Mechanical and Metallurgical Properties of MMC Friction Welds

With certain parameter adjustments, friction welding can be a successful process for joining metal matrix composites

BY Z. LI, C. MALDONADO, T. H. NORTH AND B. ALTSHULLER

ABSTRACT. The mechanical and metallurgical properties of similar and dissimilar welds involving aluminum-based metal matrix composite (MMC) base material were investigated using factorial experimentation. The test materials comprised aluminum-based alloy 6061/Al_2O_3 (W6A.10A-T6), aluminum Alloy 6061-T6 and AISI 304 stainless steel.

Notch tensile strength increased when high friction pressures were employed during MMC/MMC, MMC/Alloy 6061, MMC/AISI 304 stainless steel and Alloy 6061/Alloy 6061 friction welding. In MMC/Alloy 6061 welds, notch tensile strength also increased when high forging pressures were employed. The responses of MMC and Alloy 6061 base materials were similar with regard to the influence of joining parameter variations on notch tensile strength properties.

Applied oxide films on both the MMC and AISI stainless steel substrates had a markedly detrimental effect on dissimilar weld mechanical properties. The optimum notch tensile strength properties were produced when high friction pressure values were applied during dissimilar MMC/AISI 304 stainless steel welding. High friction pressure had two beneficial effects, *i.e.*, it decreased the thickness of the $FeAl_3$ intermetallic film and it promoted disruption and dispersal of oxide films at the joint interface. In direct contrast, the presence of thick anodized oxide films on the MMC substrate surface prior to friction welding had no observable influence on MMC/MMC weld mechanical properties.

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Introduction

The high specific strength, specific stiffness and wear resistance properties of aluminum-based metal matrix composite (MMC) base material compared with conventional aluminum-based alloys readily explains the driving force for application of such materials in automotive and aerospace industry applications. However, successful application of aluminum-based composite material in these industries depends on the availability of proven joining techniques that produce high-quality joints in rod and tubular sections. With this in mind, it would be expected that friction welding would be the natural choice during fabrication since joints are made rapidly, have consistent mechanical properties and the joining technique is readily automated. However, although much work has been carried out on friction welding of metallic alloys, only limited research has been published concerning the metallurgical and mechanical properties of friction welded composite base materials (Ref. 1–8). In addition, since aluminum-based composites will necessarily be applied in conjunction with other metallic alloys (conventional aluminum alloys and/or stainless and low-alloy constructional steels), the provision of satisfactory dissimilar joint properties is an important issue during fabrication.

KEY WORDS

Metal Matrix Composites
Friction Welding
Oxide Films
Aluminum-Based Alloy
MMC
Intermetallic Film
High-Friction Pressure

The friction welding process can be considered as a series of sequential stages, namely: Stage 1 — heat is generated by sliding friction and the torque reaches its maximum value; Stage 2 — heat is generated by mechanical dissipation in the plasticized material and softened material flows radially outward; Stage 3 — a steady-state situation is attained and the torque, temperature distribution and rate of axial shortening (burn-off) are essentially constant; Stage 4 — the rotation is terminated; and Stage S — upsetting occurs. Since friction joining depends on a rapidly applied thermal and stress/strain cycle, it would be expected that the mechanical and metallurgical properties of completed joints would be quite different from those of the base material. The metallurgical effects of friction joining on the properties of aluminum-based MMC material vary depending on the tempers in which the material is supplied. For example, in AlSiMg-T3 aluminum alloy base material, Midling and Grong (Ref. 1) found that the heat-affected zone region was hardened by the friction joining operation. In contrast, friction welding of heat-treatable casting alloy AlSiMg (AlSiMg-T6) base material resulted in a softened heat-affected zone on either side of the joint interface and full recovery of the HAZ mechanical properties was attained following postweld heat treatment (Ref. 1). Also, since the mechanical properties of aluminum-based MMC material depend on a uniform distribution of particulate material, the influence of the friction joining operation on the particle characteristics in the interface region is important. Midling and Grong (Ref. 1)

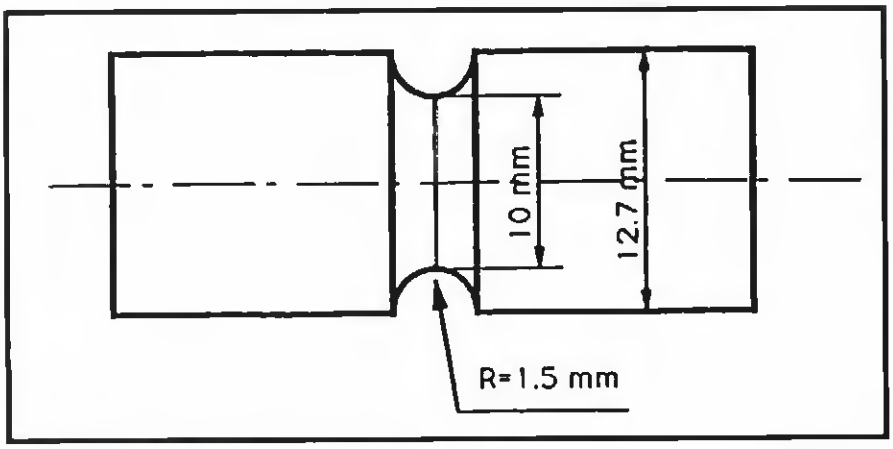

Fig. 1 — Notch tensile test specimen design.

Table 1—Factor Levels in the Design Matrix of MMC/MMC, Alloy 6061/Alloy 6061 and MMC/Alloy 6061 Joints

Variable	Code	Level (low)	Level (high)	Base	Interval
Friction Pressure (MPa)	P1	35	60	47.5	12.5
Friction Time (s)	t	3	9	6	3
Forging Pressure (MPa)	P2	35	90	62.5	27.6

Table 2—Factor Levels in the Design Matrix of MMC/Stainless Steel Joints

Variable	Code	Level (low)	Level (high)	Base	Interval
Friction Pressure (MPa)	P1	30	60	45	15
Friction Time (s)	t	3	6	4.5	1.5
Rotation Speed (rpm)	N	1000	1500	1250	250

did not observe segregation of SiC particulate in AlMgSi (A3S7) friction joints. However, particle fragmentation has been observed in joints between mechanically alloyed aluminum-based material (Dispal) and steel (Ref. 3), in dissimilar joints between MMC and Alloy 6061 and MMC and AISI 304 stainless steel base materials (Refs. 5, 6), and in friction welded Mg-based composite base material (Ref. 7).

Much research on dissimilar joining of aluminum-based material to conventional aluminum alloys and to steel has been concerned with the determination of joining parameter settings that limit the formation of intermetallic layers at the joint interface (Refs. 3, 10–12). For example, $FeAl_3$ and Fe_2Al_5 intermetallics have been detected at the joint interface in aluminum/stainless steel joints following heat treatment (Ref. 13) and Fe_2Al_5 and Fe_4Al_{13} intermetallics were found in aluminum/mild steel friction welded joints (Ref. 14). The underlying basis for joining parameter selection depends upon choosing values that lower the joint interface temperature and decrease the time available for interdiffusion and growth of the intermetallic layer at the joint interface. Although postweld heat treatment has proved successful in improving the mechanical properties of some dissimilar joints, e.g., in dissimilar titanium/AISI 304 stainless steel welds (Refs. 15, 16), this approach cannot be readily applied because of cost considerations.

The present paper represents part of a comprehensive study of the mechanical and metallurgical properties of MMC/MMC, MMC/Alloy 6061, MMC/AISI 304 stainless steel and Alloy 6061/Alloy 6061 friction welds. The influence of friction welding parameters on joint mechanical properties is investigated using a factorial experimentation approach.

Experimental Procedure

Nineteen-mm-diameter bars of aluminum-based metal matrix composite Alloy 6061/Al_2O_3 (W6A.10A-T6) — from this point referred to as MMC base material — were used throughout. The aluminum-based MMC base material contained 10 vol-% of Al_2O_3 particles with an average particle size of about 14 µm. The nominal chemical composition of the MMC base material was 0.28 wt-% Cu, 0.6 wt-% Si, 1 wt-% Mg, 0.2 wt-% Cr, balance aluminum. Nineteen-mm-diameter bars of conventional aluminum Alloy 6061-T6 and AISI 304 stainless steel were used during the evaluation of similar and dissimilar friction welded joints.

Friction welding was carried out using a direct-drive welding machine and welding parameter optimization was investigated using 2^3 factorial experimentation. The independent variables during testing of MMC/MMC, Alloy 6061/Alloy 6061 and MMC/Alloy 6061 joints were friction pressure (P1), friction time (t) and forging pressure (P2). The factor levels in the design matrix are shown in Table 1.

The independent variables during testing of MMC/AISI 304 stainless steel joints were friction pressure (P1), rotation speed (N) and friction time (t_1) These variables were chosen based on an analysis of the results of prior research concerning aluminum/stainless steel friction welding (Refs. 10, 11). The factor levels in the design matrix are shown in Table 2.

It is generally recommended that the forging (upset) pressure should be at least twice the frictional pressure for production of welded joints free of unbonded regions. For this reason the upset pressure was set at twice the frictional pressure value during factorial experimentation and all other joining parameter settings were maintained constant during the test program. The test joints were replicated for each set of welding parameters (in similar and dissimilar joints). A detailed discussion of the factorial experimentation method has been presented elsewhere (Ref. 17).

Notched tensile testing was used as the monitor of weld interface mechanical properties since the properties of similar and dissimilar joints are compared in the present paper. The notch tensile test specimen configuration is shown in Fig. 1. The cross-head speed during tensile testing was 3.6 mm/min. The postweld heat-treatment conditions were comprised of solution treatment at 530°C for 2 h followed by aging at 160°C for 16 h.

The influence of surface finish on the mechanical properties of dissimilar MMC/AISI 304 stainless steel joints was investigated by varying the thickness of the oxide films on the contacting substrates prior to friction welding. The surfaces of the MMC test samples were anodized to produce 5- and 10-µm-thick oxide films. The anodizing treatment involved electro-etching for 12 min (for the 5-µm-thick oxide film) and 24 min (for the 10-µm-thick oxide film) in 165 g/L sulfuric acid at 20°C using an applied voltage of 16 V DC. In the case of AISI 304 stainless steel base material, the oxide film thickness was substantially increased by heat treating the base material at 650°C for 3 h followed by furnace

cooling prior to friction welding. This produced a 2–3-μm-thick oxide film on the surface of the stainless steel. During friction welding, the parameter settings were maintained constant as follows: friction pressure (120 MPa), friction time (1s), rotational speed (1500 rpm) and forging pressure (240 MPa). It should be noted that in each test joint, only one of the MMC or AISI 304 stainless steel components was specially treated to produce thick oxide films.

Results and Discussion

Joining Parameter Settings and As-Welded Joint Mechanical Properties

The notch tensile strength properties of MMC/MMC, Alloy 6061/Alloy 6061, MMC/Alloy 6061 and MMC/AISI 304 joints are presented in Tables 3–6. The regression equations relating welding parameter settings with notch tensile strength for the different base material combinations are as follows:

MMC/MMC Joints:

$$312.8 + \underline{6.5P1} + 4.25\, t_1 + 3.25\, P2$$

Alloy 6061/Alloy 6061 Joints:

$$300.4 + \underline{9.75P1} + 3.8\, P2$$

MMC/Alloy 6061 Joints:

$$259 + \underline{13.8P1} + 4.3\, t_1 + \underline{3.8P2}$$

MMC/AISI 304 stainless steel

$$283 + \underline{22.6P1} + 2.4\, t_1 + \underline{15.6N}$$

In these regression equations, the units are notch tensile strength (MPa), friction and forging pressures (MPa), the friction time (s) and the rotational speed (rpm). The statistically significant variables are those terms underlined in the above equations. Frictional pressure had a statistically significant effect on the joint strength for all base material combinations. Forging pressure also had a statistically significant effect on the notch tensile strength of MMC/Alloy 6061 joints. In MMC/AISI 304 stainless steel joints, the statistically significant variables were friction pressure and rotation speed.

Joint strength was optimized when a high friction pressure was employed during MMC/MMC, MMC/Alloy 6061, MMC/AISI 304 stainless steel and Alloy 6061/Alloy 6061 welding operations. Also, for the range of the joining parameters investigated in the present study, varying the friction time had no influence on the joint notch tensile strength properties of any base material combination.

The range of notch tensile strength values was relatively narrow in MMC/MMC and Alloy 6061/Alloy 6061 joints (Tables 3, 4). Satisfactory notch tensile strength values in MMC/MMC and Alloy 6061/Alloy 6061 joints can therefore be attained using a wide selection of joining parameters. Also, since MMC and Alloy 6061 base materials perform in a remarkably similar manner (with respect to the influence of friction welding parameter settings on as-welded joint strength) the substitution of conventional aluminum alloys by composite base material will be relatively straightforward.

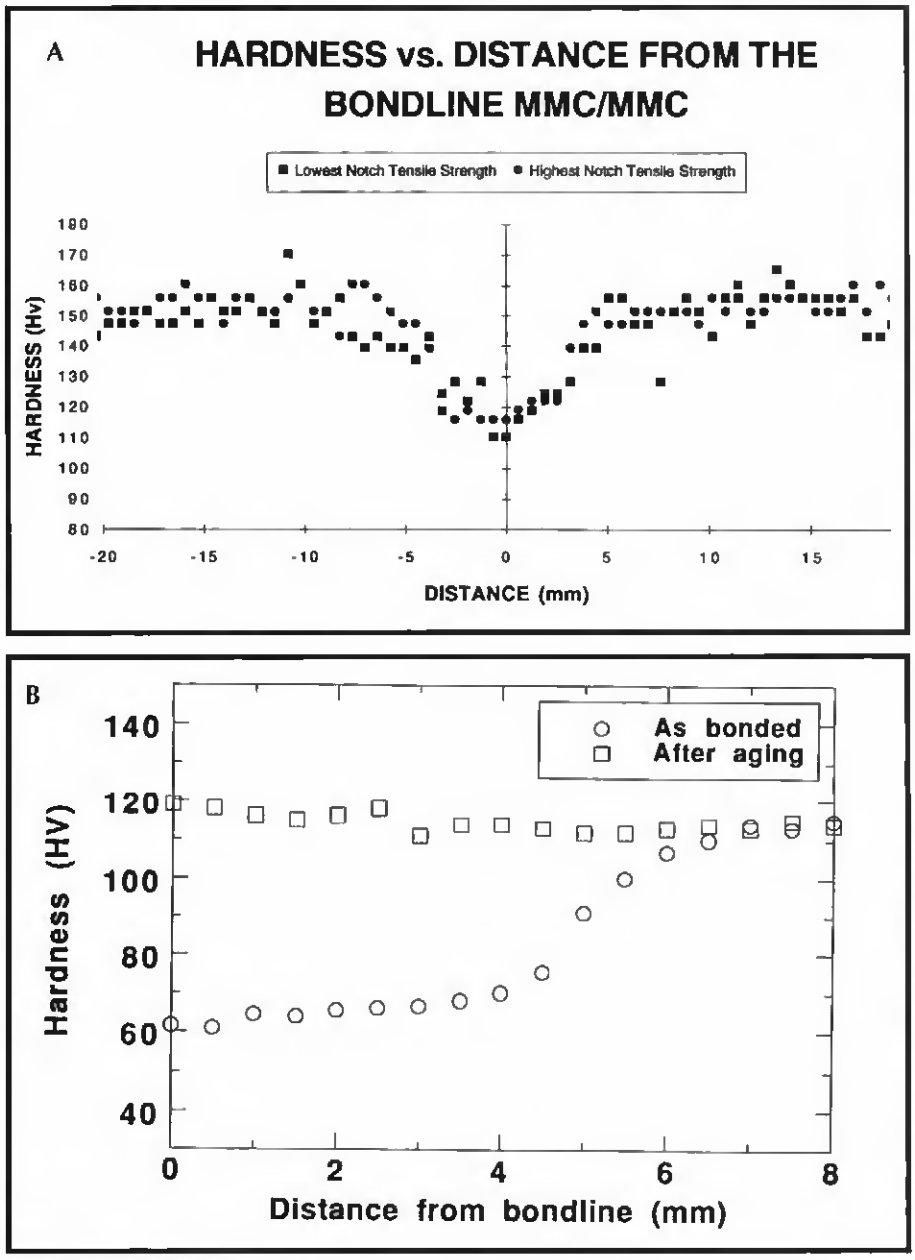

Fig. 2 — A — Hardness traverses across as-welded Alloy 6061/Alloy 6061 joints (showing softened regions in the HAZ). These results were produced in test welds that had the highest and lowest notch tensile strength properties during factorial experimentation; B — hardness traverses across as-welded and PWHT Alloy 6061/Alloy 6061 joints (0 is the weld interface location in this fig.). The welding parameters comprised a friction pressure of 60 MPa, a friction time of 1 s, a forging pressure of 240 MPa and a forging time of 1 s.

Table 5 confirms that the notch tensile strength was much lower in MMC/Alloy 6061 joints at all joining parameter settings. The lower notch tensile strength properties of these joints may have resulted from a combination of the notch tensile test specimen design employed in the present study and the profile of the joint interface produced during dissimilar MMC/Alloy 6061 friction welding. The flow stress at high temperature of Alloy 6061 base material is lower than that of the aluminum-based composite. Because of this difference in mechanical

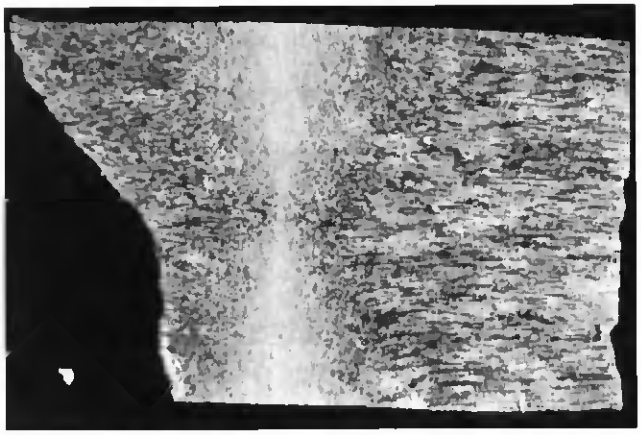

Fig. 3 — Failure in the softened region of an as-welded Alloy 6061/Alloy 6061 joint (during conventional tensile testing).

Fig. 4 — Failure at the weld interface of an as-welded MMC/MMC joint.

Table 3 — Notch Tensile Test Results for MMC/MMC Joints

Trial No.	Design Matrix P1	t1	P2	Notch Tensile Strength (MPa)	Average	Total Loss in Length (mm)
1	−1	−1	−1	293, 309	301	9.5
2	1	−1	−1	282, 342	312	9.5
3	−1	1	−1	300, 301	300	9.0
4	1	1	−1	315, 334	324	10.7
5	−1	−1	1	299, 316	307	9.0
6	1	−1	1	313, 314	313	10.5
7	−1	1	1	313, 319	316	8.7
8	1	1	1	327, 327	327	10.7

Table 4 — Notch Tensile Test Results for Alloy 6061/Alloy 6061 Joints

Trial No.	Design Matrix P1	tI	P2	Notch Tensile Strength (MPa)	Average	Total Loss in Length (mm)
1	−1	−1	−1	283, 284, 307	291	9.5
2	1	−1	−1	295, 309, 317	307	13.8
3	−1	1	−1	276, 282, 289	282	10.4
4	1	1	−1	303, 304, 311	306	13.2
5	−1	−1	1	282, 287, 299	289	12.0
6	1	−1	1	314, 315, 320	316	12.6
7	−1	1	1	286, 299, 314	300	9.7
8	1	1	1	300, 315, 319	311	13.6

Table 5 — Notch Tensile Test Results for MMC/Alloy 6061 Joints

Trial No.	Design Matrix P1	t1	P2	Notch Tensile Strength (MPa)	Average	Total Loss in Length (mm)
1	−1	−1	−1	230, 263	246	8.8
2	1	−1	−1	222, 267	244	11.2
3	−1	1	−1	250, 257	253	8.5
4	1	1	−1	275, 278	276	10.8
5	−1	−1	1	240, 244	242	10.7
6	1	−1	1	284, 288	286	11.3
7	−1	1	1	233, 245	239	10.3
8	1	1	1	272, 296	284	11.5

properties, regions of MMC material become entrained (mechanically mixed) in Alloy 6061 substrate in the region immediately adjacent to the weld interface. It has been confirmed that, in the entrainment region, many Al_2O_3 particles are fractured and there is much evidence of particle/matrix disbonding (Ref. 6). Because of the notch tensile test specimen design employed in the present study, the notch tip is located in the entrainment region, and consequently, the lower tensile strength properties of MMC/Alloy 6061 joints may have in part resulted from regions of particle/matrix disbonding acting as sites for preferential failure.

Table 6 indicates that the notched tensile strength properties of MMC/AISI 304 joints were markedly affected by joining parameter selection. The highest notch tensile strength properties occurred in dissimilar MMC/AISI 304 stainless steel joints produced using high friction pressures. Similar results were produced during friction welding of aluminum alloy base material and austenitic stainless steel (Ref. 11). It has been suggested that the operating parameters that favor optimum joint strength properties are those that promote formation of thin intermetallic films at the dissimilar joint interface. However, it is shown later in this paper that both oxide and intermetallic phases were detected at the MMC/AISI 304 stainless steel joint interface. Since it is well documented that brittle oxide films have a detrimental influence on the mechanical properties of diffusion welded aluminum alloys (Ref. 18) the mechanical properties of dissimilar MMC/AISI 304 stainless steel welds will be determined by the existence of both oxide and intermetallic phases at the joint interface.

Fig. 5 — $Fe(Al,Cr)_2O_4$ or $FeO\ (Al,Cr)_2O_3$ oxide retained at the MMC/AISI 304 stainless steel joint interface.

Fig. 6 — $FeAl_3$ formation at the MMC/AISI 304 stainless steel joint interface.

Table 6—Notch Tensile Test Results for MMC/AISI 304 Stainless Steel Joints

Trial No.	Design Matrix P1	t1	P2	Notch Tensile Strength (MPa)	Average	Total Loss in Length (mm)
1	−1	−1	−1	271, 284	277	9.5
2	1	−1	−1	257, 296	276	9.5
3	−1	1	−1	248, 294	270	9.0
4	1	1	−1	300, 337	318	10.7
5	−1	−1	1	222, 230	225	9.0
6	1	−1	1	254, 272	263	10.5
7	−1	1	1	262, 282	272	8.7
8	1	1	1	332, 343	337	10.7

Table 7—Notch Tensile and Conventional Tensile Testing Results for As-Welded and Heat-Treated MMC/MMC and Alloy 6061/Alloy 6061 Friction Welds

Material Combination	As-Welded Notch Tensile Strength (MPa)	As-Welded Ultimate Tensile Strength[a] (MPa)	Heat-Treated Notch Tensile Strength (MPa)
MMC base material	460	354	—
MMC/MMC Joint	308	257	410
Alloy 6061 base material	447	299	—
6061/6061 Joint	299	190	411

(a) conventional tensile testing.
NA = not available.

Mechanical Properties of Postweld Heat-Treated Joints

The conventional and notch tensile strengths of as-welded and postweld heat-treated MMC/MMC and Alloy 6061/Alloy 6061 joints are compared in Table 7. Postweld heat treatment at 530°C for 2 h and aging at 160°C for 16 h substantially improved the tensile strength of MMC/MMC and Alloy 6061/Alloy 6061 friction welds. In this connection, the notch tensile strength of postweld heat treated MMC/MMC and MMC/Alloy 6061 welds was about 90% of the strength of as-received MMC and Alloy 6061 base materials.

Softening in the heat-affected zone regions was clearly apparent in as-welded MMC/MMC and Alloy 6061/Alloy 6061 friction welds — Fig. 2. These softened regions were produced due to solution and overaging of precipitates in the MMC and aluminum alloy 6061-T6 materials (Ref. 1). Postweld heat treatment removed the softened heat-affected zone in both MMC/MMC and Alloy 6061/Alloy 6061 friction welds.

The presence of softened heat-affected zone regions in as-welded MMC/MMC and Alloy 6061/Alloy 6061 joints influenced the location of fracture during tensile testing. During conventional tensile testing of as-welded Alloy 6061/Alloy 6061 joints, failure occurred through the softened heat-affected zone region adjacent to the weld interface (Fig. 3). In contrast, during notch tensile testing of Alloy 6061/Alloy 6061 joints, failure occurred at the weld interface region. In MMC/MMC joints, sample failure occurred at the joint interface during notch tensile and conventional tensile testing — Fig. 4. It is worth noting that notch tensile testing evaluates the mechanical properties at the joint interface in particular. When the mechanical properties of the joint interface region markedly differ from those in the heat-affected zone, conventional tensile testing produces results that can be difficult to interpret. For example, it has been shown that dissimilar titanium/AISI 304L stainless steel friction welds with a tensile strength >400 MPa had extremely poor bend test properties due to the presence of a brittle intermetallic film at the weld interface (Ref. 16).

Interlayer Formation and Mechanical Properties in Dissimilar MMC/AISI 304 Joints

In dissimilar MMC/AISI 304 stainless steel friction welds, the highest notch tensile occurred when high friction pressure values were used (Table 6). It has been previously suggested that the mechanical properties of dissimilar Al/stainless steel friction welds are determined by intermetallic film formation at the joint interface and that particular welding parameter settings (low friction pressure and high rotational speed) promote formation of thick intermetallic films (Refs. 10, 11, 13). However, in the present study, both oxide and intermetallic

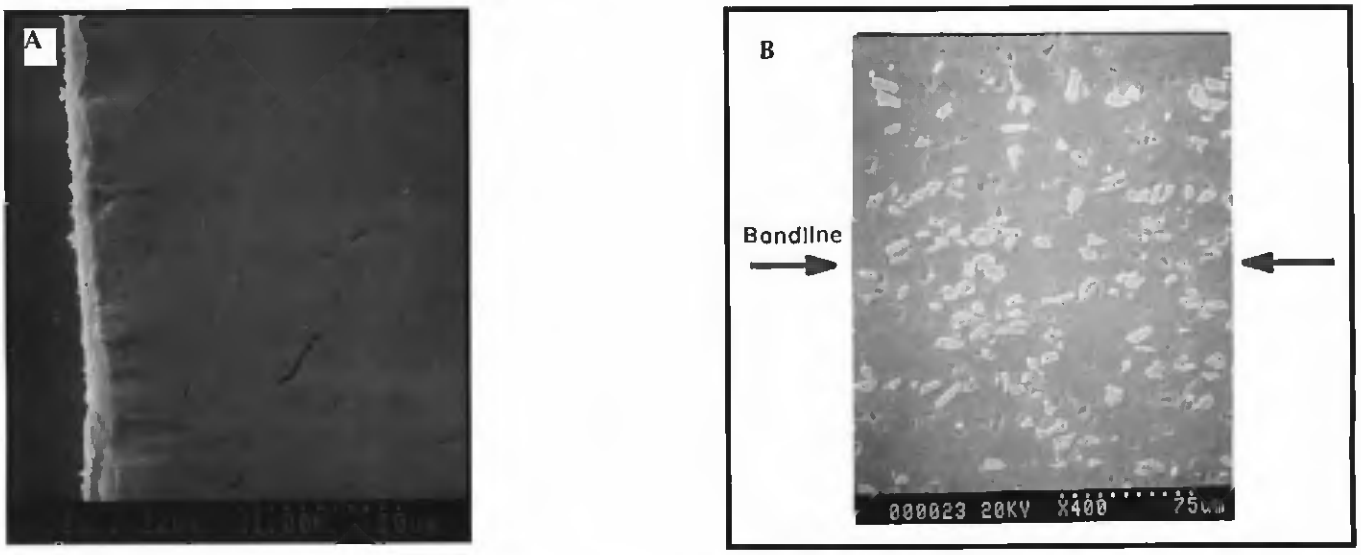

Fig. 7 — A — Oxide layer formed on the surface of the AISI 304 stainless steel substrate prior to friction welding (following heat treatment at 600°C for 3 h); B — the joint interface region in an MMC/MMC friction weld (prior to joining, a 5-μm-thick anodized oxide film was present on the MMC substrate).

Table 8 — Effect of Oxide Layers on the Notch Tensile Strength of MMC/AISI 304 Stainless Steel Friction Welds

Surface Condition	Notch Tensile Strength
10-μm-thick oxide film on the MMC substrate	0 MPa
5-μm-thick oxide film on the MMC substrate	170 MPa
AISI 304 stainless steel oxidized at 650°C for 3 h	202 MPa
MMC and AISI 304 surfaces polished using 280-μm-grit emery paper	228 MPa

Table 9 — Effect of Oxide Layers on the Notch Tensile Strength of MMC/MMC Friction Welds

Condition	Friction Pressure (MPa)	Forging Pressure (MPa)	Friction Time (seconds)	Notch Tensile Strength (MPa)
No anodizing treatment	120	240	1	354
No anodizing treatment	60	240	1	345
Anodized 5-μm oxide layer on MMC substrate	60	120	1	322
Anodized 5-μm oxide layer on MMC substrate	120	120	1	372
Anodized 10-μm oxide layer on MMC substrate	120	120	1	362

phases were detected at the weld interface of MMC/AISI 304 stainless steel welds. Using transmission electron microscopy (Ref. 19), the chemistry of the the oxide film observed at the joint interface comprised $Fe(Al,Cr)_2O_4$ or FeO $(Al,Cr)_2O_3$ — Fig. 5. The intermetallic phase detected at the weld interface was $FeAl_3$ — Fig. 6.

Table 8 shows the influence of oxide on the contacting MMC and AISI 304 stainless steel substrate films (of surface finish prior to welding) on the notch tensile strength of MMC/AISI 304 stainless steel friction welds. It is apparent from Table 8 that thick oxide films on both substrates have a markedly detrimental influence on joint mechanical properties. For example, when the MMC base material was emery-polished prior to welding, the notch tensile strength was 228 MPa. However, the presence of a 5-mm-thick anodized oxide layer on the MMC substrate decreased the notch tensile strength to 170 MPa and when the MMC substrate was covered with a 10-μm-thick oxide film, the dissimilar MMC/AISI 304 stainless steel joint had zero strength. Similarly, oxidation of the AISI 304 stainless steel substrate prior to friction welding produced a detrimental effect on notch tensile strength properties (the notch tensile strength decreased to 202 MPa in this case). Figure 7A shows the 2- to 3-μm-thick oxide layer on the surface of the AISI 304 stainless steel base material immediately prior to dissimilar friction welding. Figure 7B shows the weld interface region produced in an MMC/MMC joint when the MMC base material contained a 5-μm-thick anodized oxide layer prior to friction welding. It is apparent from Fig. 7B that there was no evidence of oxide entrapment at the weld interface region in the MMC/MMC weld.

The temperature at the joint interface increases when high rotational speed and low friction pressures are employed during friction welding (Ref. 20). Since the highest notch tensile strength properties occurred in MMC/AISI 304 stainless steel joints produced using high friction pressures (Table 6), the beneficial influence of this welding parameter setting may in part be ascribed to decreased interdiffusion resulting in formation of a thin $FeAl_3$ layer at the joint interface. However, it is important to emphasize that the use of high friction pressures will increase the torque produced during Stage 1 of the friction welding operation, will decrease the dimensions of transferred particles at the contact zone (Ref. 21) and will promote disruption and dispersal of oxide films present on the surfaces on the contacting MMC and AISI 304 stainless steel substrates. Consequently, the use of high friction pressure during dissimilar MMC/AISI 304 stainless steel friction welding produces two beneficial effects: it inhibits growth of $FeAl_3$ intermetallic films at the joint interface and it favors oxide film disruption and dispersal.

Since oxide films have such a marked

effect on the mechanical properties of dissimilar MMC/AISI 304 stainless steel welds, the influence of anodized oxide layers on the properties of MMC/MMC friction welds was evaluated. Table 9 shows the effect of anodizing the MMC base material surface prior to friction welding. It is readily apparent that there was no observable effect of thick oxide films on the notch tensile strength of MMC/MMC joints. Also, there was no evidence of oxide film retention at the MMC/MMC weld interface — Fig. 7B.

The contrasting effects of oxide contamination prior to welding on the mechanical properties of MMC/MMC and MMC/AISI 304 stainless steel joints may be explained by the markedly different weld interface profiles produced during the joining operation. The joint interface is almost planar in dissimilar MMC/AISI 304 stainless steel welds because almost all the axial deformation (shortening) occurs in the lower strength (lower flow stress at high temperature) MMC substrate. Consequently, the trapped oxide films will be retained on an essentially stationary stainless steel surface, and this may favor the formation of preferentially aligned oxide layers at the weld interface and poor mechanical properties. In MMC/MMC welds, there is an equal chance that the local contact, adhesion and shearing events which characterize Stage 1 of the friction welding process will occur equally on either side of the weld interface. Accordingly, the likelihood of formation of preferentially aligned oxide films in MMC/MMC friction welds will be much decreased.

Conclusions

The mechanical and metallurgical properties of similar and dissimilar joints involving aluminum-based metal matrix composite base material were investigated using factorial experimentation. The test materials comprised aluminum-based Alloy 6061/Al_2O_3 (W6A.10A-T6), aluminum Alloy 6061-T6 and AISI 304 stainless steel. The following conclusions were reached:

1) Friction pressure had a statistically significant effect on the notch tensile strength of MMC/MMC, Alloy 6061/Alloy 6061 and MMC/Alloy 6061 joints. Joint strength will be maximized when high friction pressure values are employed during MMC/MMC, MMC/Alloy 6061, MMC/AISI 304 stainless steel and Alloy 6061/Alloy 6061 welding operations.

2) The response of MMC and Alloy 6061 base materials were similar with respect to the influence of joining parameter variations on the notch tensile strength properties of friction welded joints. With this in mind, the substitution of conventional aluminum alloys by composite base material will be relatively straightforward in friction welding applications

3) Forging pressure had a statistically significant effect on the notch tensile strength of MMC/Alloy 6061 joints. Notch tensile strength increased when a high forging pressure was employed during MMC/Alloy 6061 friction welding.

4) Thick oxide films on both the MMC and AISI stainless steel substrates had a markedly detrimental effect on dissimilar weld mechanical properties. The optimum notch tensile strength properties were produced when high friction pressure values were applied during dissimilar MMC/AISI 304 stainless steel welding. The application of high friction pressure during dissimilar friction welding had two beneficial effects, *i.e.*, it decreased the thickness of the $FeAl_3$ film formed, and it promoted disruption and dispersal of oxide films at the joint interface.

In direct contrast, the presence of thick oxide layers on the MMC base material prior to welding had no observable influence on the notch tensile strength of MMC/MMC friction welds.

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