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Diffusion Welding of Aluminum to Titanium†

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Abstract

Diffusion welding of aluminum to titanium has been performed as an example of the joint between dissimilar metals which form brittle intermetallic compound in the bonding interface. In order to investigate the important factor which affects the joining process and the mechanical property of the joint, the microstructure in the bonding zone and the joint strength were examined in detail. The results obtained are summarized as follows.

(1) The joint strength increased with increasing welding temperature and time. The joint welded for more than 30 min at 600°C was fractured at aluminum base metal on tensile test.

(2) The interlayer which consisted of intermetallic compound Al_3Ti was formed in the bonding zone. The thickness of this interlayer increased almost linearly with welding time at the welding temperature of 600°C. The increase in the thickness did not reduce the joint strength up to 10 μm at least.

(3) The oxide film on the faying surface of aluminum is considered to be the most important factor for the joining process and joint strength. That is, the joint strength did not increase sufficiently because the oxide film inhibited the formation of metallic bond between the base metals.

(4) The joining process proceeded preferentially in the regions where the oxide film was disrupted by the micro-asperities on the faying surface of titanium.

1. Introduction

Diffusion welding is regarded as a favourable joining method to the welding between dissimilar metals, and many investigations have been reported about the diffusion welding between dissimilar metals[1,2,3]. But all of them have not resulted in obtaining good joint. The strength of joint between dissimilar metals which has brittle intermetallic compounds in the bonding interface was in many cases much lower than that of the base metal[4~8]. However, it is not necessarily clarified what kind of intermetallic compound is formed in bonding zone and how the intermetallic compound affects the joint strength.

As for aluminum, there is no conventional element which forms continuous series of solid solution with aluminum[9] and so it is important to investigate the effect of the formation of intermetallic compound on the mechanical property of the joint.

On the other hand, the surface condition of faying surface, such as the roughness, contamination, existence of oxide film and so on, has been suggested to have a large effect on the joining process because the materials are bonded without fusion and with little macroscopic deformation in base metal[1,2,10]. The existence of oxide film on faying surface of aluminum is a very important factor for the joining process.

Thus the formation of intermetallic compound in the bonding zone and existence of oxide film on the faying surface are considered to be the most important factors for the diffusion welding of aluminum to dissimilar metals.

In this investigation, the diffusion welding of aluminum to titanium has been performed as an example where the intermetallic compound is formed in the bonding interface. The microstructure of the bonding zone has been examined in detail with several metallographic methods, and the important factor for the joining process and joint strength has been discussed. As the result, it is pointed out that the existence of oxide film on the faying surface of aluminum is the most important factor for the joining process and joint strength. But the intermetallic compound of this system is not so important for joint strength.

2. Experimental Details

2.1 Base Metal

The base metals used in this investigation are commercially pure aluminum and titanium. Their chemical compositions are shown in **Table 1.** The tensile strength of the base metal is 6～8 kg/mm^2 and 39 kg/mm^2 for aluminum and titanium, respectively. Both the base metals have cylindrical shape whose diameter and

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Table 1 Chemical compositions.

Specimen	Chemical Composition (wt%)				
	Fe	N	O	H	Ti
Titanium	0.038	0.0030	0.065	0.0028	Bal.

Specimen	Chemical Composition (wt%)				
	Cu	Fe	Si	Mg	Al
Aluminum	0.032	0.20	0.08	0.02	Bal.

length are 20 mm and 37 mm. The base metals were welded with the end plane of cylinder as the faying surface. The faying surface was machined with a lathe to satisfy the flatness and the orthogonarity to the axis of cylinder.

2.2 Welding and Testing Procedure

Figure 1 shows the schematic diagram of diffusion welding apparatus. The bonding zone was heated with a high frequency induction heater as shown in Fig. 1, and so it is necessary to examine the uniformity of temperature distribution in the bonding zone. That is, we have to pay attention to the temperature gradient in radial or axial direction of the joint which is caused by the skin effect of high frequency and the difference of thermal and electrical properties between aluminum and titanium. In order to examine the temperature gradient of axial direction, the temperature was measured at the points of 1 mm and 3 mm from the bonding interface on the side surface of each base metal. And to examine that of radial direction the temperature was measured at the points of side surface and center of each base metal near the bonding interface. These measurements of temperature were carried out with chromel-alumel thermocouples percussion-welded to base metal at each point as shown in **Fig. 2.** As shown in Fig. 2, the temperature distribution in the bonding zone was sufficiently uniform after heating for 2 min.

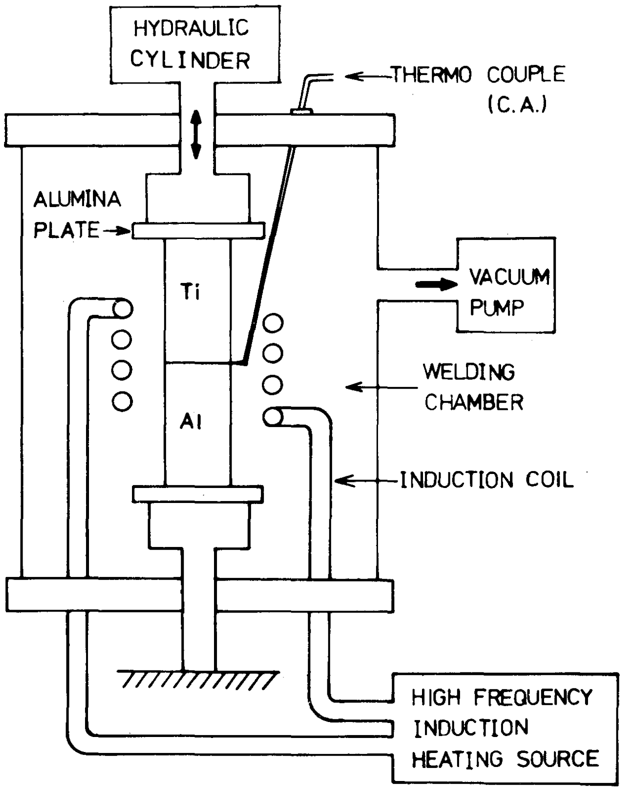

Fig. 1 Schematic diagram of the diffusion welding apparatus.

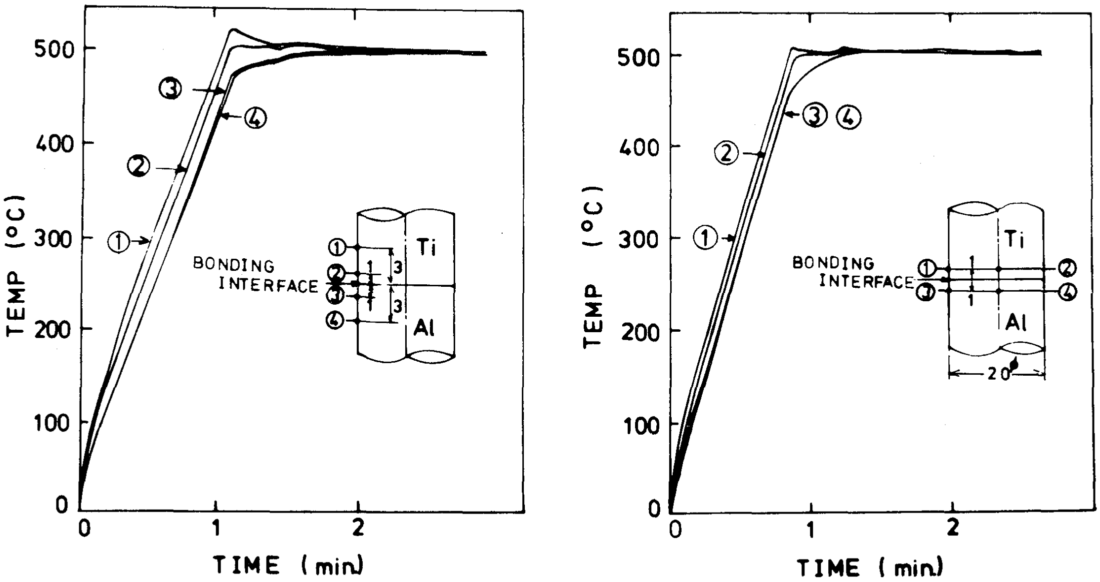

Fig. 2 Variation of temperature with heating time at each point ①, ②, ③ and ④ indicated in the figure.

The welding procedure adopted in this investigation is as follows. The faying surfaces were degreased by washing in acetone before welding. The base metals were placed in the welding chamber with their faying surfaces in contact as shown in Fig. 1, and the welding chamber was evacuated to $\lesssim 10^{-4}$ mmHg vacuum. Then the bonding zone was brought to the welding temperature with the high frequency induction heater. Considering the result shown in Fig. 2, the welding temperature was monitored with a chromel-alumel thermocouple at the point of 1 mm from the bonding interface on the side surface of titanium base metal. And welding pressure was applied after heating for 2 min. After the allocated time at the welding temperature and pressure, both heating and pressing were stopped and the bonding zone was allowed to cool to 250 °C in vacuum environment.

The details of testing procedure are summarized as follows. The etchant for the observation of microstructure was Kroll's reagent (HF 2%, HNO_3 2%, and H_2O 96%). X-ray diffraction analysis was performed by Cu-K_α radiation. The observation by scanning electron microscopy was performed with Hitachi type HSM-2B scanning electron microscopy. The accelation voltage and the spot size of electron beam were 20 kV and 100~200 Å, respectively. Instron type machine was used for tensile strength test and the deformation rate was 1 mm/min. The specimen for tensile test was prepared by machining the joint to the shape as shown in **Fig. 3.**

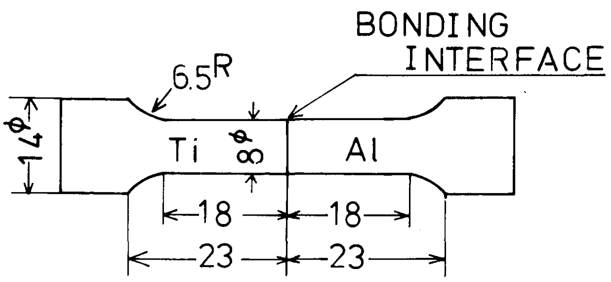

Fig. 3 Specimen for tensile strength test.

3. Results

3.1 Microstructure of the Bonding Zone

Photograph 1 shows the microstructure of the bonding zone between aluminum and titanium. As shown in Photo. 1, the interlayer which seemed to consist of intermetallic compound was observed in the bonding zone. The thickness of this interlayer increased with increasing in welding temperature and time. **Photograph 2** shows the secondary electron image of the interlayer observed with SEM (scanning electron microscopy). And it also shows the distributions of aluminum and

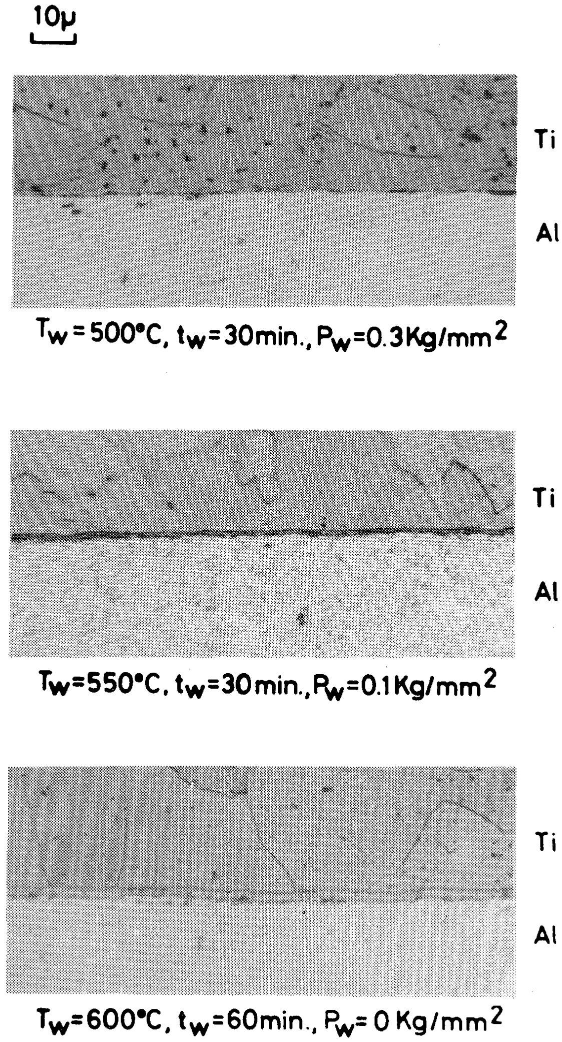

Photo. 1 Microstructures of bonding zones between aluminum and titanium. T_w, t_w, and P_w are welding temperature, time, and pressure, respectively.

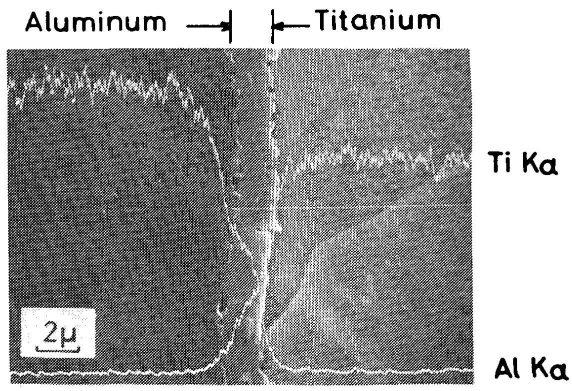

Photo. 2 Scanning electron micrograph of a bonding zone and intensities of characteristic X-ray of aluminum and titanium analyzed along the white straight line. The welding temperature, time, and pressure were 600 °C, 1 hr, and 0 kg/mm², respectively.

titanium along the white straight line analyzed with energy dispersive X-ray spectroscopy attached to SEM. As shown in Photo. 2, the slopes of the distribution curves of aluminum and titanium were reduced in the interlayer and this suggests that the interlayer consists of intermetallic compound. The hardness of this interlayer was much higher than the base metals as shown in **Fig. 4**. These results indicate that the interlayer consists of intermetallic compound.

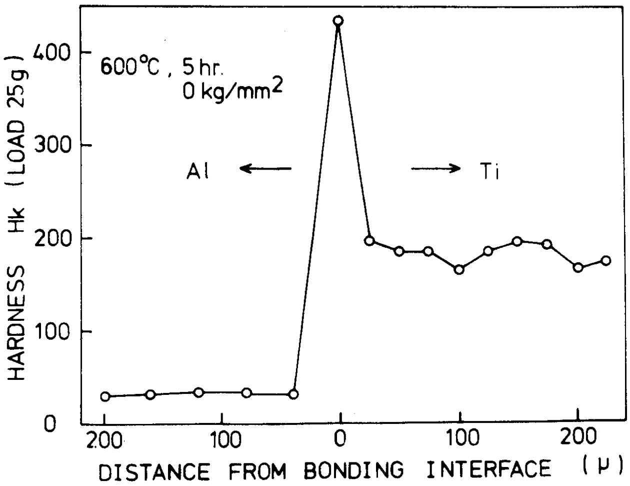

Fig. 4 Distribution of Knoop hardness numbers in the bonding zone of a joint between aluminum and titanium. The welding temperature, time, and pressure were 600 °C, 300 min, and 0 kg/mm², respectively.

In order to identify the intermetallic compound, X-ray diffraction analysis was performed. **Figure 5** shows the X-ray diffraction patterns obtained on the fractured surfaces of the joint which was fractured at the bonding zone by tensile test. As shown in Fig. 5, the diffraction lines of only Al_3Ti were observed except for aluminum and titanium. According to the phase diagram[9], the intermetallic compounds of Al_3Ti and AlTi are formed in aluminum and titanium binary system. But the diffraction lines of AlTi can not be observed as shown in Fig. 5. This result indicates that AlTi was not formed in the diffusion welding process and the intermetallic compound layer shown in Photo. 1 consists of Al_3Ti.

3.2 Tensile Test

Figure 6 shows the tensile strength of the joint as a function of welding time at various welding temperature and pressure. The tensile strength of the joint increased with increasing in welding temperature and time, and the joints welded for more than 30 min at 600 °C were fractured in the aluminum base metal. The effect of the welding pressure on the joint strength was remarkable at the welding temperature of 500 °C and the

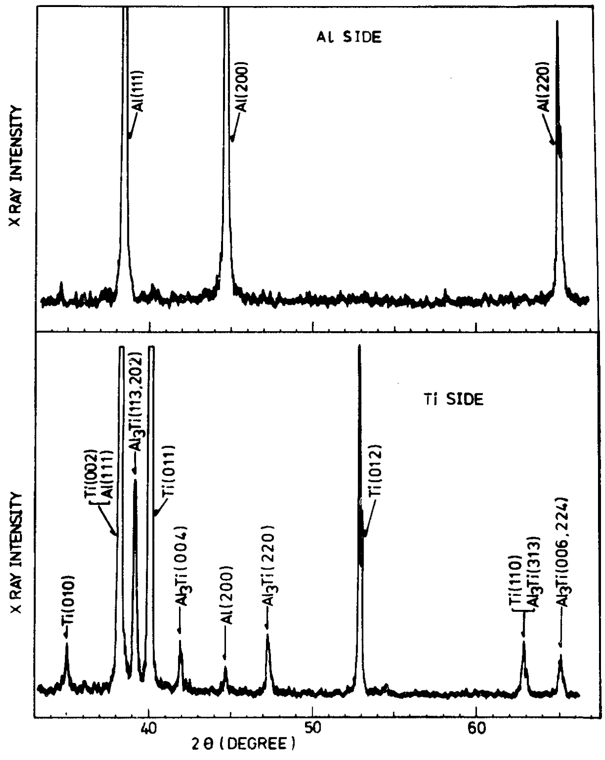

Fig. 5 X-ray diffraction patterns from the fractured surfaces of the joint between aluminum and titanium fractured at the bonding zone. The welding temperature, time, and pressure were 500 °C, 120 min, and 0.2 kg/mm², respectively.

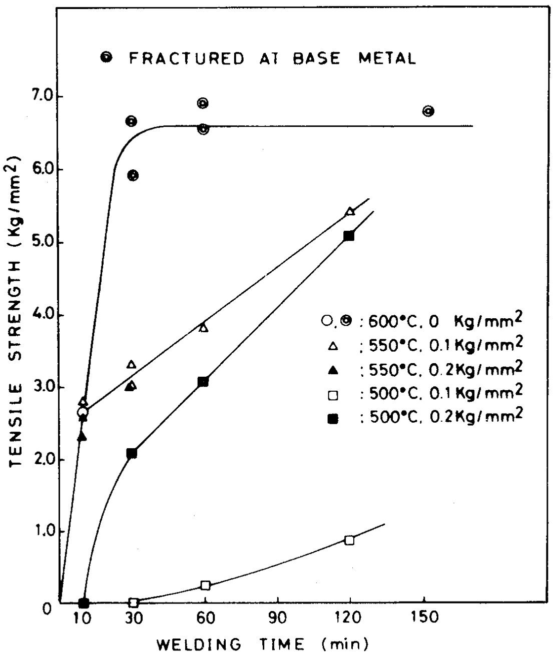

Fig. 6 Variation of the tensile strength of joint with welding time at various welding temperature and pressure for joints between aluminum and titanium.

tensile strength of the joint welded at 0.2 kg/mm^2 was much higher than that at 0.1 kg/mm^2. But at 550°C the effect of the welding pressure on the joint strength was very small and the joint strength was nearly equal between 0.2 kg/mm^2 and 0.1 kg/mm^2. Thus, the lower the welding temperature was, the larger the effect of welding pressure on the joint strength was.

It is said that the strength of the joint between dissimilar metals decreases as the thickness of intermetallic compound layer increases. For example, Kharchenko[5] said that the strength of the joint between aluminum and titanium was decreased when the intermetallic cmpound layer grew thicker than 4~6 μm. **Figure 7** shows the tensile strength and the thickness of intermetallic compound layer as a function of

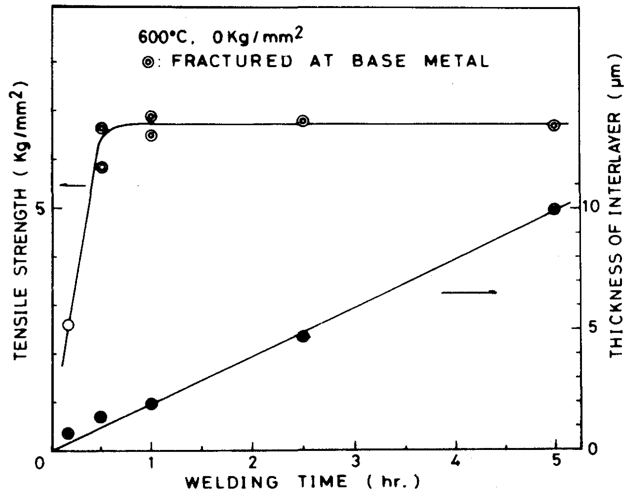

Fig. 7 Tensile strength of joint and thickness of intermetallic compound layer as a function of welding time. The welding temperature and pressure were 600°C and 0 kg/mm^2, respectively.

welding time for the joint welded at 600°C. As shown in Fig. 7, the thickness of the intermetallic compound layer increased up to about 10 μm almost linearly with welding time, but any decrease in tensile strength with increase in welding time can not be observed. Thus the growth of the intermetallic compound layer did not reduce the tensile strength of the joint within 10 μm.

3.3 Microstructure of the Bonding Zone Fractured by Tensile Test

The cross sectional microstructure of the fractured zone and the microstructure of the fractured surface were observed to investigate an important factor for joint strength. **Photograph 3** shows the cross sectional microstructure of the fractured zone obtained from the joint which had much lower tensile strength than

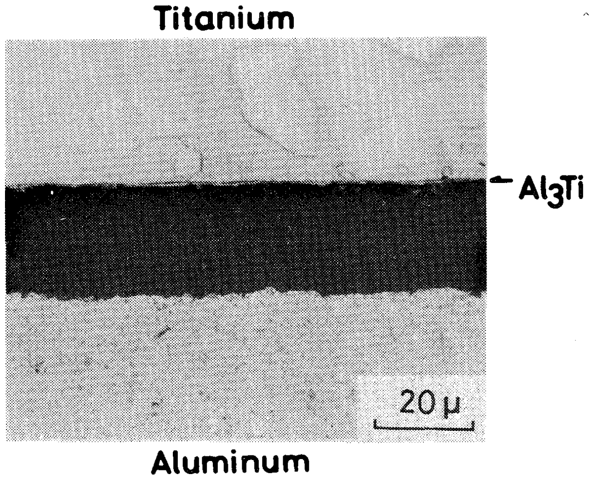

Photo. 3 Cross sectional microstructure of the fractured zone obtained from the joint which had much lower tensile strength than the base metals. The welding temperature, time, and pressure were 600°C, 10 min, and 0 kg/mm^2, respectively.

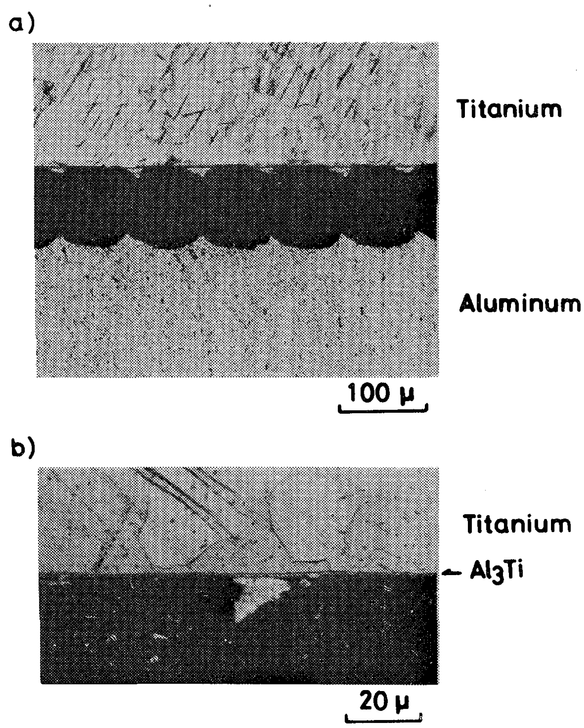

Photo. 4 Cross sectional microstructures of the fractured zone obtained from the joint which had slightly lower tensile strength than the aluminum base metal. The welding temperature, time, and pressure were 550°C, 120 min, and 0.1 kg/mm^2, respectively.

the base metals. As shown in Photo. 3, the joint was fractured at the boundary between the aluminum base metal and intermetallic compound layer. **Photograph 4** shows the cross sectional microstructures of the fractured zone obtained from the joint which had

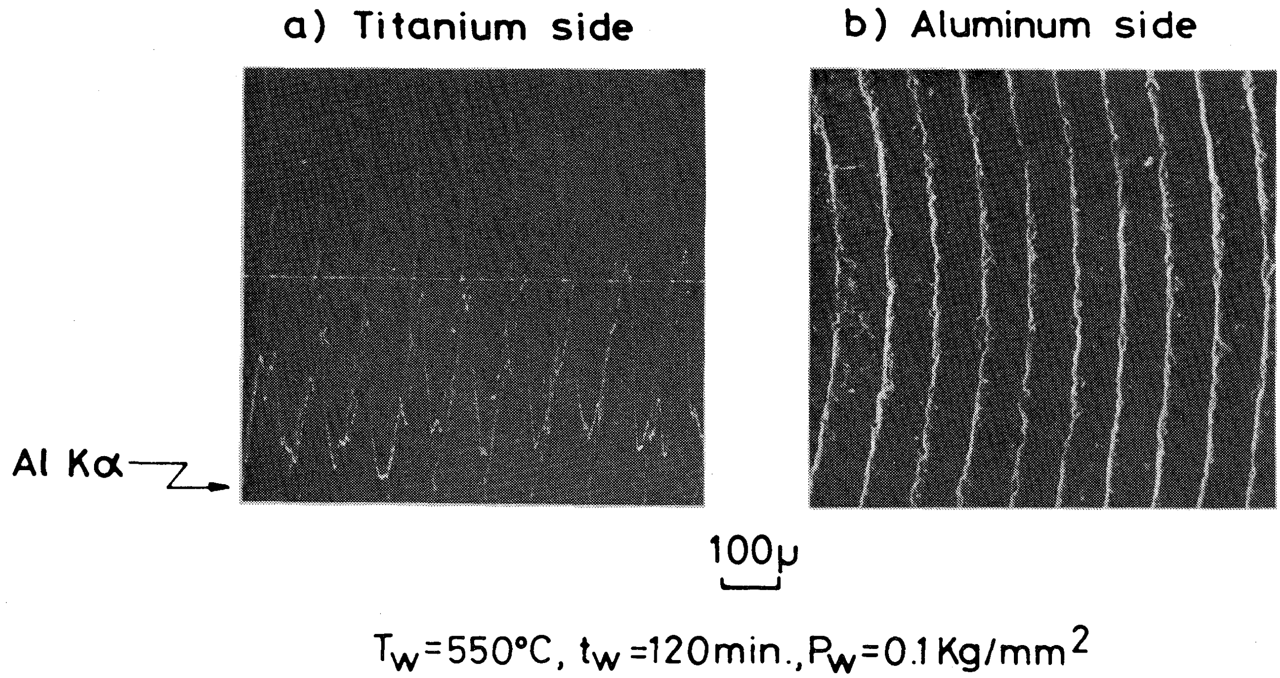

Photo. 5 Scanning electron micrographs of the fractured surfaces whose cross sectional microstructures are shown in Photo. 4. The intensity of characteristic X-ray of aluminum along the white straight line is shown in a).

slightly lower tensile strength than the aluminum base metal. In this case, although the joint was fractured mainly at the boundary between the aluminum base metal and intermetallic compound layer, the regions where some parts of aluminum were sticked on the titanium side were observed at constant intervals as shown in Photo. 4. In these regions, the joining process proceeded preferentially and the fracture occured in the aluminum base metal. The intervals between these regions were about 80 μm.

Photograph 5 shows the scanning electron micrographs of the fractured surfaces obtained from the joint welded under the same condition as that shown in Photo. 4. Photograph 5 a) also shows the distribution of aluminum on the fractured surface of titanium along the white straight line analyzed with an energy dispersive X-ray spectroscopy. As shown in Photo. 5, white concentric circles were observed on both fractured surface of titanium and aluminum. And the distribution curve of aluminum on the titanium side had peaks at the white concentric circles. The intervals of these concentric circles were about 80 μm. This interval was nearly equal to that of the region fractured at aluminum base metal shown in Photo. 4. These results indicate that the white concentric circles correspond to the regions where the fracture occured in the aluminum base metal in Photo. 4.

4. Discussion

As shown in Fig. 7, the decrease in the tensile strength with the growth of intermetallic compound layer was not observed for the joint between aluminum and titanium in this investigation. And the joints which had lower tensile strength than the base metals were fractured chiefly at the boundary between the aluminum base metal and intermetallic compound layer as shown in Photo. 3 and Photo. 4. These results indicate that the most important factor for joint strength is not the growth of intermetallic compound layer but some factors which determine the strength of the boundary between the intermetallic compound layer and aluminum base metal.

Photograph 6 shows the microstructure of the bonding zone with a marker of tungsten wire (20 μm in diameter). The marker was inserted between the faying surfaces before welding. The marker was present in the aluminum base metal contacting with the intermetallic compound layer. The marker was pressed into the aluminum base metal immediately by welding pressure because the flow stress of aluminum is much lower than that of titanium at 600°C, the welding temperature. This fact indicates that the boundary between the aluminum base metal and intermetallic compound layer is the initial bonding interface.

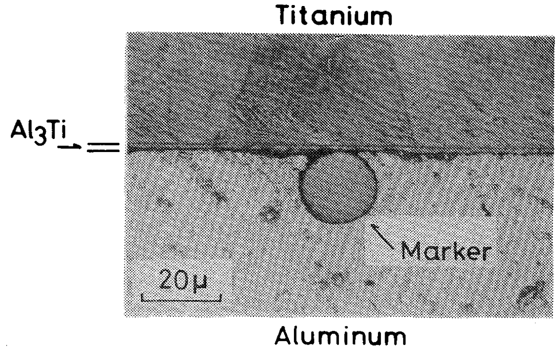

Photo. 6 Microstructure of the bonding zone with a marker of tungsten wire (20 μm in diameter). The welding temperature, time, and pressure were 600°C, 60 min, and 0 kg/mm², respectively.

Consequently, the joint strength of this system was chiefly affected by following two factors in the initial bonding interface. These factors are (1) the existence of tenacious oxide film on the faying surface of aluminum, and (2) the intimacy of contact between the faying surfaces. If the effect of the factor (2) is important, the joint strength is increased by increasing the welding pressure. As shown in Fig. 6, at the welding temperature of 500°C the joint strength was increased by increasing the welding pressure from 0.1 kg/mm² to 0.2 kg/mm², but this fact could not be observed at the welding temperature of 550°C. This indicates that the effect of the factor (2) on the joint strength was not so important at the welding temperature of 550°C, though it may be important at 500°C. Consequently, it is considered that the most important factor for the joint strength at 550°C was the factor (1). That is, even if the intimacy of contact between the faying surfaces was adequate, the joint strength did not increase sufficiently because the oxide film on the faying surface of aluminum inhibited the formation of metallic bond at the bonding interface.

As shown in Photo. 5, the joining process proceeded preferentially in the regions of concentric circles. **Figure 8** shows the profiles of the asperities of the faying surfaces of titanium and aluminum. The grooves caused by machining with a lathe were observed at nearly constant intervals of 80~100 μm and 50 μm on the faying surfaces of titanium and aluminum, respectively. The intervals of the grooves on the faying surface of titanium is nearly equal to that of the regions where the joining process proceeded preferentially. This indicates that the joining process proceeded preferentially along the microasperity on the titanium faying surface. In this case, the joining process is considered to be controlled mainly by the destruction of oxide film on aluminum faying surface. Consequently, it is considered that the joining process proceeded preferentially in the regions where the aluminum oxide film was disrupted by the microasperities on the faying surface of titanium.

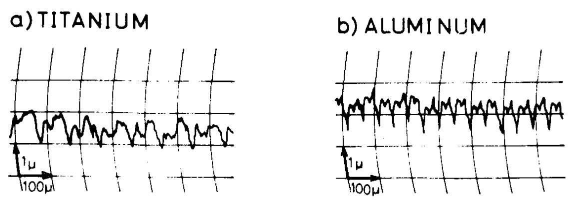

Fig. 8 Profiles of the microasperities on the faying surfaces of aluminum and titanium.

In order to confirm this consideration, titanium and aluminum base metal were ground with 800 grade emery paper to break the grooves on the faying surface caused by tarnishing, and each one of them was diffusion-welded to another not ground base metal. **Photograph 7** shows the fractured surfaces of titanium side, and a) and b) are the microstructures in the case of grinding titanium and aluminum faying surface, respectively. The concentric circles can be observed in the case of grinding the aluminum faying surface, but can not be observed in the case of grinding the titanium faying surface. This result proves that the joining process between aluminum and titanium proceeded preferentially along the microasperities on the faying surface of titanium.

Thus, it is considered that the existence of the tenacious oxide film on the faying surface of aluminum is the most important factor for the strength of diffusion-welded joint between aluminum and titanium, and the joining process proceeded preferentially along the microasperities on the faying surface of titanium.

5. Summary

The diffusion welding of aluminum to titanium was performed as an example of the joint between dissimilar metals which form brittle intermetallic compound. The microstructure in the bonding zone and the tensile strength of the joint were examined, in order to investigate the important factor which affected the joining process and mechanical property of the joint. Results obtained are summarized as follows.

(1) The tensile strength of the joint increased with increasing in welding temperature and time. The joint welded for more than 30 min at 600°C was fractured at aluminum base metal.

(2) The effect of the welding pressure on the joint strength became smaller with increasing in welding temperature. That is, at the welding temperature of

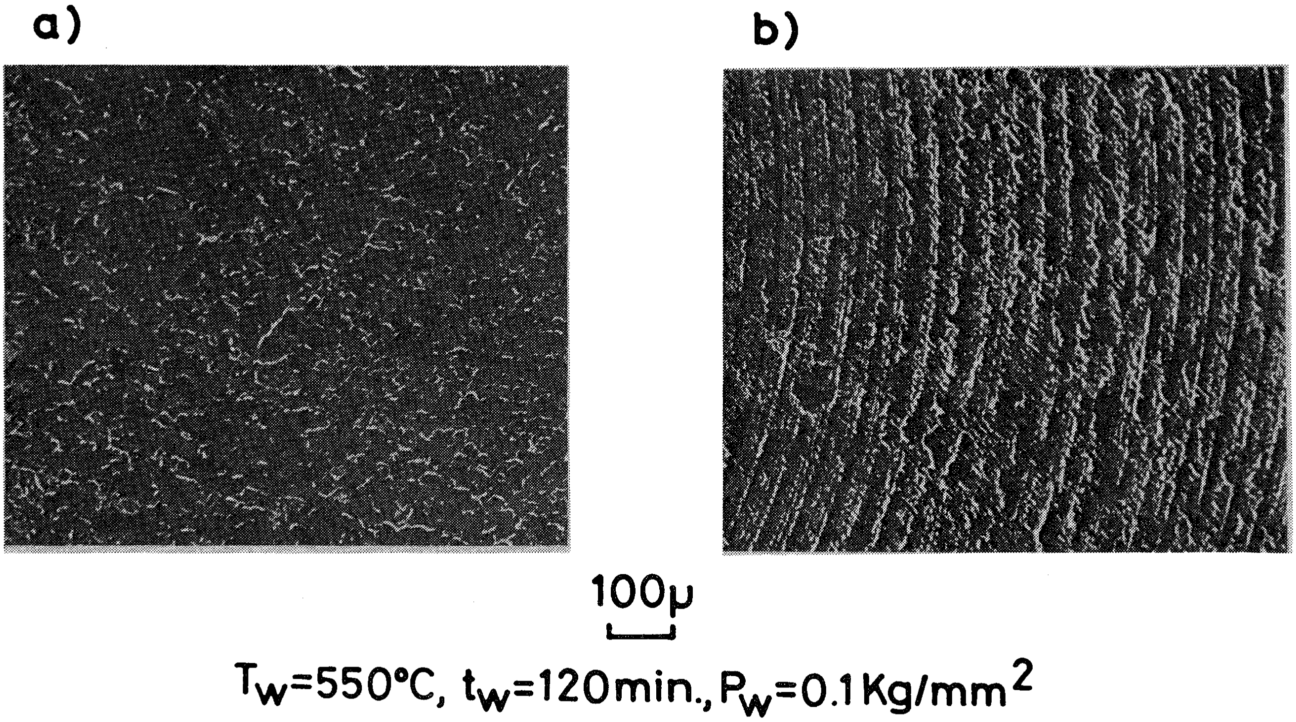

Photo. 7 Effect of grinding the faying surfaces of titanium and aluminum on the fractured surface of titanium side. The welding condition was same as that shown in Photo. 4.
a) The faying surface of titanium was ground with 800 grade emery paper prior to welding.
b) The faying surface of aluminum was ground in the same manner as a).

500 °C the tensile strength of the joint welded with the welding pressure of 0.2 kg/mm^2 was much higher than that of the joint welded with 0.1 kg/mm^2, but at 550 °C the tensile strength of the joint obtained by welding at 0.2 kg/mm^2 and 0.1 kg/mm^2 were nearly equal.

(3) The interlayer of intermetallic compound Al_3Ti was observed in the bonding zone. The thickness of this interlayer increased almost linearly with welding time at the welding temperature of 600 °C. The increase in the thickness did not reduce the joint strength up to 10 μm at least.

(4) The oxide film on the faying surface of aluminum is considered to be the most important factor which affects the joining process and joint strength. That is, the joint strength did not increase sufficiently because the tenacious oxide film inhibited the formation of metallic bond between the base metals.

(5) The joining process proceeded preferentially in the regions where the oxide film was disrupted by microasperities on the faying surface of titanium caused by machining with a lathe.

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