Effects of Ultrasonic Vibration on Diffusion Welding of Aluminum†

Toshio ENJO*, Kenji IKEUCHI** and Hiroyuki FUJITA***

Abstract

As a pretreatment of the diffusion welding of aluminum, the ultrasonic vibration has been applied to the bond interface in an attempt to break up the superficial oxide film by frictional movement between faying surfaces induced by the ultrasonic. The application of ultrasonic vibration and subsequent welding have been carried out in a vacuum of 10^{-2} Pa at a temperature of 873K to 893K under a pressure to the bond interface of 1MPa to 3MPa. The bond strength increased as the input power to the transducer and working time of ultrasonic vibration were increased. The increase in pressure to the bond interface during the ultrasonic vibration, however, lowered the bond strength. TEM observation and electric resistance measurement of the bond interface revealed that the application of ultrasonic vibration had the effect of breaking up and dispersing the oxide film, which was closely related to the increase in bond strength. On the fractured surface of joint, portions showing a dimple pattern were observed only when the ultrasonic vibration was applied, increasing in area with the rise in bond strength. These portions may be regarded as places where the application of ultrasonic vibration promotes breaking up and dispersing the oxide film.

KEY WORDS: (Diffusion Welding) (Ultrasonic Vibration) (Oxide Film) (Bond Strength) (Aluminum)

1. Introduction

In the diffusion welding of aluminum, the superficial oxide film, which is very stable and tenacious, interferes with the formation of metal-to-metal contact at the bond interface even at temperatures as high as near the melting point of aluminum[1-3]. For this reason, large amounts of welding deformation in the vicinity of the bond interface[4] or the application of insert metal[5] was required to obtain bond strength comparable to the fracture strength of the base metal. The large welding deformation, however, is unfavourable, since the feasibility of precision welding is an important advantage of the diffusion welding. The application of insert metal is also unfavourable in cases where the inhomogeneity of composition and microstructure at the bond interface should be avoided. In a previous report[6], we carried out the diffusion welding of Al-Cu-Mg series A2017 alloy in a temperature range where the liquid and solid phases coexisted, and showed that the coexistence of the liquid phase increased significantly the bond strength. This technique, however, cannot be applied to the pure aluminum or alloys in which liquid and solid phases coexist in a very narrow temperature range.

On the one hand, the ultrasonic welding is widely applied to the solid state bonding of aluminum especially in the field of electronics industry. For the ultrasonic welding of aluminum, it is generally accepted that the frictional movement between the faying surfaces induced by the ultrasonic vibration has the effects of breaking up and dispersing the oxide film, which play an essential part in the formation of metal-to-metal contact at the bond interface[7].

Therefore, it can be expected that the frictional movement by the ultrasonic vibration has the similar effects on the oxide film in the diffusion welding of aluminum, and consequently aids the increase in the bond strength. However, there has been only a little amount of information about the effect of the ultrasonic vibration on the diffusion welding[8]. Mukha[8] reported the effect of the ultrasonic vibration on the diffusion welding of steel to nickel. In his experiment, however, the direction of the ultrasonic vibration was perpendicular to the bond interface, and so no frictional movement between the faying surfaces could be expected to occur. In the present investigation, we have developed an apparatus with which the diffusion welding could be carried out immediately after the pretreatment by ultrasonic vibration to induce the frictional movement in a vacuum and at high temperatures. Using this apparatus, the effect of the ultrasonic vibration on the bond strength of the commercially pure aluminum has been examined with particular reference to the behavior of oxide film at the bond interface.

2. Experimental Details

The base metal used was a cold-drawn bar 15 mm in diameter, whose chemical composition is shown in **Table 1**. The specimen for the diffusion welding, a rod 15 mm in

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Table 1 Chemical composition of the base metal (mass%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.05	0.11	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	Bal.

diameter and 37 mm in length, was cut from the base metal by turning in a lathe. The faying surface was wire-brushed and subsequently degreased by washing in acetone just before the welding. In the diffusion welding, a couple of specimens were so arranged that grooves caused by the wire brushing on faying surfaces were nearly normal to the direction of the ultrasonic vibration.

The diffusion welding was carried out in a vacuum of 2×10^{-2} Pa using the apparatus as shown in **Fig. 1**; that is, the ultrasonic vibration generated by a magnetostrictive transducer of nickel was introduced into the welding chamber through a hone, to the end of which one specimen to be vibrated was fastened. The specimen was vibrated in the horizontal direction of the figure, and so the friction was brought about between the faying surface of the vibrated specimen and that of the other specimen fixed to the pressing axis. The nominal resonant frequency of the transducer was 17 kHz. The bond zone was heated with a ridiant resistance heater of molybdenum foil 0.1 mm thick, and the pressure to the bond interface was applied with an air compressor. The temperature of the bond interface was monitored with a C-A thermocouple percussion-welded to the specimen.

Figure 2 schematically illustrates the temperature, pressure and ultrasonic input power to the transducer during the application of ultrasonic vibration and the diffusion welding. As soon as the temperature of the bond interface reached a desired temperature T_u, the ultrasonic vibration (input power I_p) and pressure P_u were applied to the bond interface for time t_u, and subsequently the diffusion welding was carried out at a temperature T_w and pressure P_w for time t_w. Thus, the diffusion welding

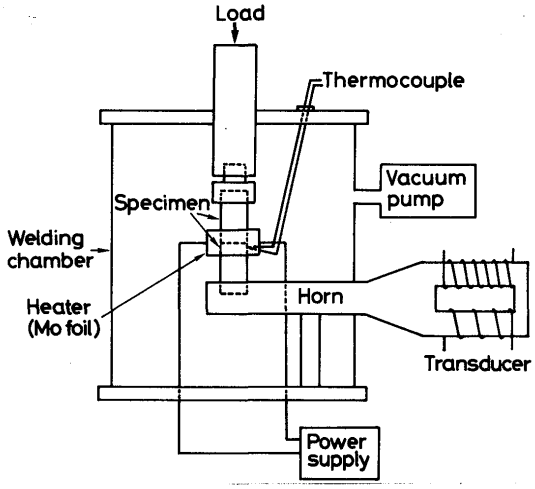

Fig. 1 Apparatus for diffusion welding equipped with an ultrasonic transducer and horn.

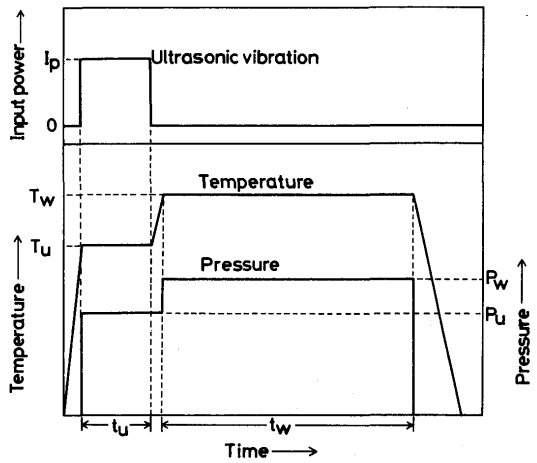

Fig. 2 Temperature, pressure and input power to the transducer as a function of time during the application of ultrasonic vibration and subsequent diffusion welding.

was carried out immediately after the application of the ultrasonic vibration in a vacuum and at elevated temperatures.

In order to investigate the effect of the ultrasonic vibration on the breakup of the oxide film, the change in electric resistance across the bond interface caused by the application of ultrasonic vibration has been measured using a potentiometric method as shown in **Fig. 3**. A couple of specimens 8 mm in diameter and 18 mm in length were fixed to the horn and pressing axis, from which the specimens were insulated with alumina plates 0.5 mm thick. A direct current of 1 ± 0.001A passed from terminal T_1 to T_4 and vice versa, and the electric resistance between terminals T_2 and T_3 was estimated from the potential difference between T_2 and T_3 using Ohm's law. The potential difference was measured with a digital voltmeter to an accuracy of 10 nV. The measurement of the electric resistance was carried out at room temperature because of the poor heat resistance of the adhesive

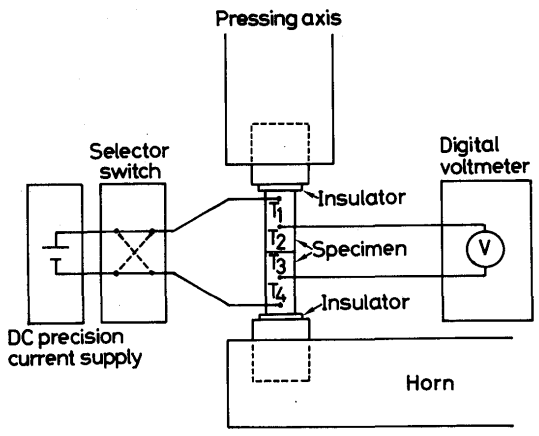

Fig. 3 Diagram illustrating the circuit for the electric resistance measurement of bond interface.

for fixing the specimen to the insulator.

Since the electric resistance between T_2 and T_3 consisted of the resistance of the matrix between T_2 and T_3 as well as the resistance of the bond interface R, R was estimated using the following equation

$$R = r - \frac{l}{S} \cdot \rho_M ,$$

where r is the electric resistance between T_2 and T_3, l the distance between T_2 and T_3, S the cross sectional area of the specimen, and ρ_M the resistivity of the specimen. The values of l, S and ρ_M were determined accurately for each specimen.

The observation of the bond interface with TEM (Transmission Electron Microscope) was carried out in a same way as reported in a previous paper[9]; that is, thin foil specimens were prepared by electropolishing and subsequent Ar ion thinning, and TEM observation was carried out at an acceleration voltage of 125 kV. The observation of fractured surfaces with SEM (Scanning Electron Microscope) was carried out at an acceleration voltage of 25 kV.

3. Results

3.1 Effects of ultrasonic vibration on tensile strength of joint

In the diffusion welding apparatus used, as seen from Fig. 1, the ultrasonic vibration brought about the frictional movement between the faying surfaces, and so the ultrasonic energy transmitted was converted to frictional energy at the bond interface. This frictional energy Q is given by

$$Q \propto \mu \cdot \delta \cdot P_u \cdot t_u , \qquad (1)$$

where μ is the coefficient of kinetic friction, and δ the amplitude of ultrasonic vibration, which increases with the input power I_p. In the present investigation, parameters δ (= I_p), P_u and t_u which controlled the frictional energy given by eq. (1) were systematically changed to examine the effect of the ultrasonic vibration on the bond strength.

The effects of the input power I_p and working time t_u on the bond strength are shown in **Figs. 4** and 5, respectively. The bond strength was increased with the rise in I_p and t_u, i.e., with the rise in the frictional energy Q. These results show that the pretreatment by the ultrasonic vibration to induce the frictional movement was very effective for the improvement of the bond strength of aluminum. For joints whose tensile strength is shown in Figs. 4 and 5, the welding deformation estimated from the increase in cross sectional area at the bond interface was

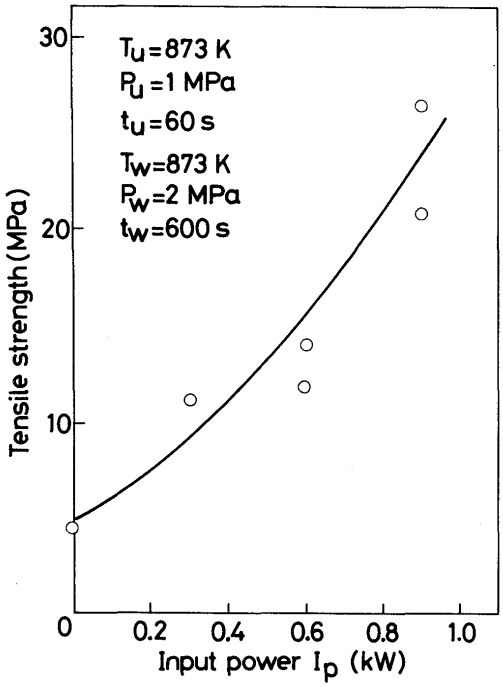

Fig. 4 Tensile strength of joints vs input power to the transducer I_p.

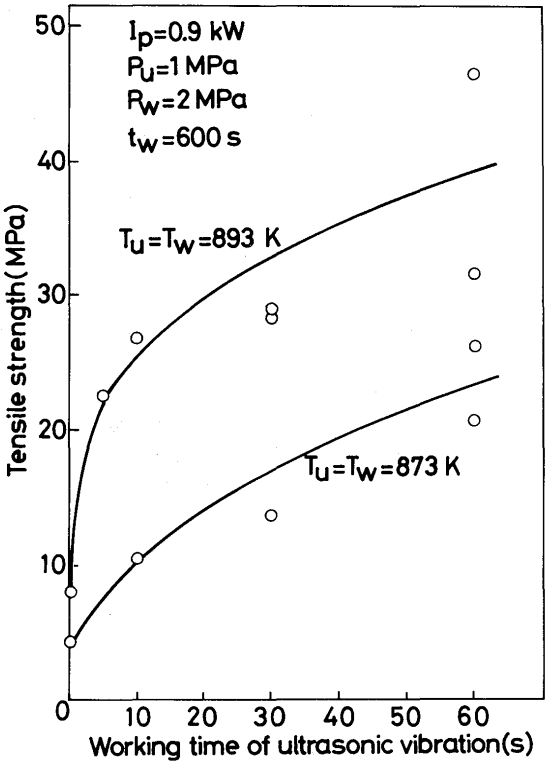

Fig. 5 Tensile strength of joints vs working time of ultrasonic vibration t_u.

less than 1.5% without any observable increase caused by the application of the ultrasonic vibration. As shown in Fig. 5, the rise in the temperature of ultrasonic vibration and diffusion welding also increased the bond strength.

Figures 6 and 7 show the effects of the application of

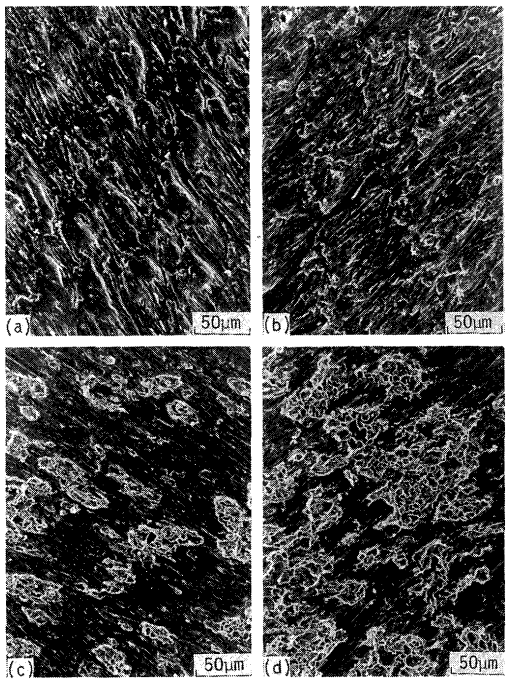

Fig. 6 Effect of ultrasonic vibration on the morphology of fractured surfaces of joints: (a) faying surface subjected to wire brushing, (b) fractured surface without application of the ultrasonic vibration (T_w = 893K, P_w = 2MPa and t_w = 0.6ks), (c) fractured surface using ultrasonic vibration at an input power I_p of 0.3kW (T_u = 873K, P_u = 1MPa, t_u = 60s, T_w = 873K, P_w = 1MPa and t_w = 0.6ks), and (d) fractured surface using ultrasonic vibration at an input power I_p of 0.9kW (T_u = 873K, P_u = 1MPa, t_u = 60s, T_w = 873K, P_w = 1MPa and t_w = 0.6ks).

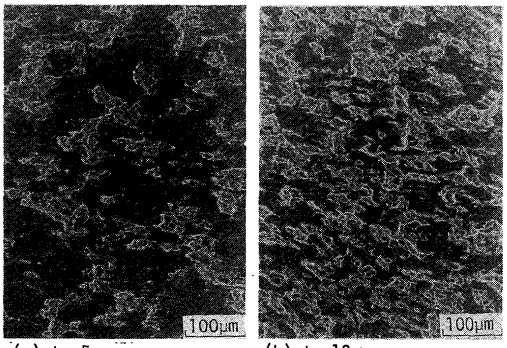

Fig. 7 Effect of working time t_u on the morphology of fractured surfaces of joints (I_p = 0.9kW, T_u = 893K, P_u = 1MPa, T_w = 893K, P_w = 1 MPa and t_w = 0.6ks).

ultrasonic vibration on the morphology of the fractured surface of joints. On the faying surface finished by the wire brushing, grooves caused by the wire brushing were observed as shown in Fig. 6(a). The groove remained over the whole fractured surface as shown in Fig. 6(b), when the ultrasonic vibration was not applied. When the ultrasonic vibration was applied, on the other hand, portions showing a dimple pattern were observed, and the total area of these portions were increased with the rise in the input power I_p, as shown in Figs. 6(c) and (d). The area of the portion showing the dimple pattern was also increased with the working time t_u, as shown in Figs. 7(a) and (b). Thus, the portion showing the dimple pattern was observed only when the ultrasonic vibration was applied, and the increase in its area led to the increase in the bond strength.

On the other hand, the increase in the pressure to the bond interface P_u during the application of ultrasonic vibration lowered the bond strength significantly as shown in **Fig. 8**. The increase in the pressure P_u also decreased the area of the dimple pattern, which could not be observed at P_u = 3MPa as shown in **Fig. 9**. According to eq.(1), the frictional energy Q increases proportionately to the pressure P_u, but the results shown in Figs. 8 and 9 indicate that the increase in P_u does not necessarily increase the frictional energy Q.

3.2 Effects of application of ultrasonic vibration on oxide film

In order to discuss the effect of the ultrasonic vibration

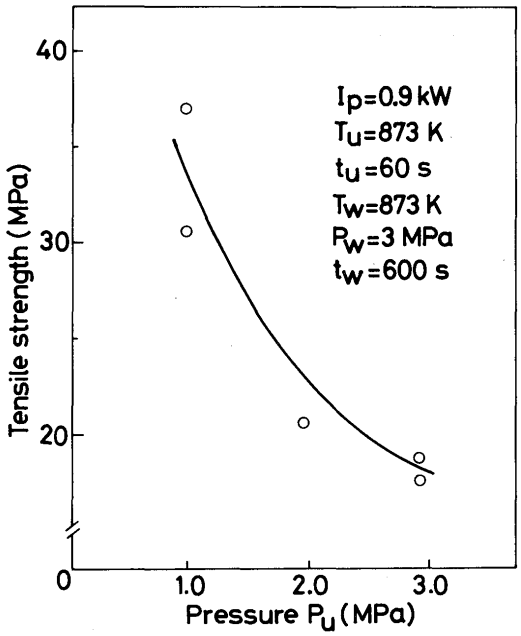

Fig. 8 Tensile strength of joints vs pressure P_u.

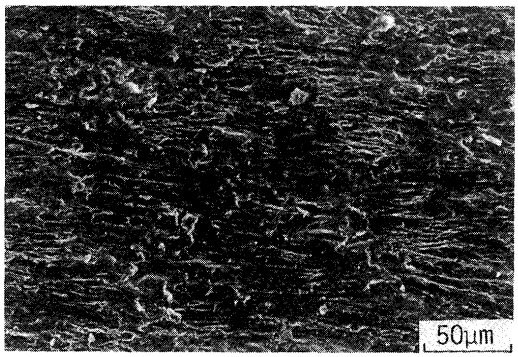

Fig. 9 Fractured surface of a joint welded under a pressure P_u of 3MPa (I_p = 0.9kW, T_u = 873K, t_u = 60s, T_w = 873K, P_w = 3MPa dnd t_w = 0.6ks).

on the bond strength in connection with the breakup of the oxide film, the behavior of the oxide film was investigated using the TEM observation and electric resistance measurement.

3.2.1 TEM observation of bond interface

Figure 10 shows the effect of the ultrasonic vibration on the optical microstructure of bond interface. Along the bond interface welded without the ultrasonic vibration, a dark interface layer a few μm thick was observed as shown in Fig. 10(a). When the ultrasonic vibration was applied, the interface layer became discontinuous as shown in Fig. 10(b). At places where the interface layer was broken, the bonding process was probably accelerated by the application of the ultrasonic vibration. However, from the optical microstructure as shown in Fig. 10, it cannot be concluded that the discontinuity of the interface layer has any correlation with the breakup of the oxide film.

A TEM micrograph of a bond interface welded without the ultrasonic vibration is shown in **Fig. 11**. In this case, a number of small inclusions were distributed within a zone a few μm thick along the bond interface. This zone can be considered to correspond to the interface layer observed with optical microscope as shown in Fig. 10(a)[9]. As reported in the previous paper[9], this interface layer, which is characteristic of the mechanical surface treatment, consists of fine grains as small as less than 1μm in diameter, and the inclusion distributed in this layer are the oxide of aluminum. It has also been indicated that this interface layer has significantly detrimental effects on the bond strength[9].

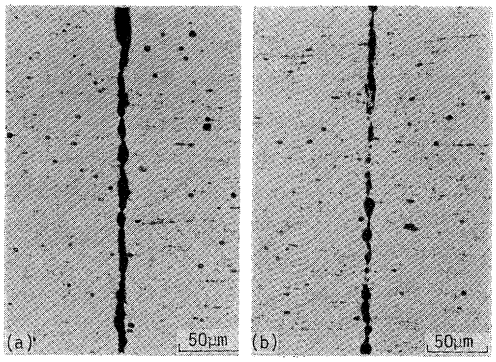

Fig. 10 Effect of the application of ultrasonic vibration on the optical microstructure of joints: (a) I_p = t_u = P_u = 0, T_w = 893K, P_w = 2MPa and t_w = 0.6ks, and (b) I_p = 0.9kW, T_u = 893K, P_u = 1MPa, t_u = 60s, T_w = 893K, P_w = 2MPa and t_w = 0.6ks).

When the ultrasonic vibration was applied, the bond interface is shown in **Fig. 12**. In this case, though the interface layer including a lot of oxide particles was also observed, the amount of the oxide became very small at some places, where the bond interface looked like a grain boundary. Under the same welding conditions as those shown in Fig. 12, these places were observed only when the ultrasonic vibration was applied, indicating that the pretreatment by the ultrasonic vibration aided breaking up and dispersing the oxide. It is considered that the place where the amount of oxide particles became very small corresponded to the place where the interface layer was broken in the optical micrograph as shown in Fig. 10(b).

3.2.2 Change in electric resistance of bond interface

According to our previous investigation[3], the formation of metal-to-metal contact at the bond interface resulting from the breakup of the oxide film can be detected sensitively with the electric resistance measurement across the bond interface. In the present investigation, the electric resistance measurement across the bond interface was also carried out to examine the effect of the ultrasonic vibration on the breakup of the oxide film. The electric resistance of the bond interface is shown in **Fig. 13** as a function of working time of ultrasonic vibration. The application of the ultrasonic vibration was carried out in a vacuum of 0.1Pa or in air. When the ultrasonic vibration was applied in a vacuum, the electric

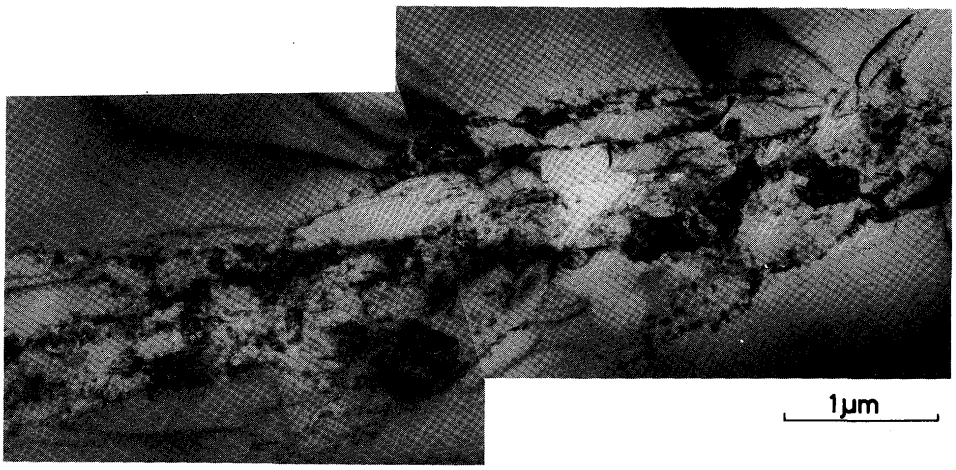

Fig. 11 TEM micrograph of a bond interface without application of ultrasonic vibration (T_w = 893K, P_w = 2MPa and t_w = 3.6ks).

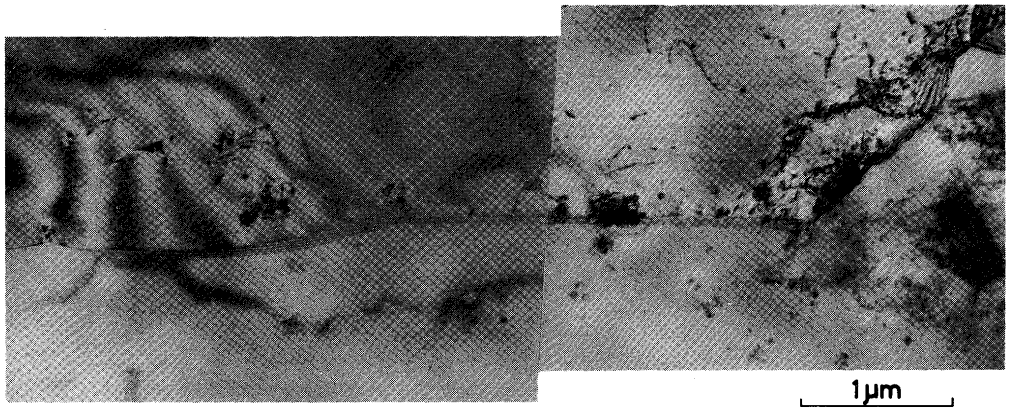

Fig. 12 TEM micrograph of a bond interface using ultrasonic vibration (I_p = 0.9kW, T_u = 893K, P_u = 1MPa, t_u = 30s, T_w = 893K, P_w = 2MPa and t_w = 3.6ks).

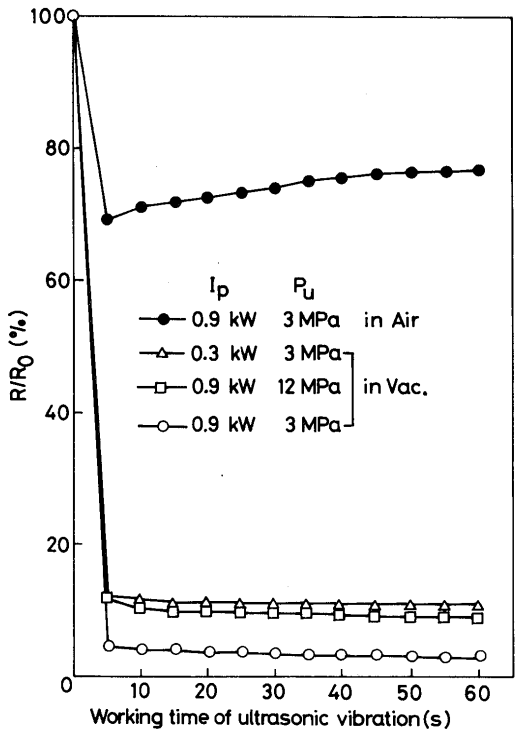

Fig. 13 Electric resistance of bond interface R vs working time of ultrasonic vibration t_u (R_0 : initial value of R).

resistance of the bond interface decreased markedly within working time of 5 s, and further gradual decrease was continued at working time more than 5 s. The decrease in the electric resistance of the bond interface became larger as the input power to the transducer I_p was increased. On the other hand, the increase in the pressure during the ultrasonic vibration P_u resulted in reducing the decrease in the electric resistance of the bond interface. These results suggest that the increase in the working time t_u and input power I_p of the ultrasonic vibration facilitated the breakup and dispersion of the oxide film, whereas the increase in the pressure P_u weakens the effects of the ultrasonic vibration. The effects of t_u, I_p and P_u on the oxide film suggested by Fig. 13 correspond well to the effects of these parameters on the bond strength as shown in Figs. 4, 5 and 8.

In the experiment to obtain the results shown in Fig. 13, the ultrasonic vibration was applied at room temperature much lower than those at which the ultrasonic vibration was applied as a pretreatment of the diffusion welding. According to Tylecote[11], the ease with which the oxide film is broken up in the solid state bonding of metals is controlled mainly by the difference in the hardness between the oxide film and substrate metal, and the oxide film of aluminum is broken up more easily with the rise in temperature. However, the oxide film of aluminum has much higher hardness than the metallic aluminum at room temperature as well as at elevated temperatures[11]. This implys that the behavior of the oxide film at room temperature is qualitatively similar to that at elevated temperatures. Therefore, the change in the electric resistance of the bond interface as shown in Fig. 13 supports that the increase in the bond strength by the application of the ultrasonic vibration was caused by the increase in metal-to-metal contact resulting from the breakup of the oxide film.

When the ultrasonic vibration was applied in air, as shown in Fig. 13, the decrease in the electric resistance of the bond interface became much smaller, and moreover the electric resistance increased gradually with working time more than 5s. This result suggests that the application of the ultrasonic vibration in air at P_2 less than 3MPa rather oxidized the faying surface.

4. Discussion

As described in §3.1, portions showing the dimple pattern were observed on the fractured surface of joints only when the ultrasonic vibration was applied as a pretreatment, and the bond strength was increased with the increase in their area. In fact, as shown in **Fig. 14**, the area of the dimple pattern increased with the working

time of ultrasonic vibration, showing a tendency similar to that of the bond strength as shown in Fig. 5. On the one hand, the TEM observation and electric resistance measurement across the bond interface, as described in §3.2, suggest that the frictional movement induced by the ultrasonic vibration facilitated the formation of metal-to-metal contact resulting from the breakup of the oxide film, and consequently increased the bond strength. From these results, it can be inferred that the portion showing the dimple pattern corresponded to the place where the oxide film was broken up by the ultrasonic vibration.

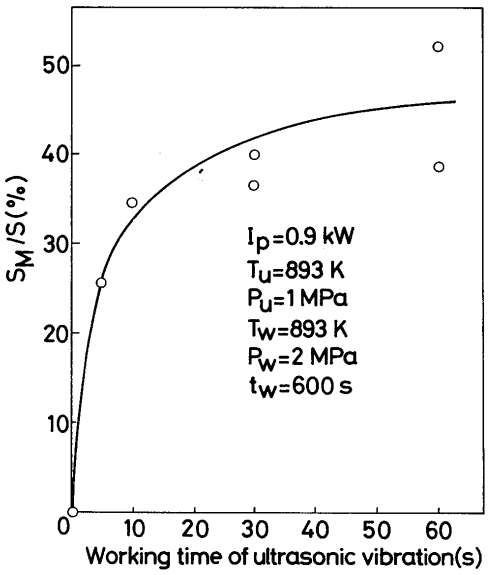

Fig. 14 Percentage of area showing a dimple pattern on fractured surfaces of joints S_M/S vs working time of ultrasonic vibration t_u.

As seen from Fig. 14, the fraction of the dimple pattern on the fractured surface was 40–60% at t_u = 60s, while the bond strength reached 50–80% of the tensile strength of the base metal (55–65MPa) as seen from Fig. 5. That is, the apparent strength per a unit area of the portion showing the dimple pattern was considerably higher than the tensile strength of the base metal. This may be explained as a consequence of the plastic constraint effect[12], since the unbonded area around the dimple pattern acts as a notch on tensile test. Nevertheless, the portion showing the dimple pattern will not show such high apparent strength, unless the bond strength at this portion is comparable to the tensile strength of the base metal. Therefore, it will not be impossible to obtain bond strength comparable to the tensile strength of the base metal by increasing the working time and input power of the ultrasonic vibration more than those of the present investigation.

It is said that in the ordinary ultrasonic welding excessive working time of ultrasonic vibration results in decreasing the bond strength[13]. This is explained as a consequence of crack formation due to the ultrasonic fatigue in contact spots once formed[13]. The excessive input power of ultrasonic vibration is also said to cause the crack formation due to the extremely heavy cold work at contact spots[13]. In the present investigation, however, neither the decrease in the bond strength nor the crack formation with the increase in t_u or I_p was observed. Jones et al.[14] have suggested that the frictional energy transmitted to the bond interface is decreased with the increase in the thickness of the vibrating specimen, because more ultrasonic energy is dissipated in the specimen. The specimen used in the present investigation was a rod as shown in Fig. 1 in contrast with the sheet specimen used in the ordinary ultrasonic welding, and so the frictional energy transmitted to the bond interface in the present investigation was probably much smaller than that used in the ultrasonic welding. Consequently, the degree of the fatigue and cold work introduced by the ultrasonic vibration of the present investigation is considered to be much weaker than that of the ultrasonic welding. It is probably for this reason that neither the decrease in the bond strength nor the crack formation due to the excessive working time and input power of the ultrasonic vibration was observed in the present investigation.

On the other hand, the increase in the pressure during the ultrasonic vibration P_u decreased both the bond strength and the area of the dimple pattern on the fractured surface of joints (see Figs. 8 and 9). The increase in P_u also reduced the decrease in electric resistance of the bond interface as shown in Fig. 13. These results indicate that the increase in the pressure during the ultrasonic vibration made the ultrasonic vibration less effective in breaking up the oxide film. The increase in the pressure P_u increases the frictional force $\mu \cdot P_u$, against which the vibrating specimen must be driven in order to induce relative motion between vibrating and standing specimens. However, since the specimen used in the present investigation was a rod, the ultrasonic energy dissipitated in the specimen was very large as described above. For this reason, as the pressure P_u was increased, the driving force of the ultrasonic vibration transmitted to the bond interface probably became insufficient to overcome the frictional force $\mu \cdot P_u$, and so the amplitude of the relative motion δ decreased rapidly. It seems likely that this decrease in the amplitude δ reduced the frictional energy at the bond interface, and resulted in suppressing the breakup of the oxide film. Besides the dissipation of the ultrasonic energy in the specimen, the lack of the force to cramp vibrating and standing specimens to the horn and pressing axis (see Fig. 1) can also be considered to cause the decrease in the driving force of the ultrasonic vibration transmitted to the bond interface.

Thus, the effect of the ultrasonic vibration on the bond strength can be explained as a consequence of the frictional movement between faying surfaces which facilitates breaking up and dispersing the oxide film.

5. Conclusions

In the diffusion welding of aluminum, frictional movement between faying surfaces has been induced by the ultrasonic vibration just before the welding in an attempt to facilitate breaking up the oxide film on the faying surface. The ultrasonic vibration was generated with a magnetostrictive transducer of nickel with a nominal resonant frequency of 17 kHz, and the input power to the transducer was varied between 0.3 and 0.9 kW. The welding temperature, pressure and time were 873 – 893 K, 2 – 3 MPa and 1.8 ks, respectively. Results obtained are summarized as follows:

(1) The bond strength was increased significantly, as the input power to the transducer and the working time of ultrasonic vibration were increased. In contrast to this, the increase in the pressure during the ultrasonic vibration P_u rather decreased the bond strength ($P_u \geqslant 1$ MPa in the present investigation).

(2) Dimple patterns were observed on the fractured surface of joints only when the ultrasonic vibration was applied, and the bond strength was increased with the area of the dimple pattern.

(3) TEM observation of the bond interface revealed that portions where the amount of oxide particles became very small and the bond interface looked like a grain boundary were formed only when the ultrasonic vibration was applied. The bond interface welded without the application of the ultrasonic vibration consisted of an interface layer a few μm thick within which a lot of oxide particles were distributed.

(4) The electric resistance of the bond interface was decreased with the increase in the input power and working time of ultrasonic vibration, suggesting that the frictional movement by the ultrasonic vibration had the effect of breaking up the oxide film. On the one hand, the increase in the pressure P_u reduced the decrease in the electric resistance of the bond interface due to the ultrasonic vibration. It is therefore considered that the increase in P_u rather weakened the effect of the ultrasonic vibration on the breakup of the oxide film.

From these results, it can be concluded that the frictional movement by the ultrasonic vibration facilitates breaking up and dispersing the oxide film, and consequently increases the area of metal-to-metal contact at the bond interface which is characterized by the dimple pattern on the fractured surface of joints.

References

1) M. M. Schwartz: *Modern Metal Joining Techniques,* John Wiley & Sons, (1969), 420.

2) R. F. Tylecote: *The Solid Phase Welding of Metals,* Edward Arnold, (1968), 301.

3) T. Enjo, K. Ikeuchi and N. Akikawa: Trans. JWRI, 10 (1981), 173.

4) G. E. Metzger: Weld. J., **38** (1978), 37-s.

5) I. M. Barta: Weld. J., **24** (1964), 241-s.

6) T. Enjo and K. Ikeuchi: Trans. JWRI, **13** (1984), 235.

7) B. E. Noltingk: Weld. Met. Fab., **28** (1960), 260.

8) I. M. Mukha: Weld. Prod., No. 12 (1979), 13.

9) T. Enjo, K. Ikeuchi and K. Furukawa: Trans. JWRI, **14** (1985), 115.

10) M. Shimakawa: *Cho-onpakogaku,* Kogyochosakai, (1975), 380 (in Japanese).

11) R. F. Tylecote: *The Solid Phase Welding of Metals,* Edward Arnold, (1968), 44.

12) A. S. Tetelman and A. J. McEvily, Jr. (Translated by H. Miyamoto): *Fracture of Structural Materials,* Baifukan, (1970), 117 (in Japanese).

13) N. E. Weare, J. N. Antonevich and R. E. Monroe: Weld. J., **20** (1960), 331-s.

14) J. B. Jones, N. Maropis, J. G. Thomas and D. Bancroft: Weld. J., **21** (1961), 289-s.