the effect of SiC incorporation efficiency on the tensile strength of the joints. The tensile strength increased with increasing SiC incorporation efficiency. The fracture surface of the deposit was almost as strong as the interface, which was due to the good interlocking of the particles in the deposit.

Results and Discussion

Joining Using Al-Si-Ti Alloy Matrix Powders with SiC Particulates

Cross-sections of the deposits were cut to fit into the sample holder of an X-ray diffractometer. The samples were then chemically polished to 0.3 mm finish. The typical fracture surface of the deposit is shown in Fig. 12. There were many fine droplets of metallic Al and SiC. The high magnification in Fig. 13 shows the presence of SiC particles embedded in the Al matrix. The fracture surface of the deposit was almost as strong as the interface, which was due to the good interlocking of the particles in the deposit.

The tensile strength of the joints was improved by adding Si to the Al matrix. The addition of Si improved the wetting of aluminum to the ceramic particles because of its excessive oxidation during ball milling and plasma spraying. The ceramic particles were more easily incorporated into the Al matrix during ball milling and plasma spraying; probably because of poor wettability between the SiC and Al matrix. This improved the bonding strength at the interface since all fracture modes, adhesive and cohesive, mixed, were present in the deposit. The tensile strength of the joints was improved by adding Si to the Al matrix. The addition of Si improved the wetting of aluminum to the ceramic particles because of its excessive oxidation during ball milling and plasma spraying. The ceramic particles were more easily incorporated into the Al matrix during ball milling and plasma spraying; probably because of poor wettability between the SiC and Al matrix. This improved the bonding strength at the interface since all fracture modes, adhesive and cohesive, mixed, were present in the deposit.
Fig. 8 — Joint efficiency, in terms of failure mode and strength, varied with preheating temperature. The highest strength occurred at 200°C in a cohesive failure mode.

Fig. 9 — Spray distance affects both the deposit efficiency and the UTS. The best combination of properties was found at 95 mm.

Fig. 10 — Increases in bevel angle increased the UTS, cohesive strength and adhesive strength. Larger bevel angles result in greater impact force of the droplets and less porosity.

Fig. 11 — The tensile strength of composites sprayed with 5-μm SiC particles was not influenced by Ti content. Higher Si contents up to 12% Al-Si eutectic composition produced higher strength.
tures were type C (cohesion failure). In the case of joints with 15-mm SiC particulates, the heat-treated specimens were stronger than the as-sprayed specimens, because bond strength between the SiC phase and the Al alloy matrix appears to be improved by the heat treatment. Nonetheless, the final strength values were not very high because the deposits did not contain constituents which create strengthening by heat treatment.

Fujiwara (Ref. 10) reported that tensile strength (and modulus of elasticity) of MMCs increased with decreasing SiC particulate size. In this study, this tendency was true to a certain extent as seen in Figs. 14 and 15 (as sprayed).

Figure 16 shows microstructures of sprayed deposits with 5, 15, or 40 mm SiC particulates. Based on XRD analysis, no Al₄C₃ phase was observed in the sprayed deposits. It is thought that since SiC particulates were in contact with the molten Al alloy particles for only a moment during plasma spraying, almost no reaction between SiC and molten Al alloy occurred.

Porosity varied from 1 to 4% in each deposit. These pores did not seem to influence the tensile strength and failure mode of deposits significantly.

Spray Powders with Al₂O₃ Particulates

As shown in Fig. 17, Si additions influenced the UTS much more than Ti content. The composition with the best joint strength was Al-6wt-%Si-1.5wt-%Ti-10vol-%Al₂O₃. As compared with spray powders with SiC particulates, however, the tensile strength was very low, although Al₂O₃ incorporation efficiency was high — Fig. 18. The Al₂O₃ content in sprayed deposits increased with the Si content.

Figure 19 summarizes the results of joint tensile strength for all the specimens joined using each spray composite powder.

Joining Using 2014Al-Matrix Composite Spray Powders

Strengthening Treatment Effect

Figure 20 shows strengthening treatments and their effect on UTS and joint efficiency. Figure 20B compares the tensile strength of five different specimens. Combination (E) using HIP and T6 heat treatment gave the highest tensile strength. As compared with as-sprayed joints (A), the strength improved dramatically (about 95%). Even without HIP, the T6 heat treatment (C) produced joints 60% stronger than those of as-sprayed specimens.

Chemical analysis of the 2014 Al-15vol-%SiC Osprey powder and its spray deposit is described in Table 6. The spray deposited contained much soluble silicon because of pyrolysis of some of the SiC particulates during plasma spraying. In the 2014 Al alloy, precipitation of intermetallic compounds, such as CuAl₂ and Mg₂Si improves the mechanical properties of the alloy. Suzuki, et al. (Refs. 11, 12), reported that Al-Mg₂Si alloys containing excess silicon have faster age-hardenability than the balanced alloy. Thus, it is thought that the excess soluble silicon content in the deposit brought about over aging, since the aging treatment followed the normal heat treatment for 2014 Al described in Ref. 6.
Therefore, it is possible that higher strength could be obtained if optimum heat treatment conditions (especially aging time) were developed for these specimens. Porosity was 1 to 3% in each deposit.

Figure 21 shows the microstructures of the 2014Al-15vol-%SiC Osprey deposit. Apparently the uniformity of dispersion and incorporation of the SiC particulates in the Al alloy matrix were better than those of ball-milled 2014 Al15vol-%SiC deposits. The typical fracture surface of the heat-treated Osprey deposit exhibited a locally ductile, dimpled morphology as shown in Fig. 22.

**Influence of SiC Content on UTS**

Figure 23 shows the effect of SiC content in ball-milled 2014 Al-SiC composite spray powders on UTS. All the specimens were heat-treated before the tensile test. The strength generally tended to decrease with increasing SiC content. There are several possible reasons why the strength values were low, among them low bond strength at the SiC/Al matrix interface and alteration of the chemical composition of the matrix during ball milling and plasma spraying. Nonetheless, the Osprey composite powder containing 15vol-%SiC produced joints with better strength than that of ball-milled powder at the same SiC content. The deposit made of the Osprey powder showed higher SiC incorporation efficiency \( h \) as compared with ball-milled powders. Ball-milled powder with smaller size SiC (5 mm) also showed better strength values than that of the ball-milled powder with 15 mm SiC.

**Joining of SiC/6061 Al and Al2O3/6061Al MMCs**

Figure 24 shows results of the strengthening treatments of Osprey deposits on 6061 Al and 6061 Al-matrix particulate reinforced composites (namely, 20vol-%SiC/6061 Al and 10vol-%Al2O3/6061 Al) substrates. Though the HIP treatment prior to the T6 heat treatment was very effective in improving the joint strength of the specimens with 6061 Al substrates, it did not produce much improvement in the strength of the specimens produced on MMC substrates. Figures 25 and 26 show the microstructures at the interfaces between the SiC/6061Al substrate and the sprayed Osprey deposit, and the Al2O3/6061Al substrate and the Osprey deposit, respectively. It is thought that the presence of SiC or Al2O3 phase on the surface of the MMC substrate to which a sprayed deposit would adhere, decreased the adhesive bonding at the deposit-substrate interface to a certain extent. Nonetheless, the adhesive or cohesive/adhesive mixed strength values of the specimens with SiC/6061Al substrates were a little higher than those of specimens with Al2O3/6061 Al substrates, although it should be noted that the former contained 20 vol-%SiC phase and the latter contained 10 vol-%Al2O3 phase. This suggests that the interface between the SiC phase on the surface of the substrates and the sprayed 2014 Al alloy had better adhesion.
Suggestion for Future Work

For comparison with some of the results in this report, several properties of the sprayed joints not containing SiC phase were investigated. Figure 27 shows the influence of Mg content in the spray deposit of ball-milled 2014 Al alloy on the joint strength. B means the Mg/Si weight ratio calculated from the chemical analysis of each deposit. Precipitation of intermetallic compounds, such as CuA12 and Mg2Si, by heat treatment provides significant improvement of the mechanical properties of 2014 Al alloy as values of B approach 1.73. The joint with maximum strength in Fig. 27 was the strongest of the joints produced in this study - Fig. 28.

Kojima, et al. (Ref. 13), reported that in Al-Si-Cu-Mg alloys, the amount of Mg is reduced by 55% during plasma spraying. Therefore, though the standard Mg content in 2014 Al alloy is 0.8 wt-%, Mg contents adopted for the ball-milled powder of this experiment were 0.5, 1.5, 3.0, and 5.0 wt-%. Before spraying, unfortunately, the Mg content of the ball-milled powders was decreased about 56% because of adherence to the inside wall of the ball mill jar and the milling media due to use of fine Mg powder - Fig. 29. In addition, the Mg content decreased even further during plasma spraying as shown in Fig. 30. The resulting Mg contents are shown in Fig. 27.

As seen in Table 6, the higher the vapor pressure or lower the boiling point of the element, the larger the weight loss during plasma spraying. It was found that the sprayed Osprey deposit contained much soluble silicon (Table 6) and hence its value of B was much less than the optimum of 1.73. Therefore, it is likely that a deposit with higher age-hardenability after plasma spraying can be produced. Hence, it is believed that an Osprey joint with excellent tensile properties might be obtained by better control of the amount of Mg in the deposit.

Ball-milled spray powders containing SiC particulates produced composite joints with lower strength and lower SiC phase content than those of the Osprey joints in this study. Thus it is preferable to make the composite powder by spray deposition rather than by ball milling. For production of composite spray powders by means of ball milling, it would be better to adopt longer periods of milling time to obtain a fully mechanically alloyed metal matrix and a highly homogeneous composite powder wherein the SiC phase is more uniformly dispersed in the soft alloy matrix.

In conclusion, future efforts should be directed towards the development of proper composite spray powder and the determination of optimum heat treatment conditions after spray joining.

Conclusions

General Conclusions

1) Plasma spray joining processes require preheating to obtain satisfactory results from joining. For Al deposits to 1100 Al substrates, 200°C was found to be an optimum preheating temperature.

2) The strength values of spray joints increased with increasing bevel angles.

3) Almost no Al4C3 phase was observed by XRD analysis in each sprayed deposit containing SiC phase, but the deposit contained much soluble silicon because of pyrolysis of some SiC particulates.

4) Bonding between the reinforcement phase and the Al alloy matrix seemed to be very poor, especially for the larger volume fractions of SiC particulates.

Use of Al-Si-Ti Alloy Matrix Composite Powders

1) Although Ti additions had almost no effect on tensile strength of the joints,
Si was a very effective additive for all the composite powders. It was found that 12 wt-% Si for the composite powder with SiC particulates and 6 wt-% Si for composite powder with Al$_2$O$_3$ particulates were the best compositions to improve the joint strength.

2) Spray joints containing SiC were generally stronger than ones containing Al$_2$O$_3$ particulates.

3) The SiC content in the deposit was smaller than the Al$_2$O$_3$ content given an equal fraction of each in the starting powder. The Al$_2$O$_3$ content in sprayed deposits increased with the Si content.

4) Heat treatment seemed to improve the bonding at the interface of the substrate-deposit and/or the SiC phase-Al alloy matrix in the deposit. Since the deposit matrix did not contain alloys capable of providing precipitation hardening, the strength values of these deposits after heat treatment were not large.

Use of 2014 Al Alloy Matrix Composite Powders

1) All heat-treated joints were much stronger than as-sprayed joints. Most of them showed wholly cohesive failure mode, which means not only the deposit, but also the deposit-substrate interface were strengthened to a considerable extent by the heat treatment (T6).

2) The combination of HIP and T6 heat treatment caused the strength of the Osprey joints with unreinforced 6061 Al substrates to increase up to 95% compared with as-sprayed joints, but the results varied considerably from specimen to specimen.

3) The Osprey joints with SiC/6061 Al and Al$_2$O$_3$/6061 Al substrates were a little weaker than those with unreinforced 6061 Al substrates, and their strength values scattered widely. A HIP treatment prior to the T6 treatment of the joints with composite substrates was not so effective in improving the joint strength.

4) The strength of the joints made with ball-milled powders tended to decrease with increasing SiC content. Both the sprayed deposits with smaller SiC particulate (5 mm) and the Osprey deposits were stronger than those made with the ball-milled powders. The Osprey deposits showed a relatively high efficiency for incorporation of SiC (n = 70.3%).

5) Loss of Mg by vaporization during spraying upsets the ratio of alloy elements and produces joints which do not respond well to precipitation heat treatment. Special alloys which reduce such losses or tolerate them more readily should be developed to provide the
The strength of 2014 Al decreased with increasing SiC content for ball-milled powders.

Fig. 23 — The strength of 2014 Al decreased with increasing SiC content for ball-milled powders.

A comparison of results of strengthening treatments of the Osprey deposits on 6061 Al and 6061 Al matrix particulate reinforced substrates shows variations with heat treatment.

Fig. 24 — A comparison of results of strengthening treatments of the Osprey deposits on 6061 Al and 6061 Al matrix particulate reinforced substrates shows variations with heat treatment.

Fig. 25 — A change in particulate size can be seen across the deposit substrate interface for the SiC/6061 Al.

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Acknowledgments

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Fig. 26 — The deposit/substrate interface marks a change in particulate size and distribution for the Al2O3/6061 Al.
Fig. 27 — The highest joint strength was obtained at an optimum Mg/Si ratio.

Fig. 28 — Comparison of ball-milled and Osprey powder joint strength.

Fig. 29 — Magnesium content in composite powder was decreased about 56% during ball milling because of adherence of magnesium to the mill balls and walls.

Fig. 30 — Magnesium was lost by vaporization during the spraying of the powder, resulting in reduced Mg contents.


7. Courtesy of B. Althueller, Kingston R&D Center, Alcan International Ltd.


