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Diffusion Bonding of Al-Mg-Si Series 6063 Alloy Reinforced with Alumina Short Fibers[†]

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Abstract

The Al-Mg-Si A6063 alloy reinforced with alumina short fibers has been diffusion-bonded with the bond interface perpendicular to the direction of fibers, i.e., direction of the highest strength, and the effects of surface treatments, bonding parameters (temperature and pressure) and insert metals on the bond strength have been systematically investigated. The surface treatments used were (i) electropolishing, (ii) turning in a lathe and (iii) wire brushing. On the faying surface finished by (i), fibers protruded from the surface of the matrix metal were observed, and their height increased with electropolishing time. Treatment (i) resulted in bond strength considerably higher than (ii) and (iii), though the bond strength was decreased with the increase in the protruded height of fibers more than 8 μm. This decrease in the bond strength was probably due to the suppression of intimate contact between matrix surfaces by protruded fibers which were broken by bonding pressure and laid on the bond interface. In case of (iii), a lot of fine fragments of the fiber broken by the wire brushing and an increase in iron content were observed at the bond interface. These fragments of the fiber and increase in iron content seem to have harmful effects on the bond strength, since (iii) resulted in the lowest bond strength. In case of (ii), the fine fragment of the fiber was observed, but no increase in iron content could be found. The application of insert metals of Al-Cu-Mg A2017 alloy, copper and silver foils extended the range of bonding conditions to obtain high bond strength, and decreased the bonding deformation; e.g., in case of (i), bond strength not less than the tensile strength of the base metal was obtained with small bonding deformation by using the insert metal of A2017 alloy or copper.

KEY WORDS: (Diffusion Bonding) (Composite) (Aluminum Alloy) (Alumina Fiber) (Bond Strength) (Copper) (Silver)

1. Introduction

In order for fiber reinforced metal matrix composites (FRM) to find extensive use in structures, it is necessary to develop techniques for joining these materials. The conventional fusion welding process, however, will find less use for joining the FRM, because the fusion of the matrix metal accompanies the change in the array of fibers and the welding heat causes the detorioration of fibers[1]. There have been several investigations reported which showed the feasibility of resistance spot welding[1-4] and brazing[1, 5-7] the lap and scarf joints of FRMs. Despite the fact that the diffusion bonding has been applied successfully to the production of a variety of FRMs[1, 8-10], little work[11, 12] has been done on the diffusion bonding of the FRM. Especially, only little amount of information is available concerning the application of the diffusion bonding to the butt joint of FRMs.

In the present investigation, in order to examine the feasibility of diffusion bonding the FRM, the diffusion bonding has been applied to the butt joint of an Al-Mg-Si A6063 alloy reinforced with alumina short fibers (Al_2O_3/ A6063 alloy), and effects of the surface treatment, bonding parameters and insert metal on the bond strength have been systematically investigated. There has been no investigation reported of the diffusion bonding of the Al_2O_3/A6063 alloy, though this composite has already been used by automobile industry as a wear resistant material.

2. Experimental Details

The base metal used was a metal matrix composite containing 15vol% alumina short fibers in Al-Mg-Si A6063 alloy with chemical composition as shown in **Table 1**. The

Table 1 Chemical composition of the matrix metal of Al_2O_3/ A6063 alloy used (mass%).

(mass%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.7	0.5	0.02	0.01	0.5	0.00	0.01	0.01	Bal.

base metal was in the form of a rod 20 mm in diameter which was produced by centrifugal casting and subsequent extrusion. The base metal in the as-received state, which was subjected to the standard T6 treatment of the A6063 alloy, had tensile strength of 180-190 MPa. The solidus temperature of the matrix metal was estimated to be about 890 K using a differential thermal analysis.

On the other hand, the alumina fiber, which contained 4vol% SiO_2, consisted of α-alumina, θ-alumina, mullite and δ-alumina. The mean diameter and length of the fiber were 3 μm and 20 μm, respectively. The fiber showed a preferential alignment in the direction of extrusion, i.e., the longitudinal direction of the rod.

Specimens 20 mm in diameter and 37 mm in length were cut from the base metal for the diffusion bonding. The faying surface, one of the end surfaces of the specimen, was finished by the following three treatments: (1) wire brushing (stainless steel wire 0.1 mm thick and 15 mm long), (2) turning in a lathe (JIS 3S) and (3) electropolishing. The electropolishing was made in a electrolyte cooled to 253 K at 18 V. The electrolyte was a solution of 10vol% hyperchloric acid in ethylalcohol. The electropolishing time was varied from 0.3 ks to 0.9 ks.

The Al-Cu-Mg A2017 alloy used as an insert metal was prepared by cold-rolling an alloy (used in a previous paper[13]) into foils 75 μm and 30 μm thick. The insert metals of copper and silver were commercial foils 5 μm and 6 μm thick, respectively.

The diffusion bonding was carried out in a vacuum of the order of 10^{-2} Pa using a same apparatus as reported in a previous paper[14]; the bond interface was heated with a radiant resistance heater of molybdenum foil 0.1 mm thick, and the pressure to the bond interface was applied with a hydraulic press. After the bonding, the joint was allowed to cool to 473 K in the vacuum environment, and subsequently to room temperature in air.

The bond strength was estimated from tensile strength using a specimen cut from the bonded joint. The gauge length and diameter of the specimen were 30 mm and 8 mm, respectively. The tensile test was carried out at room temperature at the strain rate of $5.7 \times 10^{-4} s^{-1}$ without any particular post-bonding heat treatment.

3. Results and Discussion

3.1 Effects of surface treatment on bond strength

Figure 1 shows the effect of the surface treatment on the tensile strength of the diffusion-bonded joint of the Al_2O_3/A6063 alloy. The heighest bond strength, more than 80% of the tensile strength of the base metal, was obtained for the surface treatment of the electropolishing for 0.3 ks, though the bond strength decreased with the increase in electropolishing time. On the other hand, the surface treatment of the wire brushing resulted in the lowest bond strength. Thus, the bond strength of the Al_2O_3/A6063 alloy was strongly influenced by the surface treatment. In contrast to this, in the diffusion bonding of the A6063 alloy itself (matrix metal), the bond strength was scarcely influenced by these surface treatments[15]. Therefore, the remarkable effect of the surface treatment on the bond strength as shown in Fig. 1 can be attributed to the difference in the morphology of the alumina fiber on the faying surface.

The morphology of the alumina fiber in the vicinity of the bond interface is shown in Fig. 2 for the surface treatments (1), (2) and (3). When faying surfaces were finished by the electropolishing, it was observed that a lot of fibers penetrated into the matrix metal of the other base metal across the bond interface as shown in Fig. 2 (a). These fibers penetrating into the other base metal seem
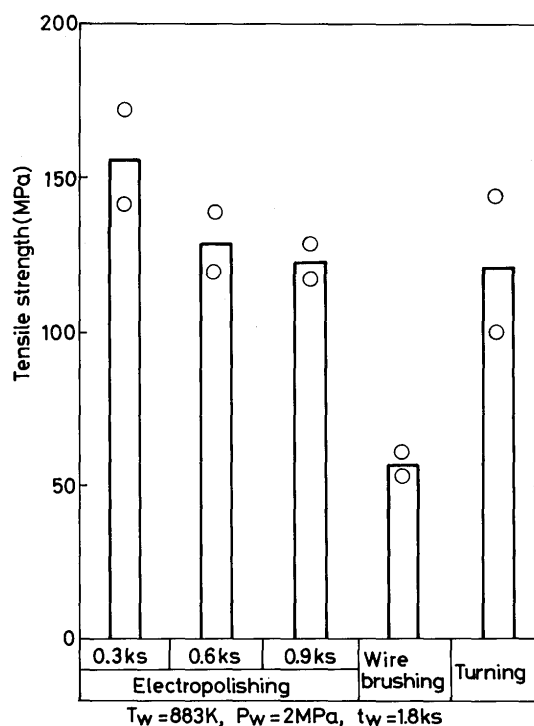
Fig. 1 Effects of the treatment of faying surfaces on the tensile strength of joints. Bonding temperature T_W was 883 K, bonding pressure P_W 2 MPa, and bonding time t_W 1.8 ks.
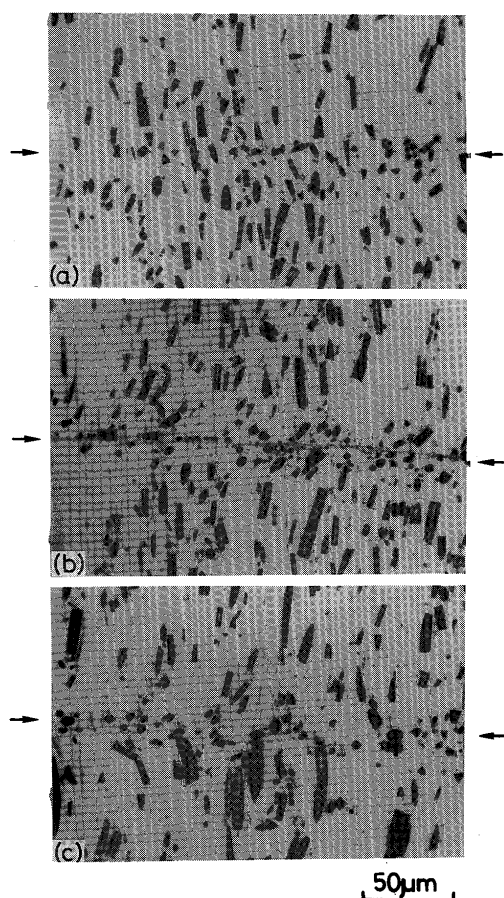
Fig. 2 Effects of the treatment of faying surfaces on the morphology and distribution of fibers in the vicinity of the bond interface (T_W = 883 K, P_W = 2 MPa and t_W = 1.8 ks): (a) electropolishing, (b) wire brushing and (c) turning in a lathe.

was probably formed by the breakup of fibers due to stress imposed on the surface during the mechanical treatments. Since the surface treatment introducing larger amounts of fiber fragments resulted in lower bond strength, it is conceivable that the fragment of the fiber interferes with the bond formation across the bond interface. The lack of the fiber penetrating into the other base metal across the bond interface also seems to be responsible for lower bond strength for the surface treatments of the wire brushing and turning in a lathe.

In addition, an increase in iron content at the bond interface was observed for the wire brushing as clearly seen in **Fig. 3**. Such increase in iron content at the bond interface could not be found for the surface treatments of the electropolishing and turning in a lathe. Considering that the Al$_2$O$_3$/A6063 alloy, including extremely hard alumina fibers, has an excellent wear resistance, the increase in iron content as shown in Fig. 3 can be attributed to wearing powders of stainless steel wires which are formed during the wire brushing and remain on the faying surface. These wearing powders of stainless steel wires also seem to cause the low bond strength for the surface treatment of the wire brushing.

In case of the electropolishing, the bond strength was decreased with the increase in electropolishing time, though no fiber fragment or increase in iron content could be observed at the bond interface (see Fig. 1). In order to explain this decrease in the bond strength, the change in the morphology of electropolished surfaces with electropolishing time was investigated. As

likely to improve the bond strength by reinforcing the bond interface. Fibers which were broken and laid along the bond interface were also observed as shown in Fig. 2 (a). However, no distinguishable difference in the fiber morphology due to the increase in the electropolishing time could be observed with optical microstructure.

On the other hand, for the surface treatment of the wire brushing, the direction of the fiber was changed by the wire brushing, and a lot of small fragments of the fiber were distributed in the vicinity of the bond interface as shown in Fig. 2 (b). In this case, no fiber could be found to penetrate into the matrix of the other base metal. For the surface treatment of the turning in a lathe, the change in the fiber direction and the small fragment of the fiber were also observed as shown in Fig. 2 (c). In this case, however, the size of the fiber fragment was larger, and its amount was much smaller than those for the wire brushing. As seen in Fig. 2, the fragment of the fiber was observed only in case of the mechanical surface treatments, i.e., wire brushing and turning in a lathe, and so
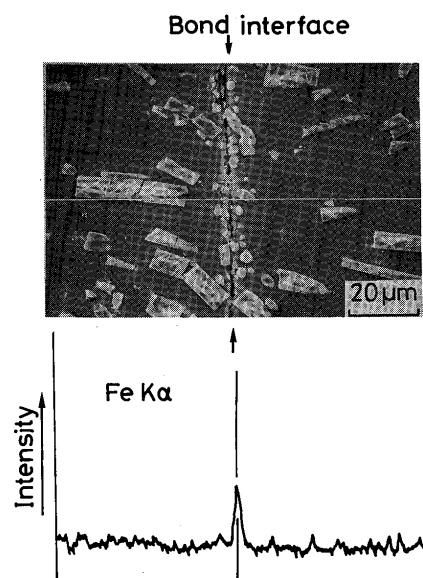

Fig. 3 Scanning electron micrograph of a joint for the surface treatment of wire brushing along with the distribution curve of iron analyzed with EDX along the white line (T_W = 883 K, P_W = 2 MPa and t_W = 1.8 ks).
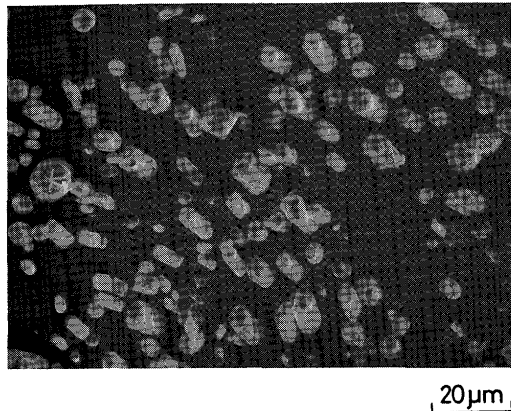
Fig. 4 Scanning electron micrograph of a faying surface finished
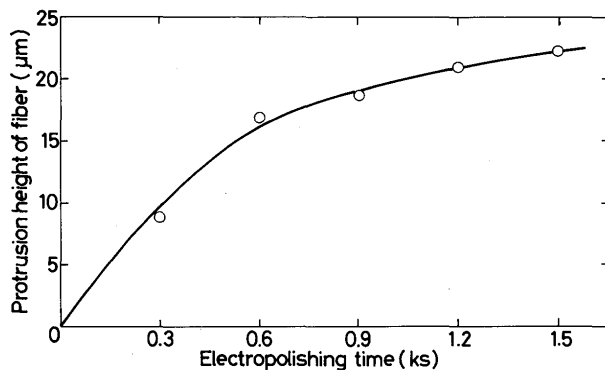by the electropolishing.

Fig. 5 Protrusion height of fibers on faying surfaces finished by
the electropolishing in ethanol solution containing 10%
hyperchloric acid as a function of electropolishing time.
The temperature and voltage for the electropolishing were
253 K and 18 V, respectively.

Fig. 6 Effects of the electropolishing time on the morphology of
the fractured surface of joints (T_W = 883 K, P_W = 2 MPa
and t_W = 1.8 ks): (a) electropolished for 0.3 ks and (b)
electropolished for 0.9 ks.

shown in **Fig. 4**, a number of fibers protruded from the
surface of the matrix metal were observed on the surface
of the Al_2O_3/A6063 alloy subjected to the electro-
polishing. The mean height of protruded fibers, which was
estimated from the optical microstructure of the sec-
tion normal to the electropolished surface, was increas-
ed with electropolishing time as shown in **Fig. 5**. The
protrusion height at the electropolishing time of 0.3 ks, at
which the maximum bond strength was obtained, was
about 8 μm.

With the increase in the electropolishing time, i.e., the
protrusion height of the fiber, the morphology of the
fractured surface of the joint was varied as shown in **Figs. 6**
(a) and **6 (b)**. In case of the electropolishing for 0.3 ks,
dimple patterns were observed in almost all area of the
fractured surface as shown in Fig. 6 (a). As the electro-
polishing time was increased, however, portions were
observed where a number of fibers were laid on the
fractured surface as shown in Fig. 6 (b). These portions,
which show rather smooth appearance, are considered to
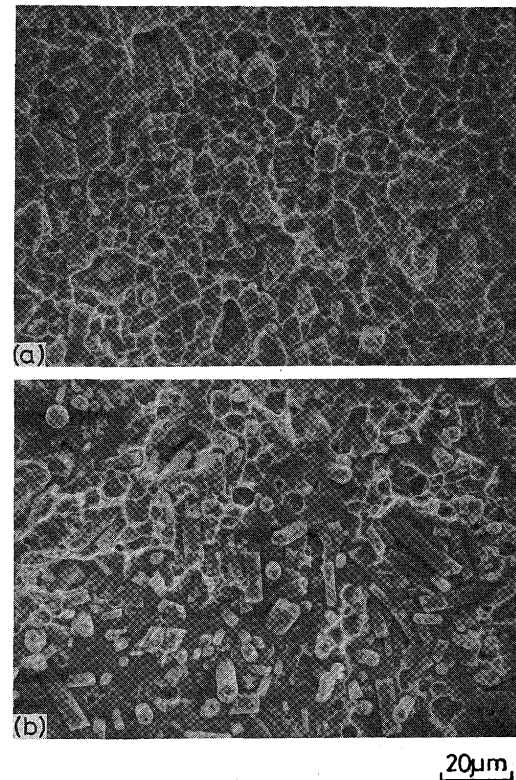be where the intimate contact at the matrix-to-matrix

interface was suppressed by the laid fiber. The decrease in
the bond strength with the increase in the electropolishing
time was probably due to these fibers laid on the fractur-
ed surface. Since these laid fibers could not be observed
before the bonding, these are regarded as protruded fibers
which were broken when pushed against the matrix metal
and the fiber of the other specimen during the bonding.

The probability for the protruded fiber to be bro-
ken during the bonding is increased with the protru-
sion height as described below. Consider a couple of
faying sufaces having protruded fibers of mean height x as
shown in **Fig. 7 (a)**. In order to attain intimate contact
between the matrix metals of these surfaces, the protrud-
ed fiber must penetrate into the matrix of the other
specimen to depth x, i.e., the protrusion height. If the
intimate contact between the matrix metals was attained
without breakdown of the protruded fiber, the increase in
the protrusion height would not decrease the bond
strength, since the penetrating fiber rather reinforces the
bond interface as shown in **Fig. 7 (b)**. However, many
protruded fibers were broken and laid on the bond
interface when pushed against the matrix metal and the
fiber of the other specimen (see **Fig. 7 (c)**). The proba-
bility for a penetrating fiber to meet with fibers in the
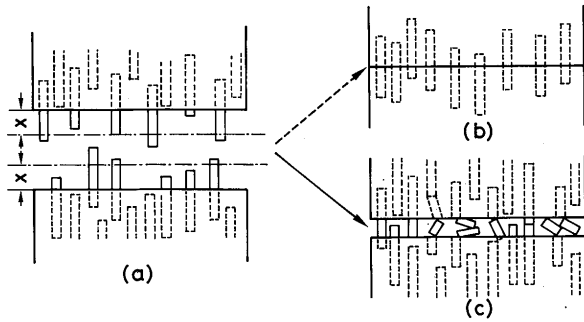matrix metal of the other specimen increases with the

Fig. 7 Schematic diagram illustrating the behaviour of protruded fibers: (a) before contact, (b) ideal contact and (c) real contact.

penetration depth. It is therefore considered that a protruded fiber meets more fibers of the other specimen with the increase in its height, until the matrix metal around the protruded fiber was brought into intimate contact with the matrix of the other specimen. In addition to this, the protruded fiber is more prone to breakdown due to the buckling, as its height is increased. Consequently, more protruded fibers are broken and laid on the bond interface with the rise in the protrusion height, and interfere with the intimate contact at the matrix-to-matrix and matrix-to-fiber interfaces. It is presumably for this reason that the bond strength was decreased with the rise in the protrusion height of fibers (at least more than 8 μm).

3.2 Effects of bonding parameters on bond strength

The relation between tensile strength of joints and bonding temperature in diffusion bonding without insert metal is shown in Fig. 8. The surface treatments used were the electropolishing for 0.3 ks which resulted in the heighest bond strength in Fig. 1 and the wire brushing which resulted in the lowest bond strength. Tensile strength of the base metals subjected to the same thermal history as those of joints is also shown in Fig. 8. The bond strength for both surface treatments was increased with bonding temperature and pressure, though the electropolishing resulted in much higher bond strength than the wire brushing under all the bonding conditions employed. As seen in Fig. 8, high bond strength comparable to the strength of the base metal could be obtained for the surface treatment of the electropolishing. Such high bond strength, however, was obtained in a very narrow range of bonding temperature and pressure; that is, the decrease in bonding temperature only by 10 K or in bonding pressure only by 1 MPa resulted in a marked decrease in the bond strength.

In addition, a large amount of plastic deformation was introduced in the vicinity of the bond interface under the
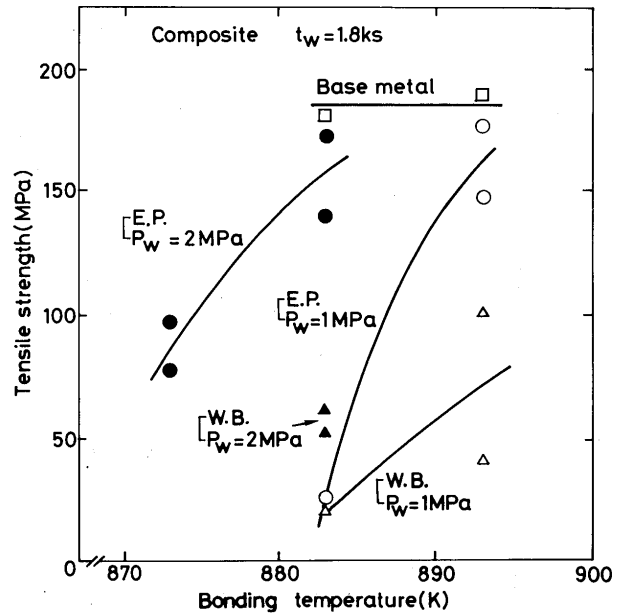

Fig. 8 Tensile strength of joints vs bonding temperature for the surface treatments of electroplishing for 0.3 ks (E.P.) and wire brushing (W.B.). Tensile strength of the base metals subjected to the thermal history similar to those of joints are also shown.
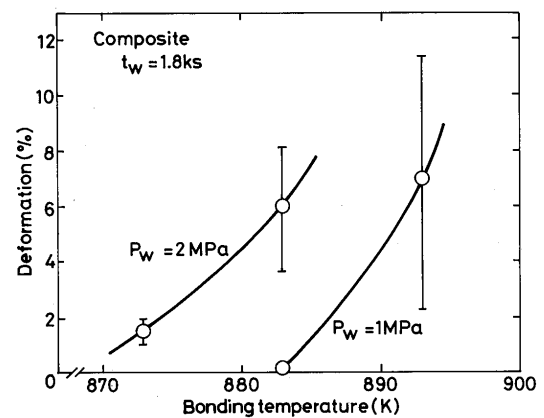

Fig. 9 Bonding deformation vs bonding temperature.

bonding conditions for obtaining high bond strength as shown in Fig. 9. The amount of deformation, which was estimated from the increase in cross sectional area near the bond interface, was as large as more than 6%. Such large deformation is unfavourable since the feasibility of precision welding is an important advantage of the diffusion bonding. Thus, in the diffusion bonding of the Al₂O₃/A6063 alloy without insert metal, the bonding temperature and pressure at which bond strength comparable to the strength of the base metal was obtained were limited to a very narrow range, and in this range the base metal near the bond interface underwent a large amount of deformation. Compared with that of the Al₂O₃/A6063 alloy, the diffusion-bonded joint of the

A6063 alloy itself had bond strength comparable to the strength of the base metal over very wide range of bonding temperature with bonding deformation less than 2%[15].

In order to make clear the reason why the Al_2O_3/ A6063 alloy is difficult to diffusion-bond, a fractured surface of a joint having the highest strength was compared with that of the base metal. As clearly seen in **Figs. 10 (a)** and **10 (b)**, the diameter and depth of dimples observed on the fractured surface of the joint were much smaller than those of the base metal, suggesting that more nucleation sites of fracture existed at the bond interface than in the base metal. Moreover, portions which represented rather smooth appearance were also observed as shown in Fig. 10 (c). These results indicate that the matrix-to-matrix interface is not completely bonded enough to show mechanical properties equivalent to the base metal.

As shown in Fig. 10 (b), fibers projected from dimples were also observed on the fractured surface of the joint, suggesting that fracture occured between the projected fiber and the matrix metal. In contrast to this, fibers observed on the fractured surface of the base metal were sited at dimple bottoms as shown in Fig. 10 (a). This result indicates that the bond strength of the protruded fiber to the matrix metal of the other base metal is lower than that of the fiber in the base metal. Thus, both the bond strength of the protruded fiber to the matrix metal and that of the matrix metal to the matrix are regarded as insufficient for tensile strength of the joint not less than that of the base metal.

3.3 Effects of insert metal on bond strength

Insert metals used were foils of Al-Cu-Mg A2017 alloy with a solidus temperature lower than that of the matrix metal of A6063 alloy and foils of silver and copper with which aluminum forms eutectics at temperatures much lower than the melting point of aluminum; that is, the solidus temperature of the A2017 alloy used is about 800 K[13], and the lowest eutectic temperatures in the Al-Ag and Al-Cu binary systems were 839 K[16] and 821 K[17], respectively. In the present investigation, the diffusion bonding was carried out at temperatures above these solidus and eutectic temperatures, i.e., at temperatures at which liquid phases were formed at the bond interface. It has been shown in several papers[13, 18-20] that insert metals forming liquid phase are very effective in improving the bond strength of aluminum and its alloys.

Tensile strength and fracture location of joints bonded with the insert metals are listed in **Table 2**. The tensile
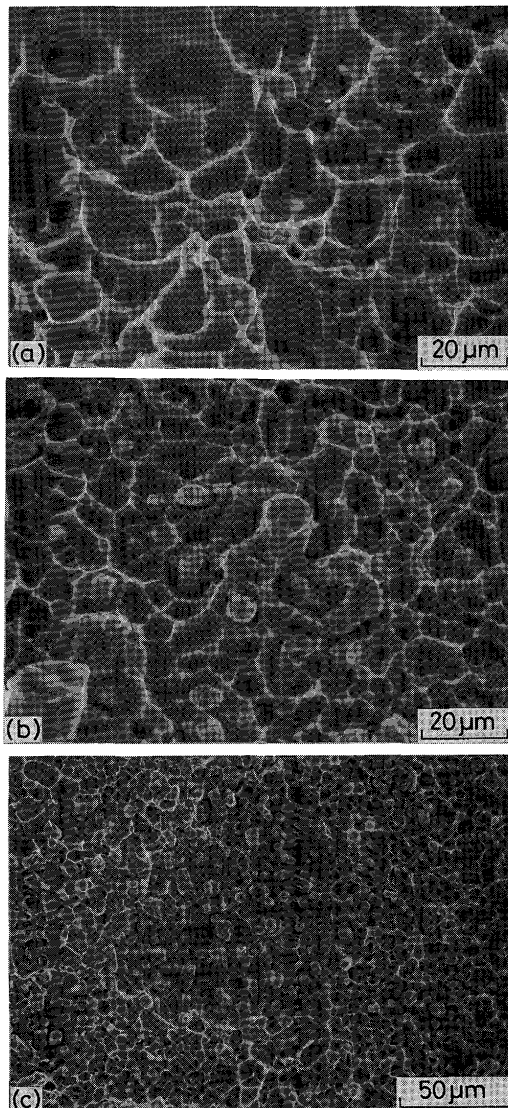

Fig. 10 Fractured surfaces of the base metal (a) and a joint for the surface treatment of the electropolishing for 0.3 ks (b) and (c). Bonding temperature, pressure and time for the joint were 883 K, 2 MPa and 1.8 ks, respectively.

Table 2 Effects of insert metals on the tensile strength and fracture location of joints (t_W = 1.8 ks).

Insert metal	Bond. temp.	Bond. pres.	Tensile strength	Fracture location
None	873 K	2 MPa	98 MPa 97 MPa	B. I. B. I.
A2017 (t75μm)	883	1	161	B. I.
	873	2	184 181	B. M. B. M.
		1	173	B. I.
A2017 (t30μm)	883	1	177	B. I.
	873	2	187	B. I.
Ag (t6μm)	873	2	188 145	B. I. B. I.
Cu (t5μm)	883	1	125	B. I.
	873	2	179 181	B. M. B. I.
		1	162	B. I.
	823	1	119	B. I.

B.I.:Bond interface, B.M.:Base metal

strength of the joint was improved markedly by the use of the insert metals. The decrease in the tensile strength with the decrease in the bonding temperature and pressure as shown in Fig. 8 was also much reduced by the use of the insert metals. In particular, joints having tensile strength not less than that of the base metal were obtained, when the insert metal of the A2017 alloy (75 μm thick) or copper was applied. The amount of bonding deformation undergone under all the bonding conditions listed in Table 2 was less than 2%. Thus, both the bond strength and the bonding deformation were improved remarkably by the use of the insert metals.

Optical microstructures of joints with the insert metals are shown in **Fig. 11**. In case of the insert metal of the A2017 alloy, a number of fibers penetrated into the insert metal, suggesting that the A2017-to-matrix interface was reinforced by these fibers. In this case, a layer without fiber remained at the bond interface. Since the A2017 alloy is inferior to the Al₂O₃/A6063 alloy in wear resistance, it is favourable to decrease the thickness of the layer without fiber. As shown in Fig. 11 (b), the layer without fiber became thinner as the thickness of the insert metal was decreased, but could not be eliminated.

In case of the insert metals of silver and copper, a number of fiber fragments were accumulated in the vicinity of the bond interface as shown in Figs. 11 (c) and 11 (d). Such large number of fiber fragments were not observed in the diffusion bonding without insert metal as

seen in Fig. 2 (a). It is therefore considered that these fiber fragments were formed by the breakdown of fibers which bore the bonding pressure without support by the matrix metal owing to the fusion of the matrix metal. Since the concentrations at the liquidus and solidus at the bonding temperature are lower in the Al-Cu system than in the Al-Ag system, the copper insert metal is considered to form a thicker fusion zone of the matrix metal than the silver insert metal. It can be explained by this difference in the thickness of the fusion zone of the matrix metal that more fiber fragments were accumulated in the joint with the copper insert metal than the silver insert metal.

4. Conclusions

In order to apply the diffusion bonding to the fiber reinforced metal matrix composite, the effects of the surface treatment, bonding parameters and insert metal on the bond strength have been systematically investigated for the diffusion bonding of A6063 alloy reinforced with alumina short fibers. Results obtained are summarized as follows:

(1) The bond strength obtained was strongly influenced by the surface treatments of the electropolishing, turning in a lathe and wire brushing; i.e., the electropolishing resulted in the highest bond strength, and the wire brushing resulted in the lowest. In case of the wire brushing, small fragments of the alumina
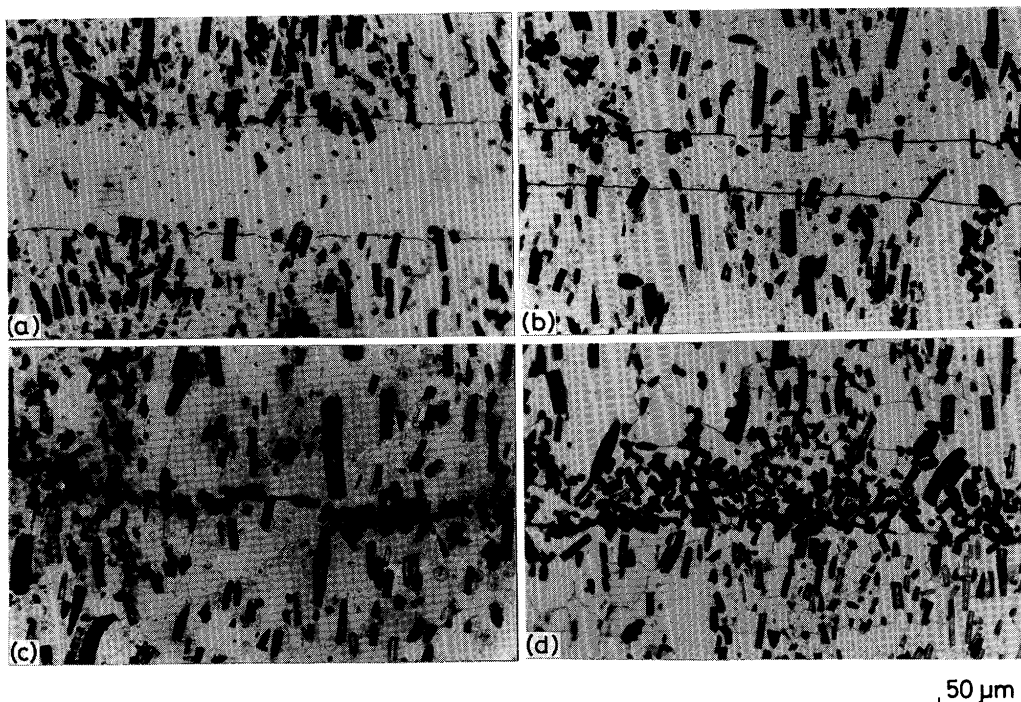

Fig. 11 Microstructures of joints using insert metals of A2017 alloy 75 μm thick (a),
A2017 alloy 30 μm thick (b), silver 6 μm thick (c) and copper 5 μm thick (d)
(T_W = 873 K, P_W = 2 MPa and t_W = 1.8 ks).

fiber and wearing powders of the steel wire which were formed during the wire brushing were accumulated on the surface and interfered with the bonding. The fragment of the alumina fiber was also observed in case of the turning in a lathe, but its amount was much smaller than the wire brushing. In contrast to this, neither the fragment of alumina fiber nor the wearing powder of steel wire was observed for the electropolishing. On the electroplished surface, alumina fibers were protruded from the matrix metal. The protruded fiber was broken and laid on the bond interface when pushed against the matrix metal and fiber of the other specimen during the diffusion bonding. The number of fibers laid on the bond interface was increased with the height of the protruded fiber. Since the laid fiber interfered with the intimate contact at the matrix-to-matrix interface, the bond strength was decreased with the increase in the height of the protruded fiber.

(2) In case of the electropolishing, tensile strength of joint comparable to that of the base metal was obtained without application of an insert metal. In this case, however, the bonding temperature and pressure for obtaining high bond strength were limited to a very narrow range, in which the base metal near the bond interface underwent a large amount of deformation.

(3) The diffusion bonding was carried out using the insert metals of the A2017 alloy, copper and silver foils at bonding temperatures at which the insert metals formed liquid phases. The application of these insert metals significantly improved the bond strength, and expanded the range of bonding temperature and pressure for obtaining bond strength comparable to the strength of the base metal. In particular, joints having tensile strength not less than that of the base metal were obtained with bonding deformation less than 2%, when the insert metals of A2017 alloy and copper were applied.

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