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Diffusion Welding of Al-Cu-Mg Series 2017 Alloy†

Toshio ENJO* and Kenji IKEUCHI**

Abstract

An investigation has been made of the diffusion welding of 2017 aluminum alloy which is very difficult to join by the conventional fusion-welding technique. In the present investigation, the diffusion welding has been carried out in the temperature range above the solidus line where solid and liquid phases coexist, though it is a kind of solid-state welding. The purpose for this is to aid the intimate contact and the disruption of the tenacious oxide film at the bond interface by the formation of the liquid phase.

As a result, the joint strength increased largely with raising the welding temperature above the solidus line, and became much higher than that of the joint welded below the solidus line. The maximum tensile strength in the as-welded state, which was obtained at the welding temperature of 853 K, was 270 MPa. It was observed with high-temperature-optical microscope that the liquid phase formed preferentially at the bond interface as well as at the grain boundary in the range between the solidus and liquidus lines. These results indicate that the liquid phase forming preferentially at the bond interface promoted effectively the bond process of diffusion welding. The maximum tensile strength was obtained when the volume fraction of the liquid phase was 2 ~ 3%.

However, when the volume fraction of the liquid phase exceeded 3%, the joint strength decreased remarkably with the increase in the volume fraction of the liquid phase. In the joint welded with the liquid phase more than 3%, many porosities were observed at grain boundaries, and the degree of welding deformation, which was estimated from the increase in the cross-sectional area at the bond interface, became much higher than that of the joint having the maximum strength. The formation of these porosities is considered to be responsible for the decrease in the joint strength. The formation mechanism of the porosity is explained as follows: In the range between the solidus and liquidus lines, the liquid phase formed preferentially at the grain boundary, and so the strength of the grain boundary decreased rapidly with the increase in the liquid phase. Therefore, when the fraction of the liquid phase exceeded a critical value (≃3%), the welding deformation of base metal caused cracks at grain boundaries. The crack which was not filled with the liquid phase is considered to remain as a porosity at the grain boundary.

The tensile strength of the joint welded at 853 K was increased to 400 MPa by a post weld heat treatment consisting of ageing for 10^3 ks at room temperature subsequent to a water quenching from 773 K.

KEY WORDS: (Diffusion Welding) (Aluminum Alloy) (Liquid Phase)

1. Introduction

Al-Cu-Mg series 2017 alloy (2017 alloy) is an age-hardenable aluminum alloy having a tensile strength more than 400 MPa after an appropriate heat treatment[1]. However, despite of its high strength, the 2017 alloy is very difficult to join with conventional fusion-welding techniques because of solidification cracking[2]. Since the solidification cracking does not occur in the solid state welding, it may be expected to obtain a sound joint of 2017 alloy by using the solid state welding. For example, Tokisue et al[3] reported that the 2017 alloy can be joined successfully with friction welding. However, there has been only a little amount of information about the diffusion welding – a kind of solid state welding – of the 2017 alloy.

On the other hand, it is generally accepted that in the diffusion welding of aluminum, the oxide film, which is very difficult to eliminate, interferes with the formation of metallic bond across the bond interface[4]. For this reason, in the diffusion welding of aluminum and its alloys, a bond strength comparable to that of the base metal could not be obtained without a large welding deformation (~10%)[5] or an appropriate insert metal[6]. However, both the large welding deformation and the application of insert metal are undesirable, since the precise welding is a remarkable advantage of diffusion welding and the application of insert metal changes the composition and microstructure of bond zone.

The present investigation aims at obtaining a joint of 2017 alloy having high strength by the use of diffusion

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welding without a large welding deformation nor insert metal. For this purpose, the diffusion welding of 2017 alloy has been carried out at temperatures above solidus line at which the liquid and solid phases coexist, considering that the coexisting liquid phase will aid the breaking-up of the oxide film and the intimate contact at the bond interface.

2. Experimental Details

The base metal used was a commercial Al-Cu-Mg series 2017 alloy having a chemical composition as shown in **Table 1**. The specimen for diffusion welding was a rod

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

Cu	Mg	Si	Fe	Mn	Zn	Cr	Al
3.42	0.36	0.31	0.19	0.48	0.02	0.01	Bal.

20 mm in diameter and 37 mm in length. The faying surface, the end surface of the rod specimen, was finished to JIS3-S with lathe and degreased by washing in acetone just before the welding. The apparatus and the procedure for diffusion welding were the same as those reported in a previous paper[7]; the bond zone was heated with a radiant resistance heater of molybdenum foil, and the welding pressure onto the bond interface was exerted with a hydraulic press; the atmosphere of the welding was a vacuum of 5×10^{-2} Pa; the temperature of the bond zone was monitored with a C-A thermocouple percussion-welded on the side surface of the base metal about 2 mm from the bond interface and kept at a desired temperature to an accuracy of ±1 K. After the welding, the joint was cooled to 473 K in vacuo and subsequently to room temperature in air.

When the 2017 alloy kept at a temperature above solid solution is cooled to room temperature, the behavior of age hardening after the cooling is significantly influenced by the cooling rate. For this reason, the cooling rate after the welding was kept nearly constant to make the strength of the base metal approximately equal; the cooling time from 673 K to 473 K, which determines the age-hardening behavior of the 2017 alloy[8], was kept for 1.14±0.06 ks.

The mechanical property of the joint was evaluated from tensile strength at room temperature. The gauge length and diameter of the specimen for tensile test were 36 mm and 7 mm, respectively. The strain rate of the tensile test was 4.7×10^{-4} s^{-1}. Prior to tensile test the joint was aged for more than 3 Ms at room temperature, because the hardness of the bond zone increased to a saturated value at ageing time about 3 Ms.

The etchant for the observation of microstructure was Keller's reagent (HF 1%, HCl 1.5%, HNO_3 2.5% and H_2O 95%). The range of temperature where the liquid and solid phases coexisted in the base metal was determined by using differential thermal analysis (DTA), which was carried out in air using a standard specimen of pure aluminum (nominally 99.99%). The microstructure of bond zone during the diffusion welding was observed *in situ* with a high temperature optical microscope (HTOM) equipped with a compressing device in order to examine the distribution of the liquid phase. The HTOM observation was carried out in a vacuum of 5×10^{-2} Pa.

3. Results and Discussion

3.1 Effect of the liquid phase on the diffusion welding

The range of temperature where the liquid and solid phases coexisted in the base metal used was determined using DTA made at the heating and cooling rates of 0.05 K/s. As shown in **Fig. 1(a)**, two conspicuous endothermic

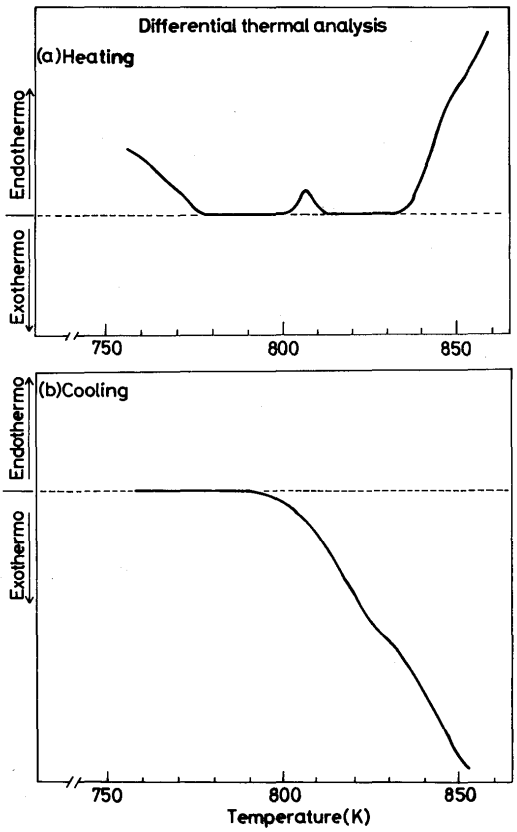

Fig. 1 Differential thermal analysis of the base metal in a heating process (a) and in a cooling process from 860 K (b). Heating and cooling rates were 0.05 K/s.

reactions were observed at temperatures below 775 K and above 830 K in a heating process. In general, the solution treatment of this alloy is made at temperatures above 770 K[8]. This means that the dissolution of the equilibrium precipitate of this alloy finishes at a temperature

around 770 K. Since the dissolution of precipitate is usually endothermic, the reaction observed below 775 K is considered to be due to the dissolution of the equilibrium precipitate. On the other hand, it is said that the lowest temperature at which the liquid phase forms in the 2017 alloy is around 790 K[8]. However, in the base metal used, no endothermic reaction was observed around 790 K except for a small one with a peak at 805 K as shown in Fig. 1(a). Therefore, the substantial increase in the liquid phase of the base metal is considered to start at the temperature of 830 K above which the large endothermic reaction was observed; accordingly the solidus line of the base metal may lie between 790 K and 830 K.

On the other hand, the differential thermal analysis in a cooling process from 860 K is shown in Fig. 1(b). As shown in the figure, a large exothermic reaction was observed until 790 K in the cooling process. This indicates that a considerable amount of liquid phase is involved until 790 K because of supercooling. In the present investigation, the welding pressure was exerted until 773 K in the cooling process after the welding, in order to avoid the solidification cracking; the welding pressure was applied to compensate the tensile stress caused by the shrinkage during the solidification of the liquid phase.

Microstructures of bond zones welded at temperatures from 768 K to 853 K are shown in **Fig. 2**. As shown in Fig. 2(a), no grain growth across the bond interface could be observed in the temperature range where the liquid phase did not coexist. Even in the temperature range where the liquid and solid phases coexisted, no grain grew across the bond interface at the welding temperature of 843 K as shown in Fig. 2(b). However, at the welding temperature of 853 K, some grains grew across the bond interface as shown in Fig. 2(c).

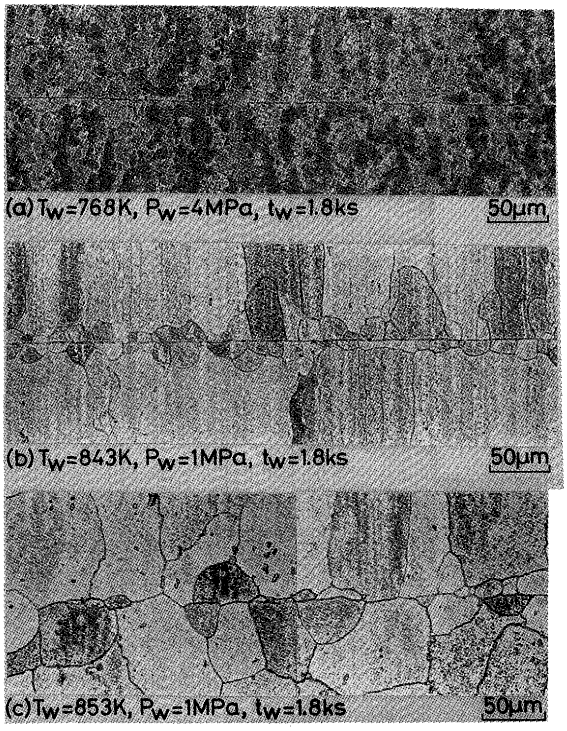

Fig. 2 Microstructures of joints of 2017 alloy welded at 768 K (a), 843 K (b) and 853 K (c) where T_W is welding temperature, P_W the welding pressure and t_W the welding time.

Fig. 3 shows the variation of the tensile strength of joint with welding time. The tensile strength of the joint was very low when the welding temperature was in the range of solid state. At the welding temperature above the solidus line, the tensile strength increased largely with welding temperature and took a maximum value at 853 K. On the other hand, the deformation of base metals caused by the welding was less than 1% at welding temperatures below 853 K despite the coexisting of the liquid phase (the welding deformation was estimated from the increase in the cross sectional area adjacent to the bond interface). These results shown in Figs. 2 and 3 suggest that the coexisting liquid phase promotes the bonding process and increases the bond strength.

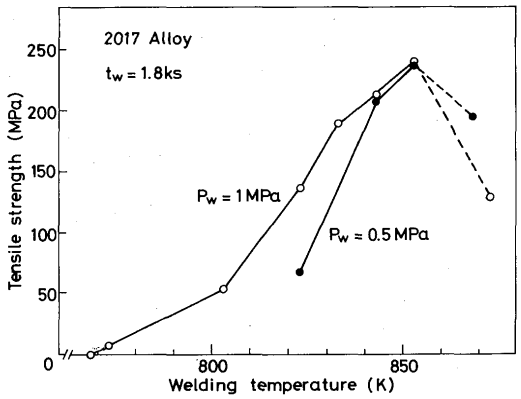

Fig. 3 Tensile strength of joints in the as-welded state as a function of welding temperature. The welding time t_W was 1.8 ks, and the welding pressure P_W was 1 MPa and 0.5 MPa.

However, at welding temperatures above 868 K, as shown in Fig. 3, the tensile strength of the joint decreased with the rise of welding temperature, though the joint fractured at the base metal. This indicates that a degradation in the base metal took place when the amount of the liquid phase exceeded a critical value. In order to make clear the mechanism of the degradation, the microstructure close to the bond interface was investigated for a joint welded at 873 K. As shown in **Fig. 4**, many porosities were observed along grain boundaries in the vicinity of the bond interface (the welding pressure was applied in the vertical direction of the figure). The mechanism of the formation of these porosities can be interpreted as follows: At the welding temperature of 873 K, above which many porosities were observed, the welding deformation increased to about 10% much larger than that

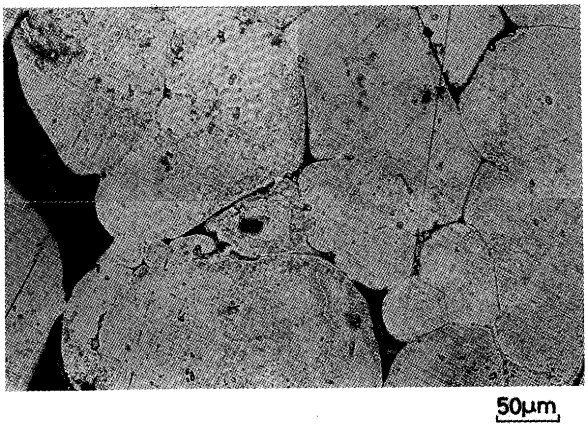

Fig. 4 Microstructure of the joint welded at 873 K (P_W=1 MPa, t_W=1.8 ks).

of the joint having the maximum strength (less than 1%). On the other hand, the liquid phase formed preferentially on grain boundaries (see Fig. 8) and covered almost all grain boundaries at temperatures above 873 K. Therefore, at temperatures above 873 K, the stress for intergranular sliding is considered to become lower than that of the transgranular; the fact that the welding deformation increased remarkably at 873 K supports that the stress for intergranular sliding decreased largely around this temperature. Therefore, it is considered that at temperatures above 873 K the deformation occurs chiefly by the intergranular sliding without large sliding in grains. The intergranular sliding is considered to form cracks at grain boundaries. The crack which is not refilled with the liquid phase is considered to remain as a porosity. The formation of these porosities is responsible for the degradation in the joint strength as shown in Fig. 3.

Thus the tensile strength of the joint of 2017 alloy is strongly influenced by the volume fraction of the liquid phase. In order to estimate the volume fraction of the liquid phase, the microstructure after quenching from temperatures above the solidus line into iced water was investigated. As shown in **Fig. 5**, many black particles were observed in a specimen quenched from 853 K. These black particles increased with the rise of quenching temperature. On the other hand, a scanning electron micrograph of a quenched specimen is shown in **Fig. 6** together with a result of electron prove microanalysis of copper along the white line A-A′. As shown in the figure, the distribution curve of the characteristic X-ray of copper, which has peaks at white particles, indicates that the copper concentration of the white particle is higher than that of the matrix. According to the ternary phase diagram of Al-Cu-Mg system[9], the copper content of the liquid phase is higher than that of the solid in the temperature range where the liquid and solid phases coexist. Therefore, the white particle with copper content higher

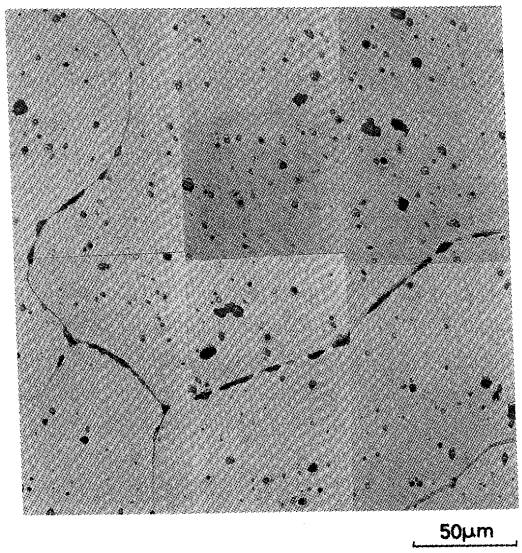

Fig. 5 Microstructure of the base metal quenched from 853 K into iced water.

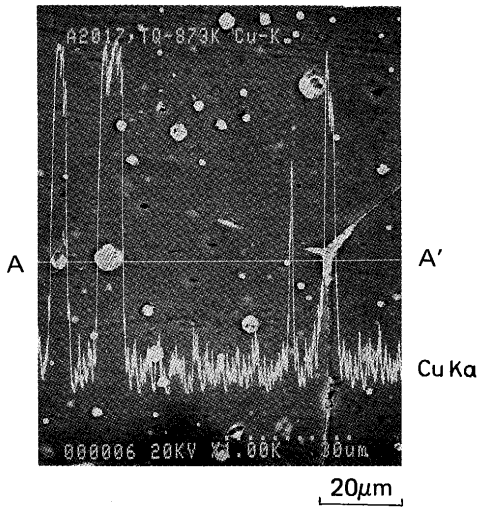

Fig. 6 Scanning electron micrograph of the base metal quenched from 873 K. The intensity of the characteristic X-ray of copper along the white straight line is shown.

than the matrix is regarded as the liquid phase at the quenching temperature. These white particles in Fig. 6 are considered to correspond to black particles in the optical microstructure shown in Fig. 5. The volume fraction of the liquid phase was estimated from the ratio of the total area of black spots to the area of the observed field in optical microstructures. **Fig. 7** shows the variation of the volume fraction of the liquid phase with temperature. As shown in this figure, the volume fraction of the liquid phase was 2~3% at the temperature of 853 K at which the maximum strength of the joint was obtained. And the liquid phase more than 3% caused the degradation in the base metal as shown in Fig. 3.

On the other hand, it is apparent that the liquid phase forming only in the close vicinity of the bond interface

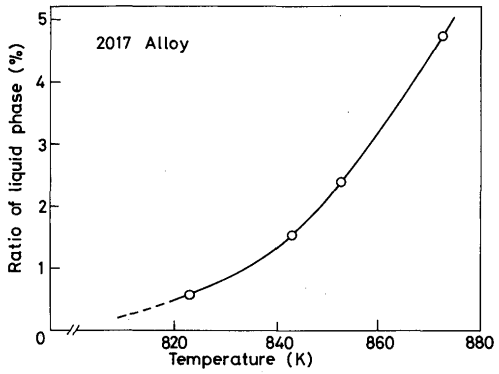

Fig. 7 Volume fraction of the liquid phase as a function of temperature. The volume fraction was estimated from optical micrographs as shown in Fig. 5.

can contribute to the increase in the bond strength. Therefore, the fact that the liquid phase of only 2~3% can accelerate significantly the increase in the bond strength implys that the liquid phase forms preferentially on the bond interface. In order to make it sure that the liquid phase formed preferentially on the bond interface, the microstructure of the bond zone was observed at temperatures above the solidus line by the use of HTOM. The specimen for the HTOM observation (3 x 3 x 6 mm) was prepared from a joint welded at 768 K below the solidus line, and the microstructure of cross section of the bond zone was examined with the pressure of 1 MPa applied onto the bond interface. As shown in **Fig. 8**, small drop-

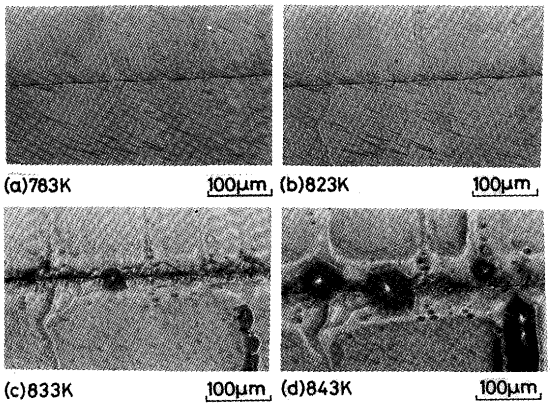

Fig. 8 Formation of the liquid phase in the bond zone at temperatures of 783 K (a), 823 K (b), 833 K (c) and 843 K (d) observed with high-temperature-optical microscope. The specimen for the observation was prepared from a joint welded at 768 K below the solidus line (P_W=2 MPa, t_W= 1.8 ks).

lets appeared on the bond interface at 833 K, and the number and volume of the droplet increased with the rise of temperature. These droplets are regarded as the liquid phase forming on the observation surface. As shown in Fig. 8, the droplet of the liquid phase fromed preferentially on the bond interface as well as on grain boundaries. This indicates that the liquid phase forms preferentially on the bond interface. Therefore, it is possible for the liquid phase to accelerate the increase in the bond strength even though its volume fraction is only 2~3%. That is, the liquid phase is considered to accelerate the intimate contact and breaking-up of the oxide film by promoting the deformation of microasperities on the faying surface and also to aid the intimate contact by flowing into voids at the bond interface.

3.2 Effect of post weld heat treatment on the joint strength

Since the 2017 alloy is age hardenable, the tensile strength of joint may be expected to be improved by an appropriate post weld heat treatment. **Fig. 9** shows the

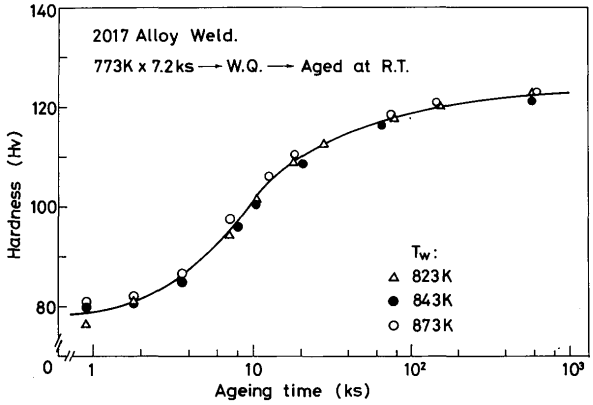

Fig. 9 Hardness vs. ageing-time curve at room temperature for joints quenched from 773 K into iced water. Welding temperatures for the joints were 823 K (△), 843 K (●) and 873 K (○) (P_W=1 MPa, t_W=1.8 ks).

variation of the hardness of joint with ageing time at room temperature after quenching from 773 K into iced water. As shown in Fig. 9, the hardness was independent of welding temperature and approached a saturated value at ageing time about 10^3 ks. **Fig. 10** shows microstructures

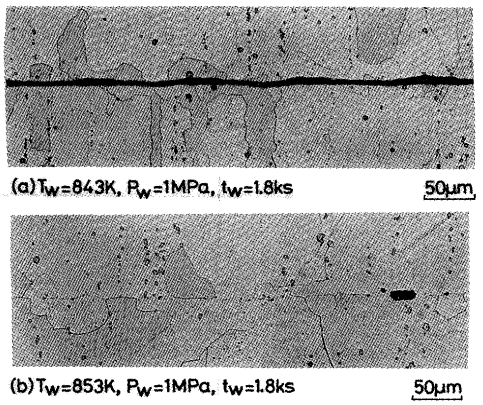

Fig. 10 Microstructures of joints quenched from 773 K into iced water. Welding temperatures for the joints were 843 K (a) and 853 K (b).

of joints after the solution treatment (quenching from 773 K into iced water). As shown in Fig. 10(a), cracks were observed along the bond interface in joints welded at temperatures below 843 K. Owing to the formation of this crack, the solution treatment decreased the tensile strength of joints welded below 843 K. The formation of the crack is attributable to thermal stress which is set up by the quenching, since it was not found before the quenching. On the other hand, as shown in Fig. 10(b), no crack was found in a joint welded at 853 K. As shown in **Fig. 11**, the tensile strength of joints welded at 853 K was improved remarkably by the post weld heat treatment. Though the joint fractured at the bond interface, the maximum tensile strength obtained was 400 MPa after the post weld heat treatment.

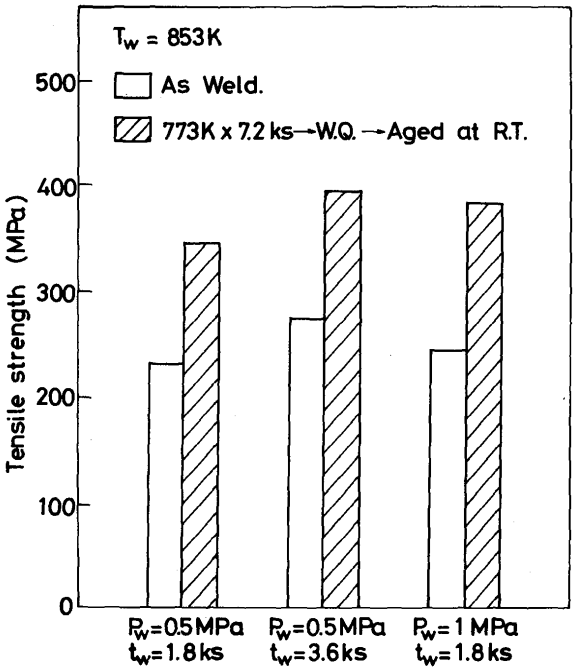

Fig. 11 Effect of a post weld heat treatment on the tensile strength of joint. The heat treatment consisted of ageing for more than 10^3 ks at room temperature subsequent to quenching from 773 K into iced water.

4. Conclusion

An investigation has been made of the effect of the liquid phase coexisting with the solid phase on the diffusion welding of Al-Cu-Mg series 2017 alloy. Results obtained are summarized as follows:

(1) The coexisting liquid phase, which formed preferentially on the bondinterface, accelerated significantly the increase in the bond strength. The maximum tensile strength of joint, which was obtained at the welding temperature of 853 K, was 270 MPa without post weld heat treatment.

(2) The post weld heat treatment which consisted of ageing for more than 1 Ms at room temperature subsequent to water quenching from 773 K increased remarkably the tensile strength of joints welded at 853 K. The maximum tensile strength obtained was 400 MPa.

(3) The tensile strength of joint took a maximum value when the volume fraction of the liquid phase was 2~3%. The liquid phase more than 3% caused the formation of porosities on grain boundaries of the base metal and so decreased the tensile strength of joint.

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