Joining of alumina short-fibre reinforced AA6061 alloy to AA6061 alloy and to itself

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The weldability of aluminium short-fibre reinforced AA6061 alloy (FRM) to AA6061 alloy and to itself using aluminium brazing materials has been investigated. AA4045 and BA03 were selected as brazing materials. When FRM was brazed to AA6061 alloy with AA4045 sheet, a disorder of fibre orientation near the interface was recognized at a brazing temperature above 863 K. Furthermore, the interface became very irregular and porous. The tensile strength achieved was about 100 MPa on brazing below 863 K. On the other hand, BA03 sheet, which has thin AA4045 layers on an AA3003 alloy layer, made the joint strong. The strength was about 200 MPa. BA03 induced little disorder of fibre arrangement and better contact at the interfaces. The BA03/AA6061 alloy interface was more porous than the FRM/BA03 interface and, hence, weaker. FRM/FRM joints with BA03 sheet had good strengths above 200 MPa.

1. Introduction

Aluminium short-fibre reinforced aluminium alloys (denoted as FRM below) have been known as light, wear-resistant and high-modulus materials. They are expected to be car-engine components such as a piston head, a connecting-rod, and a cylinder. However, there are some difficulties for making a large and complex component as a single FRM product. In addition, because FRMs are still expensive today, their use will be restricted to small bodies in order to utilize their characteristics. This therefore requires the joining of FRMs to base alloys or to themselves.

Numbers of works have been carried out on joining aluminium alloys by TIG or MIG welding [1, 2], solid-state bonding [3], brazing [4, 5], friction welding [6] and so on. However, there has been little work on the joining of FRMs. Several effects must be considered to join FRMs. One of the most important points is to maintain the fibre arrangement across the bonded interface. In addition, when FRM is bonded to itself, it is needed to remove the weak interface area as well as to induce no disorder of the fibre arrangement. From this point of view, solid-state bonding and brazing processes will be two of the most beneficial methods. A brazing process will be convenient for industrial use because it has wide applications.

The joining of aluminium-base FRM requires another important factor. Oxide films at the interface sometimes weaken aluminium joints. It is needed to remove the oxide films existing before bonding and, in addition, to protect them from oxidation during bonding treatment.

In the current study, alumina short-fibre reinforced AA6061 alloy has been brazed to AA6061 alloy and to itself with aluminium-based brazing materials.

2. Experimental procedure

The short-fibre reinforced aluminium alloy (FRM) was made by Nippon Light Metal Co. Ltd (Kambara 161, Kambara-chou, Ihara-gun, Shizuoka 421-32, Japan). It was extruded at an elevated temperature to a rod of 10 mm diameter. The alumina fibres lay almost along the longitudinal direction. They were made by Imperial aluminium fibres was 3 μm and the aspect ratio was about 5. The volume fractions of aluminium fibre were 0, 5, 10 and 15 vol %. The FRM with 10 vol % alumina fibre was used for most experiments. The matrix was AA6061 alloy (Al–0.4 to 0.8% Si–0.8 to 1.2% Mg). The FRM rods were cut to 20 mm length. The surface to be bonded was ground and finally polished with No. 800 SiC abrasive paper.

The brazing materials were two kinds of aluminium alloy sheet based on AA4045 (Al–10% Si) type alloy. One was 150 μm thick AA4045 sheet and the other was 160 μm thick clad sheet, BA03, which has an AA3003 alloy (Al–1 to 1.5% Mn) layer as a central material and both sides are clad by AA4045 alloy. The thickness of the surface AA4045 layer is 6% of the total thickness.

All specimens were cleansed ultrasonically in acetone before brazing treatment. The brazing was performed by the butt-joint construction of FRM/blazing sheet/(AA6061 or FRM). These were put into a fixing jig made of carbon steel (Fig. 1). The specimens were slightly compressed in the longitudinal direction at an elevated temperature by the thermal expansion mismatch between the steel and the FRM. The brazing temperature was between 853 K and 883 K. This was above the melting temperature of AA4045 alloy, about 853 K. The highest brazing temperature, 883 K, is far below the melting temperatures of AA6061 alloy

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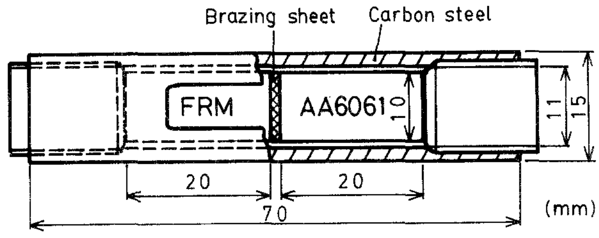

Figure 1 Construction of the brazing jig.

and of AA3003 alloy. The brazing time was 10 min, and brazing was carried out in a vacuum of 5×10^{-5} torr.

Tensile specimens, 2 mm thickness × 6 mm width × 40 mm length, were cut from the joints and then they were heat treated. The T-6 treatment was adopted (annealed at 793 K for 30 min + water quench + aged at 446 K for 6 h). The cross-head speed for the tensile test was $0.5\,mm\,min^{-1}$.

Observations by electron probe microanalysis (EPMA), scanning electron microscopy (SEM) and optical microscopy (OM) were carried out across the interfaces and partly on the fracture surfaces.

3. Results and discussion

3.1. Brazing with AA4045 sheet

Fig. 2 shows the typical microstructure of the FRM/AA4045/AA6061 interface brazed at above 873 K. There was a thin layer of brazing material remaining on the interface. Some pores on the irregular-shaped interface were recognized. In addition, one of the most remarkable features was the rearrangement of the alumina fibres near the interface. The thickness of the layer is about 200 μm in Fig. 2. The fibres were clustered and their arrangements were disordered. This disorder of fibre arrangement might be caused by the partial melting of the matrix of the FRM accompanied by the melting of AA4045 alloy during brazing treatment.

Fig. 3a shows X-ray line profiles by EPMA across the interface brazed at 873 K. It was recognized that magnesium was enriched at the interface as well as silicon. Of course, the brazing material, AA6061 alloy, contains silicon. This silicon might remain at the interface after brazing. However, magnesium must have come from the matrices of AA6061 alloy and of the

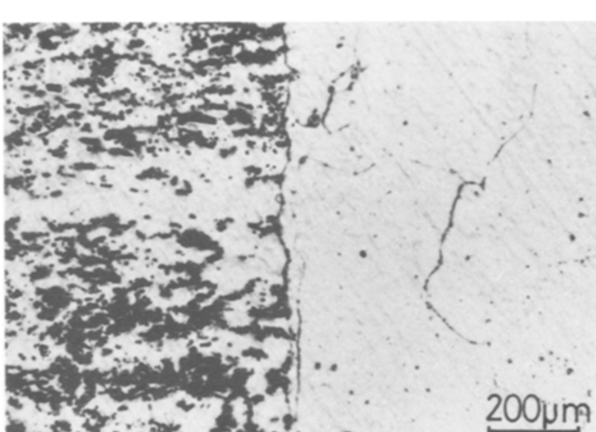

Figure 2 Interfacial structure of an FRM/AA4045/AA6061 joint brazed at 873 K (OM).

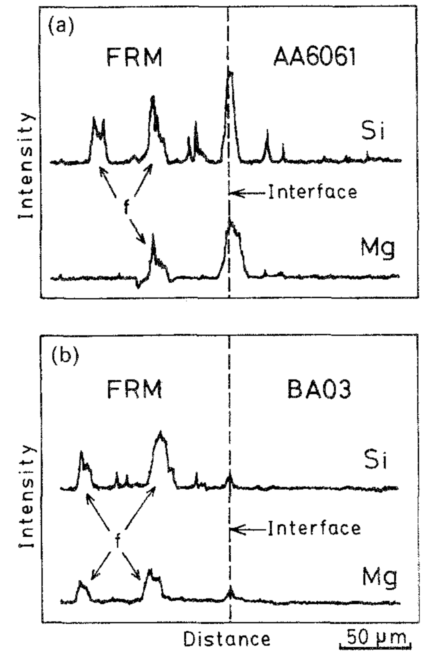

Figure 3 EPMA line profiles. (f) indicates the positions of alumina fibre. (a) FRM/AA6061 interface brazed at 873 K; (b) FRM/BA03 interface brazed at 873 K.

FRM. The enrichment of silicon and magnesium were also recognized in the alumina fibres in the FRM. Because these fibres contained SiO_2, the silicon enrichment was observed in the fibres before the brazing treatment, but the enrichment of magnesium was observed only after the brazing treatment. In addition, this enrichment occurred all over the FRM. Thus, it is concluded that this phenomenon was caused by the heat treatment at 853 to 883 K. X-ray diffraction analysis of the longitudinal cross-section of the FRM after the brazing treatment could not recognize any reaction product.

Fig. 4 shows the temperature dependence of tensile strength. For brazing below 873 K it was possible to

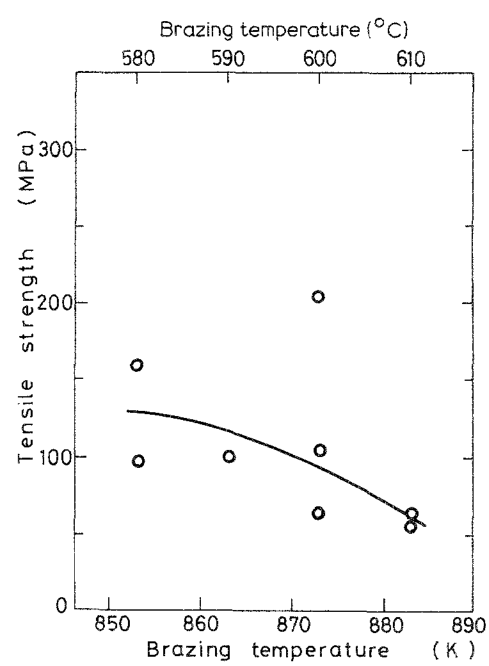

Figure 4 Tensile strength of the FRM/AA4045/AA6061 joint brazed at various temperatures.

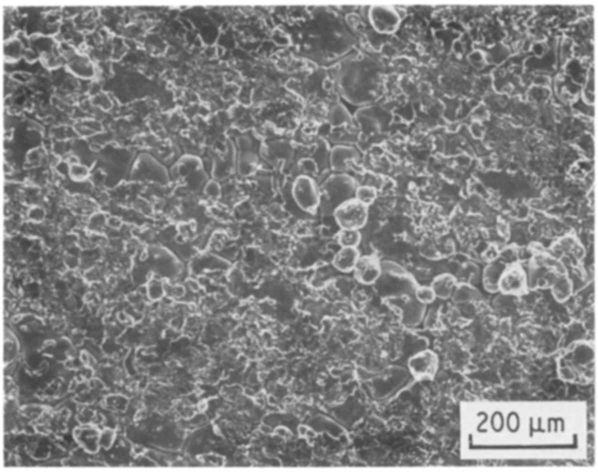

Figure 5 Fracture surface of the FRM side of the FRM/AA4045/AA6061 joint brazed at 863 K (SEM).

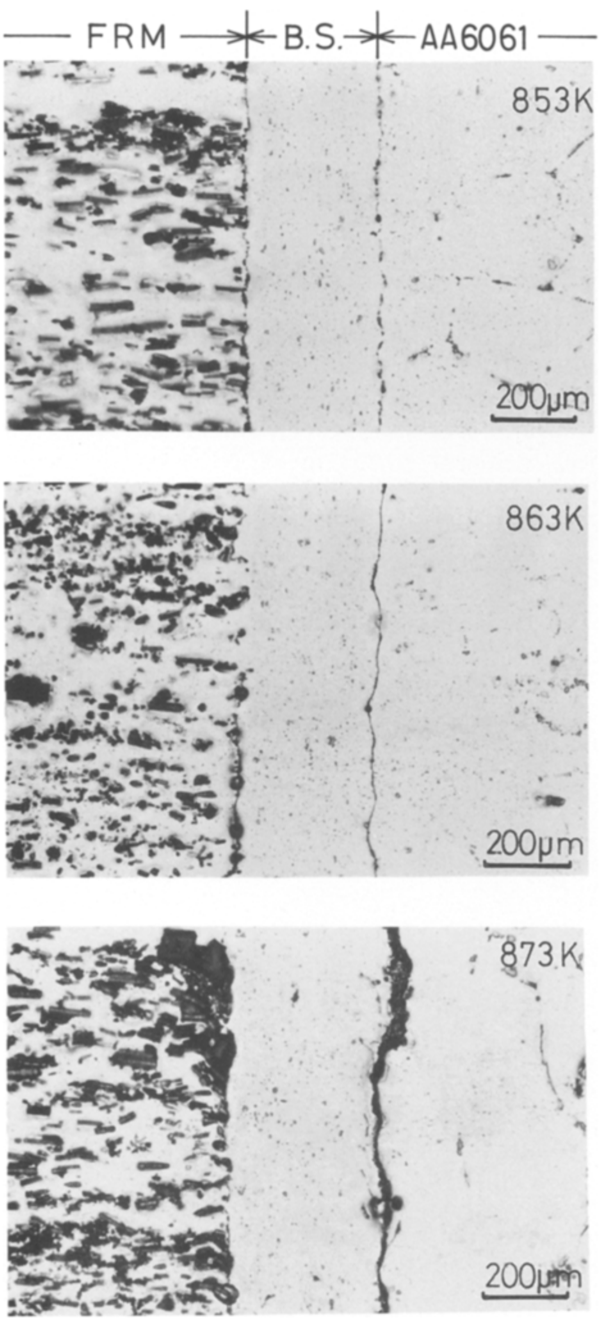

Figure 6 Interfacial microstructures of the FRM/BA03/AA6061 joint brazed at various temperatures (OM). B.S. = brazing sheet.

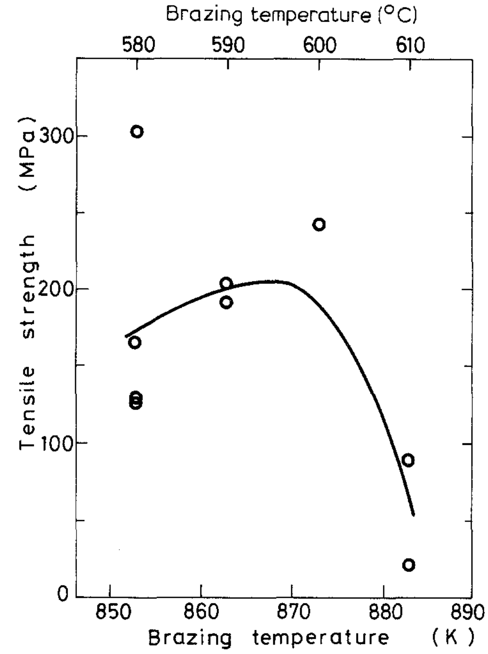

Figure 7 Tensile strength of the FRM/BA03/AA6061 joint brazed at various temperatures.

get a strength of 100 MPa, but the scatter in strength was somewhat wide. Fig. 5 shows the fracture surface of the FRM side brazed at 873 K. In all temperature ranges, many unbonded regions were recognized on the fracture surface. These unbonded regions became wider with raising the brazing temperature. From Fig. 5, grain boundaries are apparently eroded. Silicon diffusion from the brazing material into the AA6061 matrix during brazing seems to cause melting and vaporization of the matrix, especially in the grain-boundary region. The degradation in strength seems to be caused by the expansion of the unbonded regions due to the erosion of matrix, in addition to the disorder of alumina fibre arrangement near the interface.

3.2. Brazing with BA03 sheet

Fig. 6 shows the microstructures of cross-sections of joints brazed with BA03 sheet brazed at various temperatures. Pores were recognized at every interface. The joint brazed at 853 K had arrays of fine pores at both interfaces of FRM/BA03 and of BA03/AA6061. Both interfaces were relatively straight. With increased brazing temperature the pores at the interfaces grew, their number decreased and, in addition, the interface of BA03/AA6061 became irregular. However, the FRM/BA03 interface remained straight even when brazed at 873 K. There was none of the disorder of fibre arrangement which was recognized in the FRM/AA6061 joint with AA4045 sheet. In the photograph the flow line of the fibre seen near the interface brazed at 873 K was caused by grinding before brazing. Fig. 3b also shows the line profiles of X-ray analysis by EPMA. Slight enrichment of magnesium and silicon was recognized at the interface. The amount was very small as compared with that of the case with AA4045 sheet. This difference seems to be caused by the difference in volume of the liquid phase, i.e. that of the AA4045 layer. The enrichment of magnesium in the alumina fibres was also recognized.

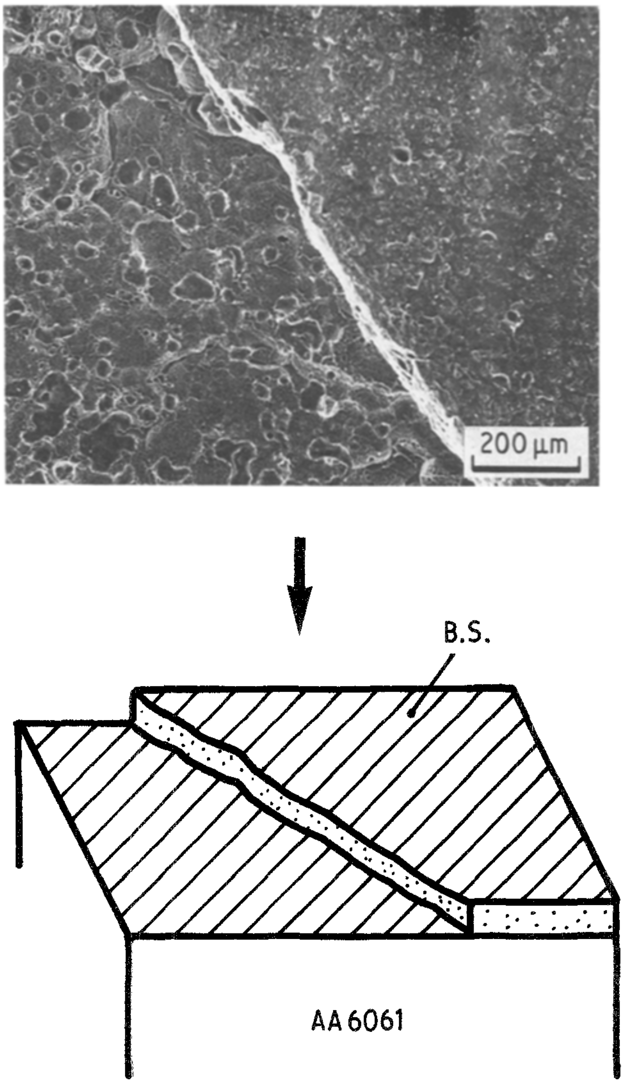

Figure 8 Fracture surface of the FRM/BA03/AA6061 joint brazed which has two surfaces (SEM). B.S. = brazing sheet.

Fig. 7 shows the tensile strength of joints brazed with BA03 sheet at various temperatures. It is apparent that the average strength of the joints with BA03 sheet is higher than that with the AA4045 sheet. The maximum strength beyond 200 MPa could be achieved when they were brazed below 873 K. However, they had a still large scatter in strength. Most of the fracture of the joint with BA03 sheet proceeded along the BA03/AA6061 interface. Fig. 8 shows the fracture appearance, which exhibited fracture surfaces both at the FRM/BA03 interface and at the BA03/AA6061 one. A lot of large pores were recognized at the BA03/AA6061 interface while only a few at the FRM/BA03 interface. Such a difference was also recognized in the cross-sections of the interface as seen in Fig. 6. The BA03/AA6061 interface became wavy during brazing treatment. This wavy interface prevented complete contact between the two materials. On the other hand, the FRM/BA03 interface remained relatively straight during brazing, which promoted completing the contact. There are several reasons to be considered for the difference in shape between the FRM/BA03 and the BA03/AA6061 interfaces. The first is the difference of rigidity. Because the FRM, which contains a lot of alumina fibres, is harder than AA6061, the deformation of the matrix and the boundary migration will be suppressed to some extent, while the AA6061 alloy does not show such effects. The second is that, because erosion of the grain boundaries takes place during brazing as seen in Fig. 5, the FRM (which has finer grains due to the dispersed alumina fibres) resists erosion and then the interface remained relatively straight, but not with AA6061 alloy.

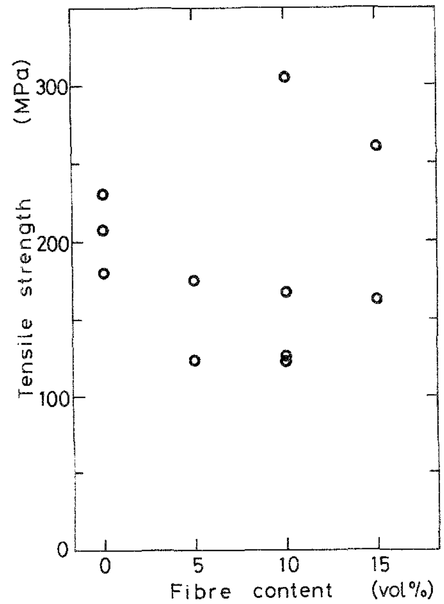

Figure 9 Tensile strength of the FRM/BA03/AA6061 joint with various fibre contents brazed at 853 K.

In any case, the large pores remaining on the BA03/AA6061 interface seem to restrict the strength of the joints.

3.3. Effect of alumina fibre content

Fig. 9 shows the effect of fibre content on the tensile strength of the FRM/BA03/AA6061 joints brazed at 853 K. Because the scatter in strength was wide in the content range, we could not determine the effect of the fibre content. Most of the fracture of the joints took place along the BA03/AA6061 interface. This is the same as the result obtained in the preceding section. This interface restricted the strength of the joints in the fibre content range. However, relatively high strength beyond 100 MPa could be achieved in all contents.

Table I compares the tensile strength data for FRM/BA03/AA6061 and FRM/BA03/FRM joints when they were brazed at 853 K. The FRM contains 5 vol % alumina fibre. It is apparent that the strength of the FRM/BA03/FRM joint is much higher than that of the FRM/BA03/AA6061 joint. Thus, it is concluded that the FRM/BA03 interface is stronger than the BA03/AA6061 interface.

4. Conclusion

The alumina short-fibre reinforced AA6061 alumin-

TABLE I Comparison of tensile strength data for joints brazed at 853 K; the FRM contains 5 vol % alumina fibre

Joint	Tensile strength (MPa)
FRM/BA03/AA6061	160, 187, 208, 231
FRM/BA03/FRM	230, 251, 282

ium alloy has been brazed to AA6061 alloy and to itself using AA4045 sheet and BA03 sheet, which has thin AA4045 layers cladding both surfaces of an AA3003 layer, as brazing materials.

The BA03 sheet was superior for high-strength joining. The AA4045 sheet disordered the fibre arrangement near the interface and severely eroded the AA6061 matrix. These two effects made the joint weak. On the other hand, because BA03 sheet has a small amount of melting volume during brazing, the fibre arrangement at the interface was not disturbed so much. The interface of the FRM/BA03 was stronger than that of the BA03/AA6061.

The strength of the FRM/AA4045/AA6061 joint was about 100 MPa while that of the FRM/BA03/AA6061 joint was about 200 MPa.

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