Study of the Brazeability of Aluminum Matrix Composites

Brazeability of aluminum alloys (6xxx and 7xxx) series reinforced with alumina particles depends both on matrix composition and reinforcement proportion

BY A. UREÑA, J. M. GÓMEZ DE SALAZAR, M. D. ESCALERA AND M. I. FERNÁNDEZ

ABSTRACT. The brazeability of several aluminum matrix composites has been evaluated in the present paper. Tested materials were two different 6061 aluminum alloys, reinforced with 10 and 20% alumina particles, respectively, and a 7005 aluminum alloy containing 10% alumina also in the form of discrete particles. A drop formation test was selected to evaluate the brazeability of the studied composites, using a commercial filler metal (BAlSi4) generally used for brazing of aluminum alloys. Wettability of molten braze on the metal matrix composites (MMCs) was determined by measurement of the solidified contact angle in sessile drop tests and determination of the spread area. The wettability and spreading increase with the brazing temperature in the studied range (550–625°C, 1022–1157°F), and decrease when the reinforcement proportion is increased. Both properties are also influenced by the type of the composite aluminum matrix being enhanced in the Al-Zn-Mg reinforced alloy. This study was completed with the microstructural characterization of the drop test specimens and of real brazed joints made on "T-shaped" specimens. The influence of postbrazing heat treatment was also studied. Shear mechanical tests were conducted out on brazed overlap specimens to determine the joint strength and values controlled by the strength of the brazing filler metal used. Maximum shear strengths higher than 90% of the nominal BAlSi4 filler metal shear strength were obtained for both composites reinforced with 10% of alumina particles, representing nearly 50% of the strength of these composites.

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Introduction

Joining of metal matrix composites (MMCs) is still one of the unsettled subjects which limit their generalized use in structural applications. Most of the previous efforts were conducted on fusion welding and, principally, using joining procedures such as arc, laser and electron beam welding (Refs. 1–4). However, the application of this kind of welding technique creates several problems, especially when the weldments are applied to composites with an aluminum matrix. Among those limitations are the following:

1) The high temperature required by conventional fusion welding methods may initiate chemical reactions in the matrix/reinforcement interfaces. In the specific case of alumina reinforcement, which reacts with the Mg contained in the Al-Mg-Si alloys (*i.e.*, 6xxx series) forming a surface layer of spinel (Ref. 5):

$$3Mg[Al] + 4Al_2O_3[s] \approx 3MgAl_2O_3[s] + 2Al[l]$$

2) The distribution of reinforcement particles tends to be strongly disturbed in the molten pool and may be entirely absent, even when a MMC filler is used. These reinforcement distribution problems cannot be remedied by postwelding heat treatment (Ref. 6). One way to minimize these limitations is to apply heterogeneous joining techniques, in which a filler alloy with a lower fusion point than the parent metallic matrix is used. Brazing is a commonly used method for joining aluminum and some of its alloys (6xxx and 7xxx series) (Ref. 7).

KEY WORDS

Brazeability
Metal Matrix Composites
6061 Aluminum
BAlSi4 Filler Metal
Drop Test
7005 Aluminum
Shear Strength
Postbrazing Heat Treatment

This paper presents a study of the brazeability of different aluminum matrix composites reinforced with alumina particles. The main objective of this research was to determine the wettability of the selected filler metal (an Al-Si alloy) on different aluminum MMCs, evaluating the influence of matrix composition, reinforcement proportion and brazing temperature. A second objective of this work was to characterize the microstructures of the brazed joints to obtain information on the bond quality and on the behavior of the ceramic particles in the molten pool.

Experimental Procedure

Materials

The materials used in this study were three aluminum matrix composites reinforced with alumina particles. Two of them were composed of an A6061 matrix (Al-Mg-Si) reinforced, respectively, with 10 and 20 vol-% of alumina particles; the third one was an AA7005 (Al-Zn-Mg) with 10% of Al_2O_3 particles. The standard designations used for these materials are: AA6061/Al_2O_3/10p, AA6061/Al_2O_3/20p and AA7005/Al_2O_3/10p, respectively. These composites were manufactured by Duralcan USA and supplied in the form of 6 mm thick sheets in the as-extruded condition. The chemical compositions of the aluminum alloy matrix are shown in Table 1. Details of the microstructure of the as-received materials are presented in the following section.

The brazing filler metal used in this

Table 1 — Chemical Compositions (wt-%) of Base Matrix Alloys Used in Brazed MMCs

Matrix Alloys	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Al
AA6061/10p	0.55	0.06	0.27	0.005	0.89	0.12	0.003	0.008	—	bal.
AA6061/20p	0.55	0.06	0.27	0.004	1.19	0.12	0.01	0.01	—	bal.
AA7005/10p	0.035	0.10	0.002	0.40	1.07	0.14	4.43	0.05	0.13	bal.

work was an BAlSi4 alloy (AA4047), supplied by Castolin-Eutectic, with the chemical composition shown in Table 2 and a tensile strength of 180 MPa (26.0 ksi). It was applied in the form of 2 mm (0.079 in.) diameter brazing wire. Prior to the brazing tests, the fusion parameters of the selected filler metal (solidus and liquidus temperatures) were determined by DTA tests.

Table 2 — Chemical Composition (wt-%) of Brazing Filler Metal Used

Filler Metal	Si	Cu	Mg	Zn	Mn	Fe	Al
AWS BAlSi-4	12.0	0.30	0.10	0.20	0.15	0.80	bal.

Drop Formation and Brazing Tests

The testing method selected to evaluate the wettability of the BAlSi4 filler on the base composites studied was a drop formation test (Ref. 8). Flat segments of the MMCs were cut from the sheets in the form of 15 x 15 mm (0.59–0.59 in.) square pieces. One face of the specimens was ground to a 600 emery paper finish after deoxidant pickling, and all surfaces were washed by ultrasonic cleaning with acetone. A fixed volume of the brazing metal was placed on the prepared surfaces. It was obtained by cutting a portion of 10 mm (0.39 in.) length from the filler wire, forming it in a coil shape to obtain a consistent coverage area on the base composite ($A_0 \approx 8$ mm^2) (0.0124 in.^{2}), as shown in Fig. 1.

Drop formation tests were carried out in a resistant furnace, covering the filler metal with a small amount of a commercial flux (Castolin 190) composed of a mixture of hygroscopic halides (chlorides of alkali earth metals) with an activity temperature range of 500–660°C (932–1220°F). The powders were mixed with distilled water to constitute a wet paste and applied. The specimens were heated at 30°C/min (86°F/min) from room temperature to the brazing temperature, held at this temperature for 10 min and cooled in the furnace. Wetting temperatures were in the 550–625°C (1022–1157°F) range. Each test was conducted only once, but three specimens of each material were heated together, for each wetting temperature, to ensure the same test conditions.

Once the test was completed, the area of spread (A_s) and the contact angle (θ) were measured. This last parameter was determined from cross sections of the solidified drops, taking two measures from both edges of each solidified drop. To use a relative index of wettability for comparative purposes, the spread ratio (Sr) was also chosen (Ref. 9), and is defined as:

$$\text{Spread ratio } (S_r) = \frac{\text{Total plane area wetted by molten metal}}{\text{Original plan area of braze metal coil}} = \frac{A_s}{A_o} \quad (1)$$

Solidified drops were also prepared for metallographic study using light and scanning electron microscopes. EDS semiquantitative microanalyses using the ZAF correction method were conducted to determine the influence of the different alloying elements present in the composite matrices on the wettability and grain penetration phenomena.

Additional microstructural studies

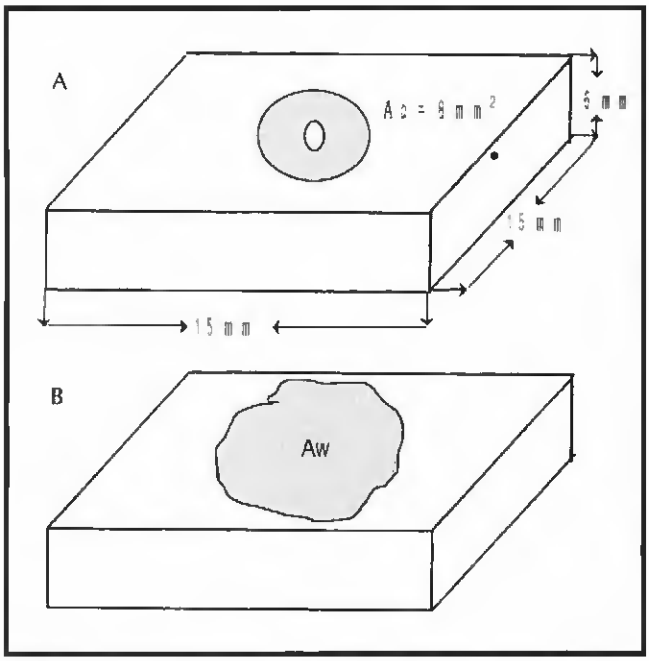


Fig. 1 — Schematic diagram of the drop formation test. A — before melting; B — after melting.

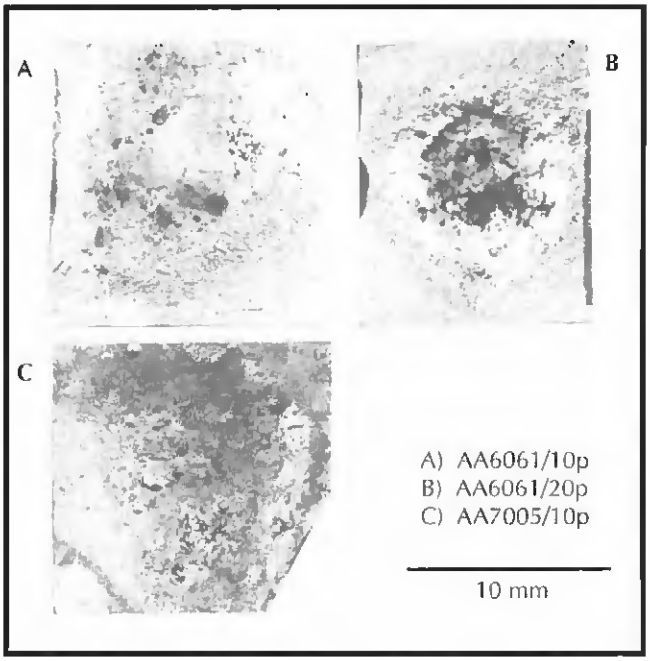


Fig. 2 — Scheme of brazed joints. A — T-shape specimens; B — single overlap specimens for shear tests.

were performed on brazed joints made on "T-shaped" specimens. These brazing tests were carried out as is shown in the schematic of Fig. 2A. Two 20 mm long portions of braze wire were located at both sides of the "T" configuration to make a double fillet braze. Both rods were covered with the flux and heated in the brazing furnace. Brazing conditions used for these joints were similar to those utilized in the drop formation tests, although shorter brazing times were used (2–5 min). The purpose of this type of test was both to evaluate the flowability of the filler metal in an actual joint, which may be determined by the joint clearance (Ref. 10), and to study the microstructural characteristics of the brazing interfaces formed. In this last case, the study was developed both on as-brazed joints and on post-brazed heat treated joints.

Post-brazing heat treatment consisted of a spheroidization treatment carried out at 530°C (986°F) for 24 h, to aid the change in the shape of the Al-Si eutectic aggregate formed in the molten pool, thus generating less brittle structures.

To complete this study, mechanical tests of brazed joints were carried out to evaluate the joint strength. Samples of 30 x 10 x 6 mm were placed in a single overlap configuration with a 5 mm overlap length. A 10 mm-long piece of the braze alloy wire was located on the upper side of each specimen to form a single fillet weld — Fig. 2B. Braze alloy was again covered with flux and heated to brazing temperature. Three brazed specimens of each composite material were tested in a universal tensile machine. The shear strength was determined from the maximum load and the initial overlap area. The brazing conditions used to prepare these test pieces were the same as those used to prepare T-brazed samples.

Results and Discussion

Base Composites Microstructure

Figure 3A–C shows the typical three-dimensional microstructures of the AA6061/Al_2O_3/10p, AA6061/Al_2O_3/20p and AA7005/Al_2O_3/10p materials, respectively. Alumina particles are aligned along the extrusion direction which is marked (L) in the micrographs of Fig. 3. Particle-free zones and clustering areas are commonly observed, principally in the less reinforced materials. Studies at higher magnifications showed that the particle size increase in proportion to the volume fraction increase. In the 10 vol-% reinforced alloys (both 6061 and 7005 ones), the average length of the particles is 10 µm, although there is a range of particle length from 5 to 20 µm. However, in the AA6061/Al_2O_3/20p material, average alumina particle size is approximately 20µm, and the increase in reinforcement volume fraction of this material relative to AA6061/Al_2O_3/10p, is a result of the larger size of the particles rather than an increasing number of them. The average particle aspect ratio (l:d) is 5:1 in all three alloys, according to the information provided by Duralcan USA, although particles with lower l:d ratios can be observed.

The size and distribution of the particles affects the final grain size of the matrix, resulting in smaller grains in the AA6061/Al_2O_3/20p sample than in the other samples. For both matrix types, their characteristic equilibrium precipitates were observed: Mg_2Si in AA6061 and $MgZn_2$ in AA7005, respectively.

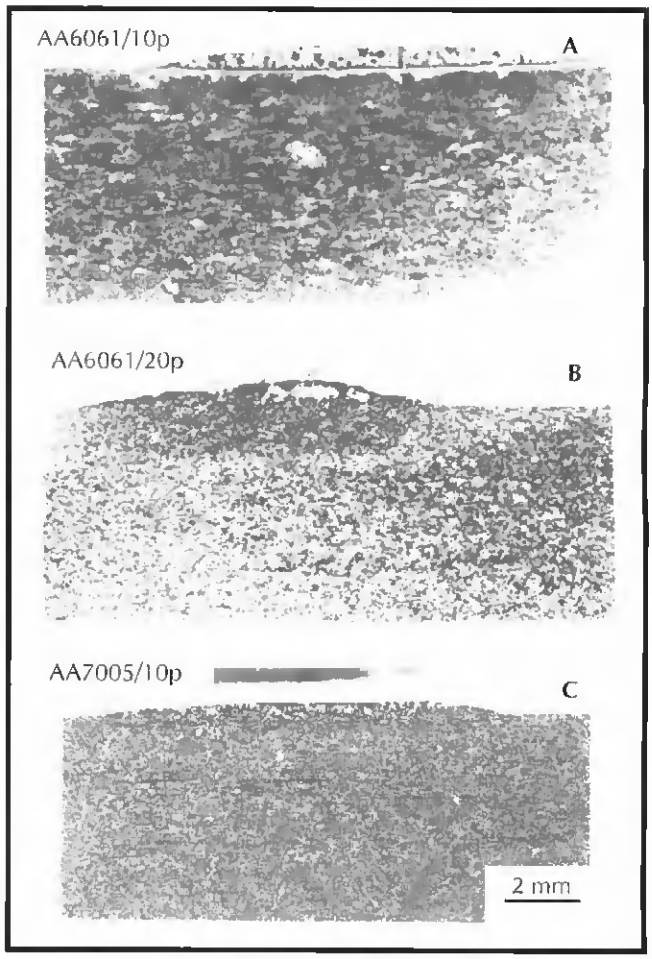


Fig. 3 — Three-dimensional microstructures of MMCs extruded sheets. A — AA6061/Al_2O_3/10p; B — AA6061/Al_2O_3/20p; C — AA7005/Al_2O_3/10p.

Braze Metal Characterization

The brazing filler metal BAlSi4 (Al-12 wt-% Si) was selected over other possible candidates because of the presence of a liquidus temperature lower than the incipient melting point of both base matrix alloys. In addition, it has a narrow fusion range because its composition is close to the eutectic one (Al-12.6Si). Eutectic composition alloys are often regarded as having the best spreading characteristics, in comparison with off-eutectic alloys of the same system. In the case of noneutectic filler metals, melting, wetting and spreading start before the alloy is entirely molten, due to its tendency to be somewhat viscous.

Figure 4 shows the DTA record obtained from the filler alloy having a melting range of 563–617°C (1045–1143°F), although the wetting tests carried out in the present work have shown that braze alloy is practically melted at temperatures higher than 590°C (1094°F). The microstructure of this alloy is shown in Fig. 5. Primary dendrites of (Al) phase, visible inside the Al-Si aggregate have the typical needle morphology of silicon in a continuous aluminum matrix. This microstructure corresponds with a lightly hypoeutectic composition for the system Al-Si — Fig. 6 (Ref. 11).

Wettability and Spreading of the BAlSi4 Braze Alloy on the MMCs

Figures 7 and 8 show the macrographies obtained from drops, formed at 580°C (1076°F), on the three MMCs studied, both of the wetting surfaces and of cross sections. The results of θ and S_r for the three types of MMCs, obtained from specimens such as the previous ones, are plotted in Fig. 9A–C, respectively, vs. the brazing temperature. Scatter in the measurement of θ are plotted from the differ-

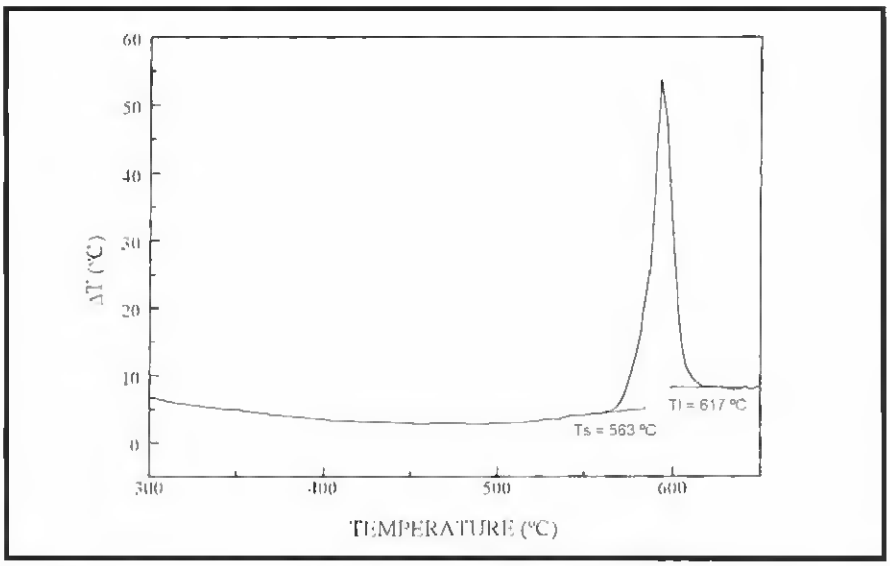


Fig. 4 — DTA record obtained for BAlSi4 brazing filler metal.

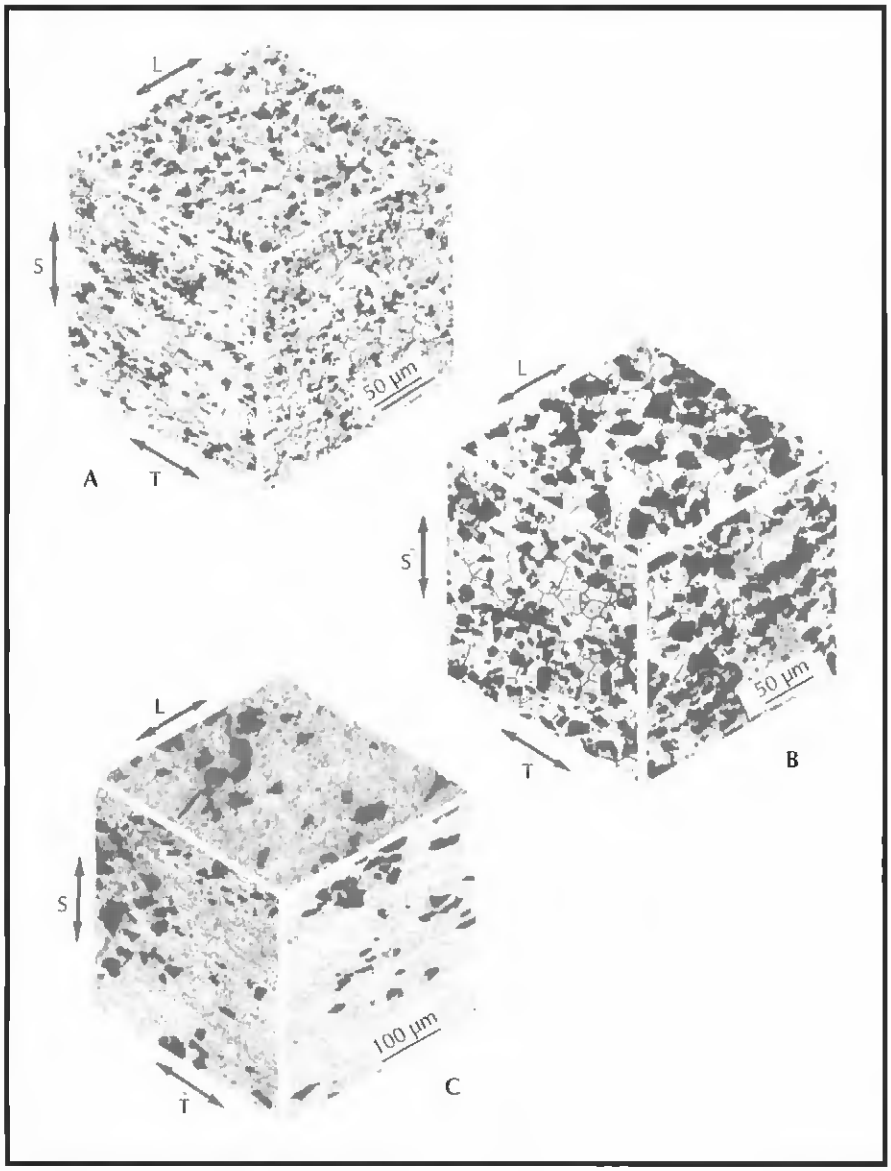


Fig. 5 — Microstructure of the BAlSi4 brazing filler metal.

ence between two measures from each solidified drop (Fig. 9B); the lower the wettability, the greater the difference. The value of θ, which is related to the surface tensions associated with the solid/vapor, solid/liquid and liquid/vapor interfaces through the Young-Dupre equation (Ref. 12), determines the phenomenon of wetting which must occur during brazing. Spreading is a dynamic process related to the contact angle and can be described as an increase in the liquid surface, and eventually in the interfacial area as well. In terms of θ (Ref. 13), there are generally three behaviors:

Nonwetting:	$\theta > 90°$
Wetting:	$\theta < 90°$
Complete spreading:	$\theta = 0° \rightarrow S_r = \infty$

In most brazing operations wetting is required, but a high degree of spreading can be detrimental to joint filling, as the filler metal can flow out of the joint, resulting in voids and unwanted coverage of other parts of the brazed components. On the other hand, although the wetting condition implies contact angles lower than 90°, the current literature advises brazing with angles lower than 20° (Ref. 14).

From the results obtained in the present work, it can be established that wettability increases with temperature in the three composites studied. For temperatures lower than 570°C (1058°F), the filler material does not form a drop, and when the temperature is higher than 600°C (1112°F), the contact angle is practically 0°, but there is a complete penetration of the molten filler into the MMC substrate, causing an erosion phenomenon (Ref. 9).

At 590°C (1095°F), the contact angle for the three base materials is lower than 10°. This behavior is due to the decrease of the molten filler viscosity, which is higher at lower temperatures because of the presence of a solid phase (primary) in the drop.

The wettability also depends on the proportion of reinforcement, determined by comparing the values measured for θ and S_r, on both AA6061/Al_2O_3/xxp materials. For the same temperature, in the tested range, the wettability decreases when the proportion of alumina particles increases in the AA6061 matrix. This behavior is more evident at lower temperatures (< 590°C), as the contact angle measurements have shown — Fig. 9A. The low surface tension (γ) of most ceramics, especially the very ionic oxides (*i.e.*, γ_{Al2O3} = 0.892 and γ_{Al} = 1.160 J/m²) (2.12 and 2.76 x 10^{-5} BTU/ft²)
(Ref. 15), has the effect of creating a

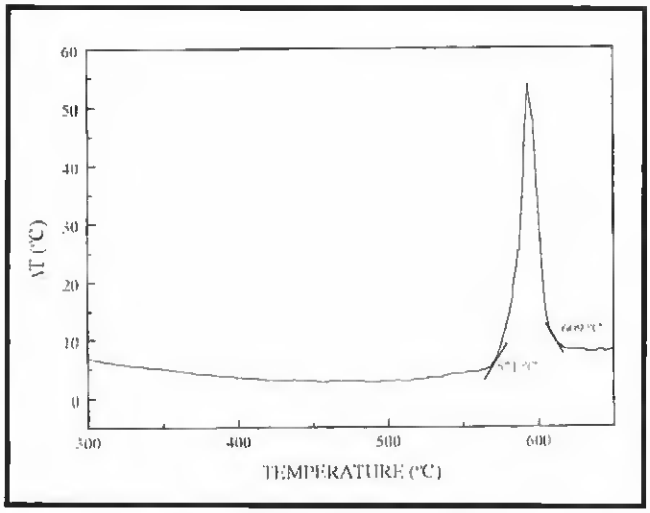


Fig. 6 — Al-Si equilibrium phase diagram (Ref. 11).

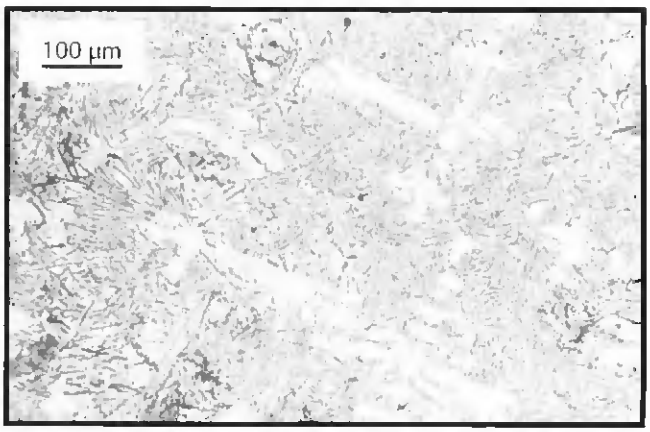


Fig. 7 — Spreading surfaces on MMCs obtained at 580°C (1076°F) in drop formation tests.

situation where it is unlikely that the molten filler will satisfy the wetting condition. Besides, the presence of more ceramic particles reduces the molten braze spreading, principally in the temperature range of 580–590°C (1076–1094°F). Therefore, although AA6061 matrix composites demonstrate θ lower than 20° for temperatures in the range 580–590°C (1076–1094°F), making it theoretically possible to braze with the selected filler, the poor spreading for 20 percent reinforced composite would result in brazeability problems.

At all test temperatures, θ is lower for the AA7005/Al_2O_3/10p than for the other systems, perhaps attributable to the decrease in the melting point of the brazing filler metal caused by diffusion of Zn from the composite matrix, aiding the wettability of this material at low temperatures. It may, however, hinder the erosion phenomenon when the brazing temperature is close to 590°C (1094°F). Thus, with this material it will be necessary to braze at lower temperatures (570–580°C, 1058–1076°F), where the wettability and spread ratio (Fig. 9) are high enough.

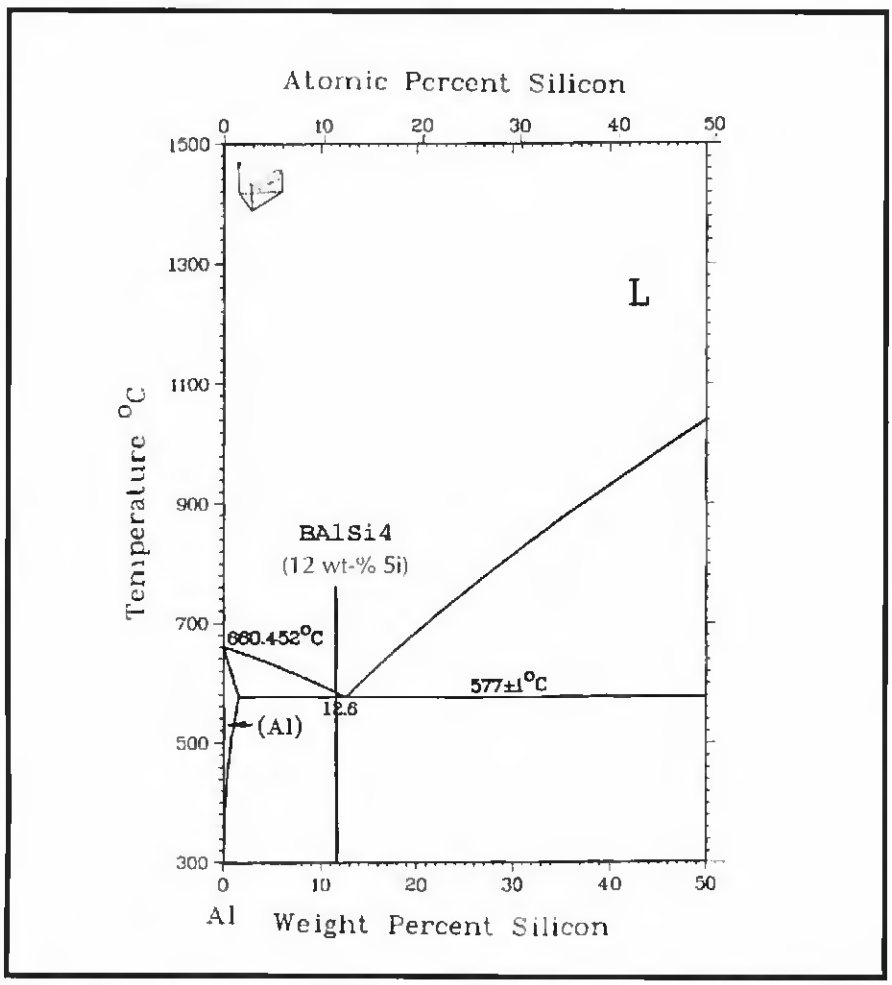


Fig. 8 — Cross-sections of drop formation tests used for contact angle measurement (T_W = 580°C, 1076°F).

Microstructure of Drop Test Specimens

The microstructural study of the cross sections obtained from solidified brazed drops formed on the MMCs has revealed the existence of important changes in the formation of the molten pool — not only in relation to braze temperature, but also with the characteristics (matrix nature and reinforcement proportion) of the MMCs tested.

AA6061/Al_2O_3/10p Material

Figure 10 shows the typical microstructure of a solidified drop generated on a AA6061/Al_2O_3/10p sheet at 580°C (1076°F). Since the original composition of braze metal is close to the eutectic composition (12.6 wt-% Si), the presence of large amounts of primary phase (Al) shows that there has been an important enrichment in Al. These aggregates have a cellular structure with the Al-Si eutectic located inside the intracellular spaces — Fig. 11A. Reinforcement particles which come from base MMCs also appear to be associated with the eutectic microconstituent — Fig. 11B. Although it is probable that the Al enrich-

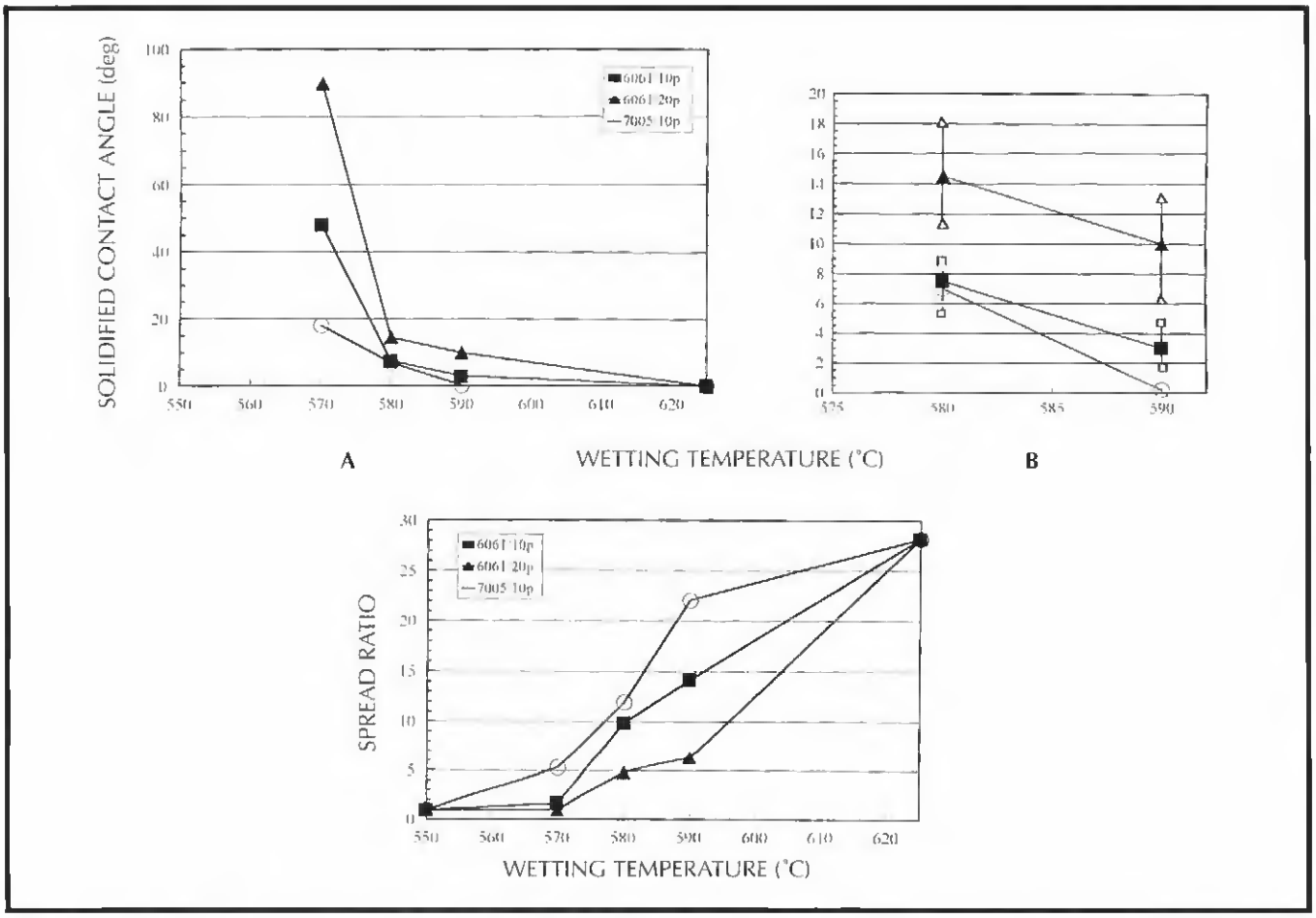


Fig. 9 — Effect of brazing temperature on: A — contact angle (θ); B — detail of the variation with temperature and scatter of values, in the optimum wetting temperature range (580–590°C); C — spread ratio (S_r) for the three MMCs tested.

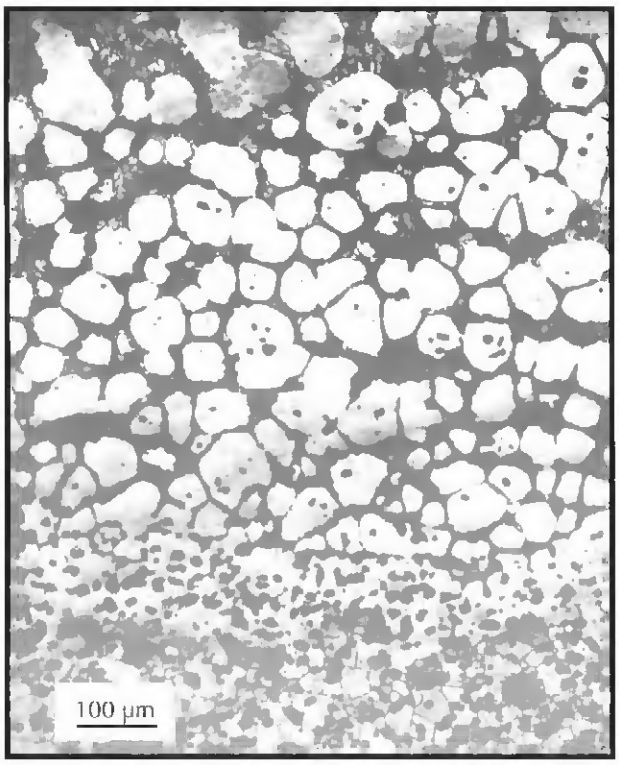


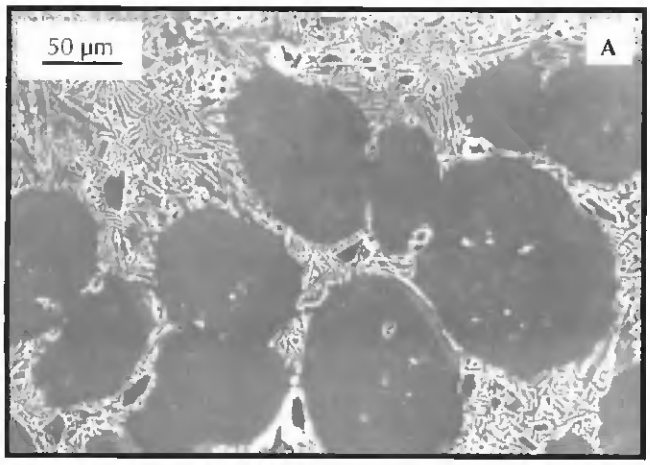
Fig. 10 — Microstructure of a solidified braze drop on a AA6061/Al_2O_3/10p sheet. Wetting temperature (T_W) of 580°C (1076°F).

ment is partially due to Al solid state diffusion from the composite matrix during the heating stage, the presence of Al_2O_3 particles in the molten pool can only be explained by the melting of a portion of the MMC, and its dissolution into the drop.

In addition, it has been observed that the drop microstructure is not homogeneous, being richer in aluminum in zones close to the wetting interface, where the proportion of alumina particles is also higher. Figure 12 shows the microstructure of this interface. It presents a high degree of continuity and is free of voids. The presence of particles inside the aluminum cells formed in this zone indicates that the filler metal has penetrated through the MMC grain boundaries by a capillary action.

The Al enrichment of the molten pool and the penetration of the molten braze into the base composite matrix are both due to the diffusion of the Si from the filler metal to the MMC. This phenomenon starts during the heating process in the brazing cycle, and is initially a function of diffusion between solids. However, when the brazing temperature is reached, liquid-solid diffusion may lead to the braze penetration into the composite matrix. When wetting times are too long, as occurred in the present tests (~ 10 min), the penetration goes too far resulting in erosion. Drop formation tests done at a higher temperature (> 590°C) (> 1094°F) produce a higher degree of erosion, reaching in maximum erosion when brazing temperature was 625°C (1157°F) (θ < 0°).

The dissolution of the base material into the braze metal reduces its wettability, because of increases in the proportion of primary solid phase in the drop, and the increased presence of alumina particles in the liquid. Both solid constituents in-



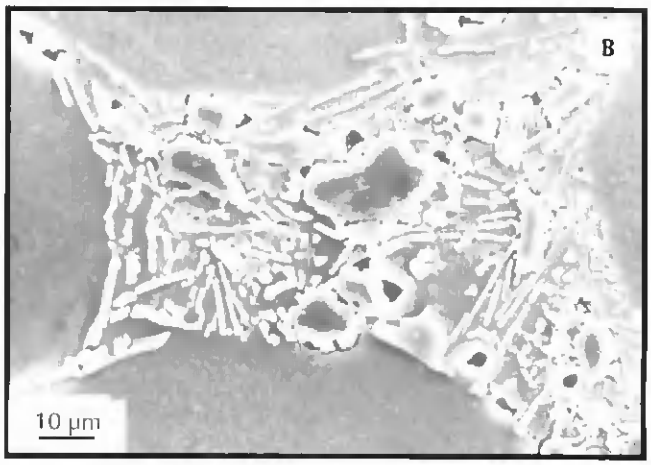


Fig. 11 — A — Primary (Al) cells in brazing molten pool with Al-Si eutectic for AA6061/Al_2O_3/10p; B — details of Al_2O_3 particles inside the intracellular spaces associated to the eutectic aggregate.

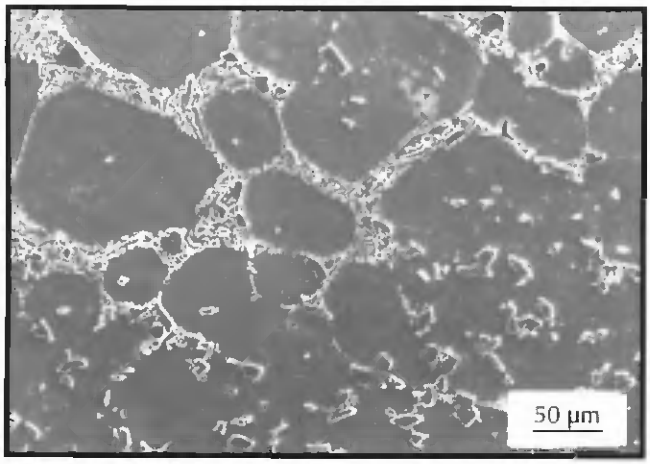


Fig. 12. Brazing interface in a BAlSi4-AA6061/ Al_2O_3/10p drop test showing reinforcement particles inside the (Al) cells (base composite is at bottom of figure).

crease the viscosity of the molten filler. The erosion may be limited by lowering the process temperature, shortening the heating cycle and/or restricting the volume of molten filler metal.

AA6061/Al_2O_3/20p Material

Microstructures of braze drops obtained on 6061 alloy reinforced with 20% particles, with the same wetting conditions as those discussed in the previous section, showed a higher proportion of alumina particles, which reduce the primary (Al) cell size, especially in zones close to the wetting interface where the particle proportion is the greatest — Fig. 13. For this material, the aluminum enrichment by Si penetration and base matrix dissolution is higher than for the alloy with lower particle contents. The increase in the proportion of solid phases in the molten drop reduces the wettability, in addition to the effects caused by the low surface tension of the alumina. As in the previous material, there are alumina particles inside the molten pool which are segregated in the intracellular spaces, as a result of particle pushing by the advancing solidification front — Fig. 14A. Backscattered electron images of these zones showed a possible chemical interaction between the alumina particle and the Al-Si eutectic liquid, most notably a Si enrichment on the particle surface — Fig. 14B).

The higher Al enrichment for drops obtained on this material, is explained by the more rapid diffusion between solids

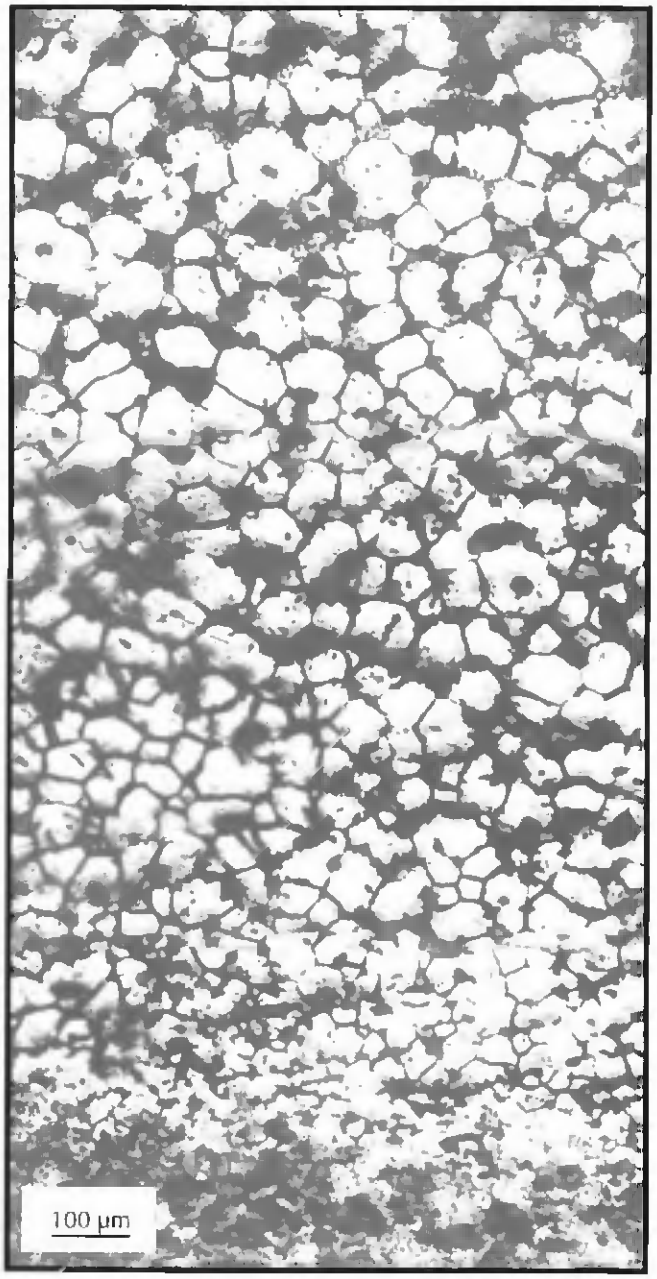


Fig. 13 — Microstructure of a solidified braze drop on AA6061/Al_2O_3/20p material (T_w = 580°C, 1076°F).

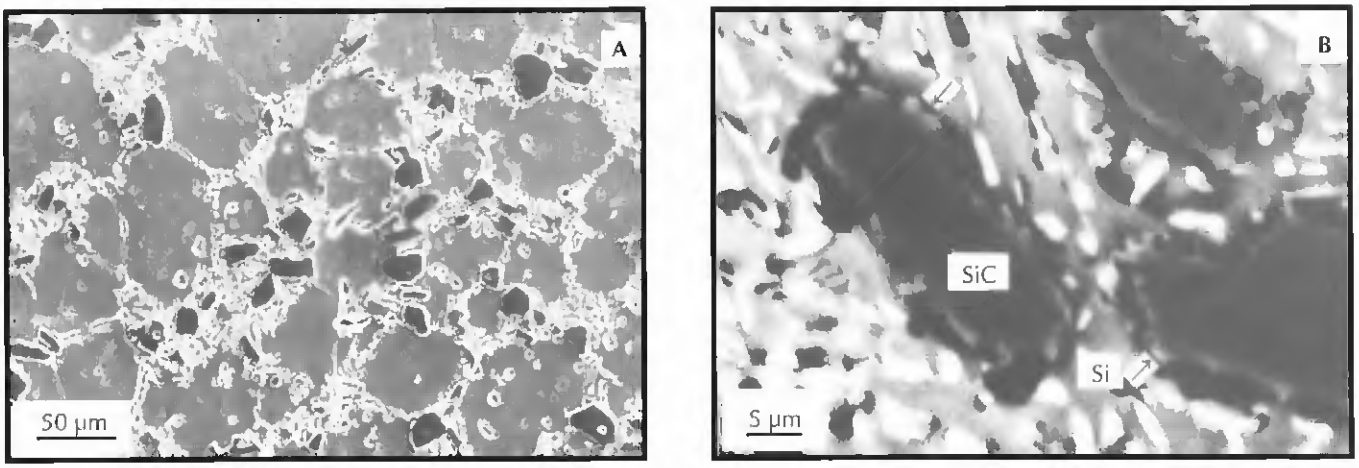


Fig. 14 — A — Al_2O_3 particles inside the intracellular spaces. The smaller size of (Al) cells can be noticed. B — Backscattered electron images of Al_2O_3 particles associated to Al-Si eutectic, showing Si enrichment on the particle surface (marked with arrows).

when the grain size is fine, as in the case of the more reinforced 6061 alloy. In addition, the higher proportion of particle/matrix interfaces may also aid the Si diffusion. In this case, the Si penetration into the base MMC is enhanced, and the erosion is accelerated. However, as several authors have shown (Ref. 7), the effect of grain size is minimal when the brazing cycle is short.

From the previous results, the authors conclude that, to avoid the Si penetration and erosion during brazing of AA6061/Al_2O_3/xxp composites, brazing temperature should be as low (and the wetting times as short) as possible, within the required range determined in the drop formation tests. Consider that 6061 alloy is more deeply penetrated by Si-rich molten braze alloy than other Al alloys (*i.e.*, AA7005) because of its higher Mg and Cu contents (Ref. 16). Both elements diffuse from the composite matrix to the molten pool while Si diffuses from the liquid to the aluminum matrix. The grain boundaries are the preferential paths for the diffusion of these elements. The copper enrichment of the Al-Si liquid is sufficient to lower the melting point and increase the solubility of aluminum. This enrichment aids the preferential melting of grain boundaries.

AA7005/Al_2O_3/10p Material

Microstructural characteristics of braze drops formed on the AA7005/Al_2O_3/10p composite are different from those discussed for the AA6061/Al_2O_3/xxp materials, which account for the higher wettability and spreading measured for this composite. In general, the proportion of primary phase (Al) in the microstructure of the braze drop is, in this case, lower than in the previous materials. Figure 15 shows one of these molten pools formed at 580°C (1076°F), where it appears that there is an almost eutectic microstructure with minor (Al) dendrites. Most of the dendrites have nucleated from the MMC surface. Also, the proportion of alumina particles in these pools is very limited, and always located near the wetting interface.

The higher wettability and spreading of BAlSi4 filler on this composite can be explained by the diffusion of Zn from the base matrix into the liquid, which reduces its melting point and moves the molten braze composition nearer to the eutectic composition. This reduces the liquid viscosity and enhanced the rate of spreading. These are not local phenomena, but occur across the entire wetting interface, and do not produce any preferential grain boundary melting. EDS microanalyses carried out on aluminum dendrites nucleated on the original wetting interface showed a Zn concentration close to 2 wt-%. Some higher levels of zinc have been found in the aluminum matrix of the Al-Si aggregates within the wetting region.

Micrographs taken at the wetting interfaces (Fig. 16) show that the inter-

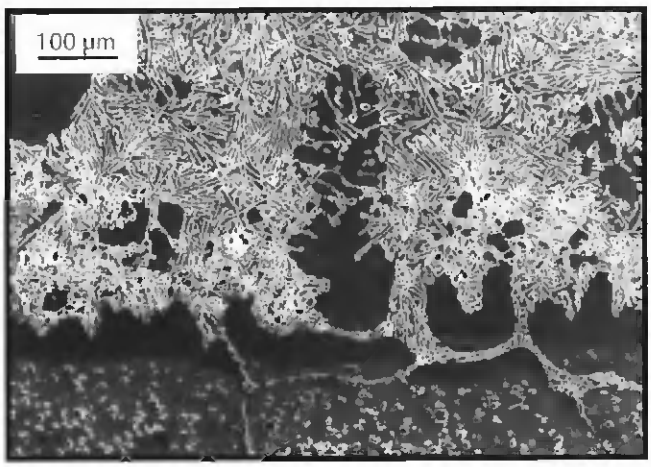


Fig. 15 — Microstructure of a solidified brazing drop on the AA7005/Al_2O_3/10p material (T_w = 580°C) (1076°F).

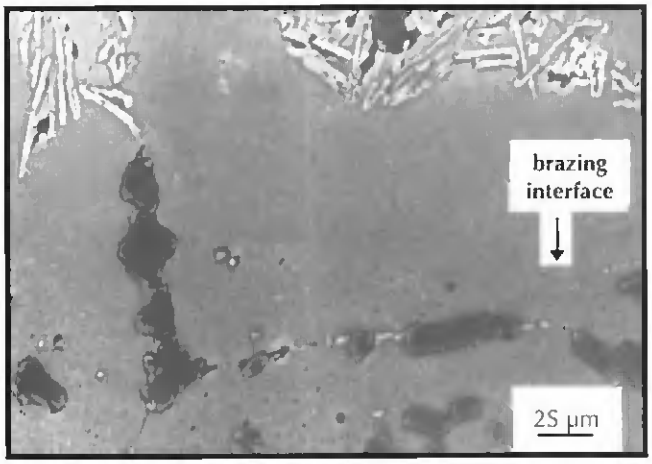


Fig. 16 — Details of BAlSi4-AA7005 matrix composite wetting interface showing a high continuity degree and low filler metal penetration through the grain boundaries (BSE image).

granular penetration of molten filler metal is less favored, especially when alumina particles are present. The lower Cu content of this alloy (0.002 %) and, especially, its higher Mn content (0.40 %) might be the factors responsible for the insignificant amount of penetration observed for this composite. Studies on grain boundary penetration during brazing of unreinforced aluminum alloys carried out by other authors (Ref. 16) have shown that penetration appears to stop because of the existence of very stable precipitated phases inside the grain boundaries. Manganese in the alloy inhibit liquid penetration, possibly because of the formation of stable Mn-rich particles (*i.e.*, $MnAl_6$). The results of the EDS microanalyses at the termination of liquid regions have shown concentrations in manganese (> 0.6%) higher than in the rest of the base 7005 matrix (< 0.4%). Microanalyses results indicate also the presence of iron-rich particles at the ends of the liquid boundaries which also appear to restrict the penetration.

Microstructure of "T-shaped" Brazed Joints

T-shaped brazed joints (double fillet) made with the different MMCs studied showed acceptable flowability (capability to fill a capillary gap) for the tested braze filler, for both of the 10% reinforced composites. However, it is poor for the AA6061/Al_2O_3/20p material. In the first two cases, the presence of porosity and incomplete joint filling is limited, despite the use of a small joint gap (< 0.1 mm) (< 3.94 x 10^{-3} in.). However, for the material with the greatest reinforcement volume, there is incomplete joint filling and entrapped flux caused by the improper flow of the molten filler metal. Consider that these tests were carried out with shortened wetting times (2–5 min). The reasons to use shorter brazing times were: 1) to simulate a real brazing process in which the wetting times are usually shorter; and 2) to avoid excessive braze/metallic matrix chemical interactions which generate braze penetration and partial composite melting.

Examples of the microstructures obtained in the "T brazed" joints are shown in Fig. 17A–C, for the AA6061/Al_2O_3/10p material. Both fillet welds and the inner filled gap exhibit an almost eutectic microstructure, with the nucleation of primary (Al) aggregates on the wetted MMC surfaces. The relative proportion of alumina particles in the filler metal is, in this case, very low because of the short wetting time used, which limits the Si penetration in composite matrix. High magnification studies show the high degree of continuity obtained in the brazed interfaces, where the proportion of microvoids is very limited — Fig. 18.

The application of a spheroidization heat treatment for the brazed specimens made it possible to control the shape of the Si eutectic aggregates, and to aid the homogenization and elimination of residual discontinuities by solid state diffusion. Figure 19A and B shows the spheroidization phenomenon undergone by the Si needles present in the molten pool. This process reduces the stress concentration points in the joint. The brazing interface appears free of voids, showing a high degree of continuity and homogenization — Fig. 19C.

Shear Strength of Brazed Joints

The mechanical shear test results exhibit significant scatter (usually in the range of 15–20%). This is because of the difficulty in producing test pieces with the same joint filling, a problem especially pronounced when AA6061/Al_2O_3/20p is brazed using the single overlap method (scatter higher than 50%).

Figure 20 shows the maximum shear strengths measured for the brazed materials in the as-brazed condition. The shear strengths for both alloys reinforced with 10% of alumina particles are higher than 90% of the BAlSi4 nominal shear strength (108 MPa) (15.6 ksi), which has been calculated taking into account that

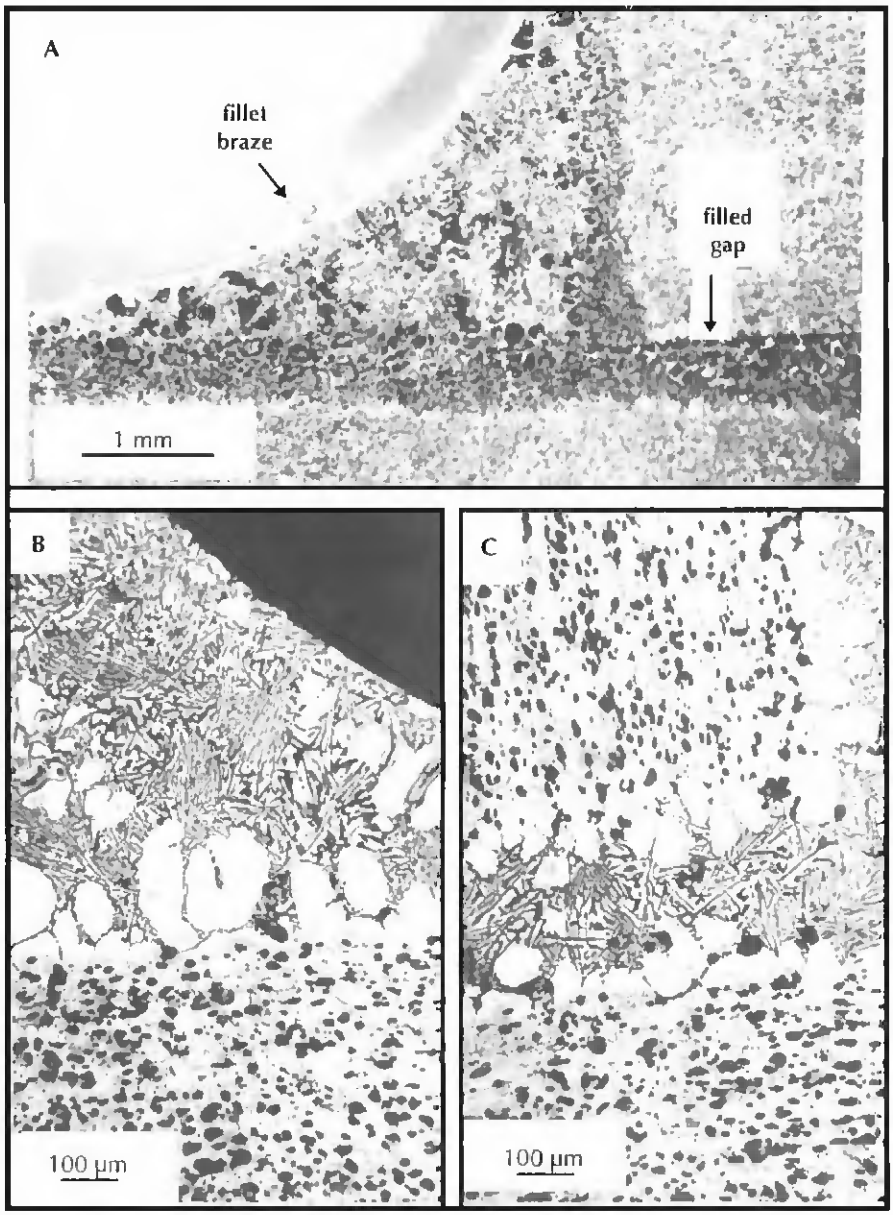


Fig. 17 — A — T-shape brazed joint in a AA6061/Al_2O_3/10p material; B — microstructure of fillet braze; C — microstructure of filled gap.

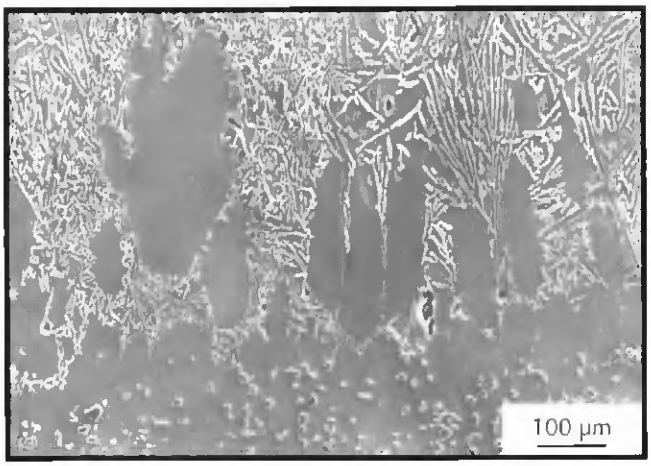


Fig. 18 — SEM micrography of the brazing interface formed in the filled gap.

shear strength of Al alloys is approximately the 60% of its tensile strength (Ref. 17). Thus when proper joint filling by the brazing filler metal is obtained, its mechanical strength is controlled by the braze metal alone. The soundest joints are those in which 100% of the joint area is wetted and filled by the brazing filler metal. These joints displayed shear strengths similar to the filler metal tensile strength.

The maximum strength values obtained for both brazed 10% particle reinforced materials can be also compared with the base MMC tensile strength, considering again that the measured shear strengths are 0.6 of the tensile strengths. So those values are approximately 50% of tensile strength for both composites in the T6 condition, which are 310 MPa (44.8 ksi) for AA6061/Al_2O_3/10p-T6 (Ref. 18) and 337 MPa (48.7 ksi) for AA7005/ Al_2O_3/10p-T6 (Ref. 19). However, the strength of the brazed joints may be increased with proper heat treatment and an appropriate joint design may be used to compensate for this lower strength.

In the case of the AA6061/Al_2O_3/20p material, the maximum shear strength measured in the as-brazed condition was too low (40 MPa) (5.78 ksi) because of the wetting, spreading and flowability problems explained in the previous sections, which limit the joint filling and result in voids or shrinkage cavities when the filler metal solidified.

Conclusions

1) Wettability and spreading of anAl-12Si brazing filler metal on aluminum alloys reinforced with alumina particle depend on the temperature, type of matrix and reinforcement fraction. An increase in reinforcement fraction decreases both wetting and spreading, which hinders the brazeability of the aluminum composites.

2) AA7005 matrix composites present higher wettability and spreading than AA6061 matrix composites, because of the decrease in the melting temperature of the braze metal by Zn diffusion. Optimum wetting temperatures determined by drop formation test are 570–580°C (1058–1076°F), for AA7005 matrix composite, and 580–590°C (1076–1094°F), for AA6061 ones.

3) Long wetting times aid Si penetration in the base matrix and the reduction of its melting point, and can lead to the penetration of molten braze into the substrate, resulting in erosion. This problem is less significant for the 7005 composite matrix, and can be reduced if shorter wetting times are used.

4) The flowability of braze metal into a capillary gap in real MMC joints ("T" or single overlap joints) is appropriate in the case of 10 vol-% reinforced alloys, but is limited when AA6061/Al_2O_3/ 20p is brazed because of its low spread behavior.

5) When proper joint filling is obtained, the mechanical strength is controlled by the brazing filler metal alone. Maximum shear strengths greater than 90% of the nominal BAlSi4 alloy alone have been reached for the brazed 10% particle reinforced composites, which

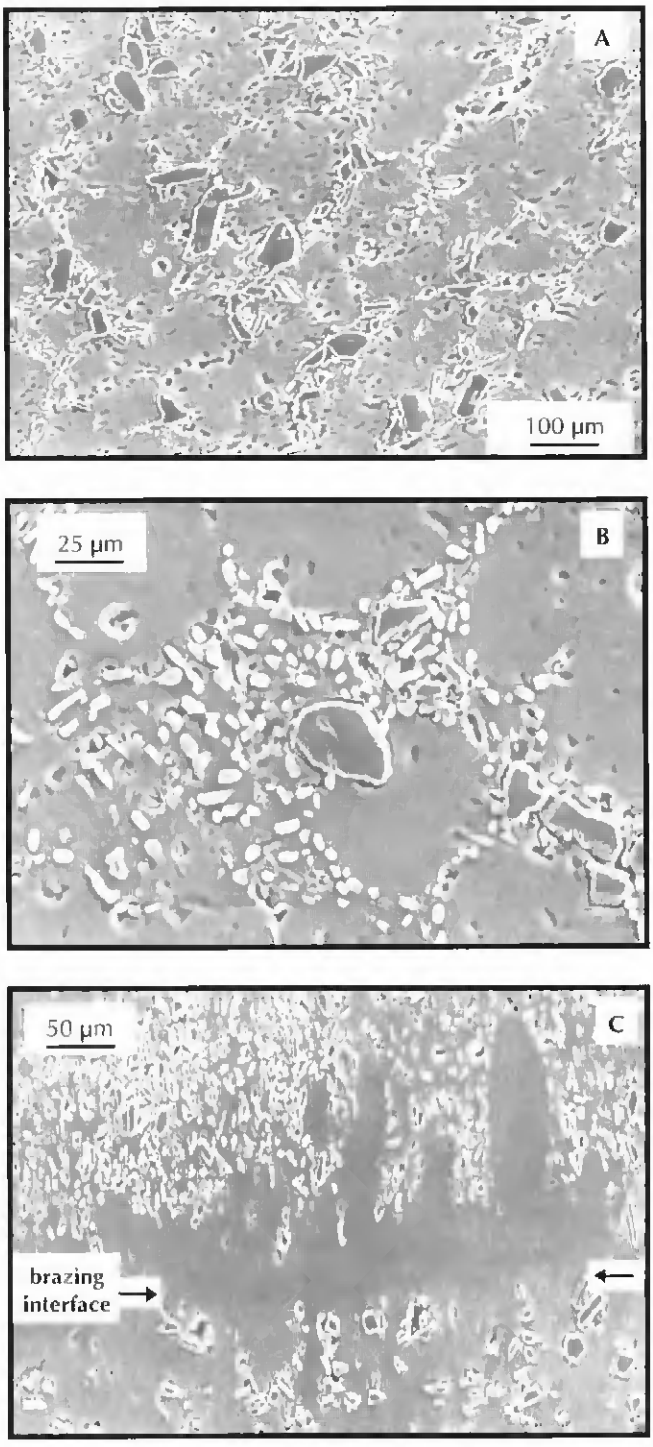


Fig. 19 — A — Microstructure the braze pool in a heat treated joint; B — detail of Si needle spheroidization; C — microstructure of the braze interface in a heat treated joint.

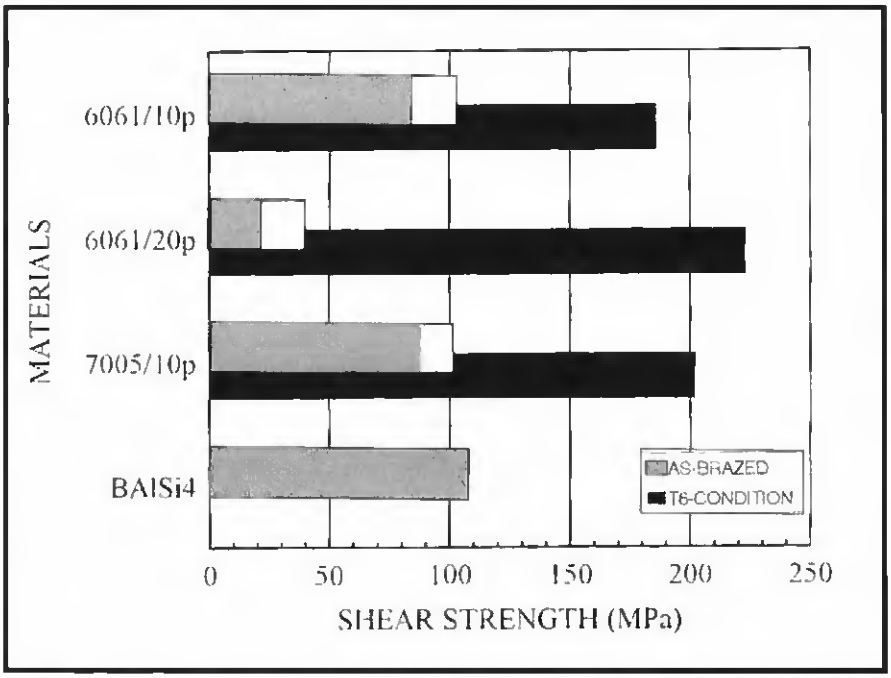


Fig. 20 — Maximum values and error bars of the shear strengths obtained in single overlap brazed joints, in relation to the theoretical shear strengths of the base composites in T6 condition and of the braze alloy (theoretical values calculated as 0.6 of the respective tensile strengths).

are close to 50% of their strengths in the T6 condition.

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