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<tr>
<td><strong>Citation</strong></td>
<td>Transactions of JWRI. 6(2) P.251-P.257</td>
</tr>
<tr>
<td><strong>Issue Date</strong></td>
<td>1977-12</td>
</tr>
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<td><strong>Text Version</strong></td>
<td>publisher</td>
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<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/11094/6368">http://hdl.handle.net/11094/6368</a></td>
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Effects of Insert-metals on Diffusion Welding of Aluminum to Titanium

Toshio ENJYO*, Kenji IKEUCHI** and Toshiharu MARUYAMA***

Abstract

Diffusion welding of aluminum to titanium with an insert-metal has been carried out and the effects of the insert-metal on the joining process and mechanical properties of the joint have been investigated. Silver and zinc were selected as insert-metal because the oxide film on the faying surface of aluminum inhibited the bonding between titanium and aluminum as shown in a previous paper. The effects of the insert-metals were studied by the observation of microstructure in the bonding zone and fractured zone. The results obtained are summarized as follows.

1) The tensile strength of joint was increased by using the silver insert-metal. Joints subjected to the diffusion-welding at 550°C for more than 30 min. or at 600°C for more than 10 min. fractured at the aluminum base metal.

2) In the case of welding at 500°C with silver insert-metal, the insert-metal remained in the bonding zone and the bonding strength between this insert-metal and the base metals was lower than the strength of aluminum base metal. On the other hand, in the case of welding at 550°C or 600°C, the silver insert-metal was dissolved by the aluminum base metal and promoted the destruction of the oxide film on aluminum faying surface by the formation of localized region of low flow stress or liquid. Therefore, the joint welded at 550°C or 600°C had a enough tensile strength to fracture at the aluminum base metal.

3) The intermetallic compounds of Ag₃Al and Al₅Ti were formed in the bonding zone of joint welded with silver insert-metal.

4) For the joint welded with zinc insert-metal, a thick intermetallic compound layer and many voids were formed in the bonding zone. The tensile strength of the joint welded with zinc insert-metal was not necessarily stronger than that of the joint welded without insert-metal and the reproducibility of the strength was quite poor, because of the formation of these intermetallic compound layer and voids.

5) The intermetallic compounds of Al₅Ti and TiZn₅ were formed in the bonding zone of the joint welded with zinc insert-metal.

1. Introduction

In a previous paper¹, the authors investigated important factors which affected the diffusion welding process and mechanical properties of joint between titanium and aluminum. In the paper¹, it was shown that the joint welded for more than 30 min. at 600°C under the pressure about 0.01 kg/mm² had such strong tensile strength as the fracture occurred at the aluminum base metal and the deformation caused by welding was quite little in the welding condition. However, most of ordinary aluminum alloys cannot be hold at 600°C without the extinction of excellent characteristics of the alloys. Consequently, it was desirable to obtain a joint strength higher than the base metal by welding at lower temperature.

In the diffusion welding, an insert-metal is often used to accelerate the diffusion welding process or improve the mechanical properties of joint. In this investigation, insert-metals were selected using the results reported in the previous paper¹, and the effects of the insert-metals on the joining process and mechanical properties of joint were studied. In the previous paper¹, it was made clear that the joining process between titanium and aluminum proceeded preferentially in the region where the oxide film on aluminum faying surface was destructed. In this investigation, silver and zinc, which form a low melting solid solution or eutectic composition with aluminum, were selected as insert-metal. They were considered to promote the destruction of aluminum oxide film because the localized regions consisted of low flow stress alloy or liquid were formed by using these insert-metals. Ohashi and Hashimoto⁴ reported that the joint between copper and aluminum improved in mechanical properties by using silver and zinc as insert-metal.

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* Received on November 1, 1977
** Professor
*** Research Instructor
**** Graduate Student
2. Experimental Details

The base metals used in this investigation were commercially pure titanium and aluminum which were the same as those used in the previous paper. Their chemical compositions are shown in Table 1.

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<tr>
<td></td>
<td>Fe</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.038</td>
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<thead>
<tr>
<th>Specimen</th>
<th>Chemical Composition (wt %)</th>
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<tbody>
<tr>
<td></td>
<td>Cu</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.032</td>
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Both the base metals had cylindrical shape whose diameter and length were 20 mm and 37 mm, respectively. The faying surface was machined with a lathe and the roughness of the surface was 3-S in JIS standard number. The tensile strength of aluminum and titanium used as the base metals were 6~8 kg/mm² and 39 kg/mm², respectively. The foil of silver and zinc used as the insert-metals was 6 μm and 50 μm in thickness, respectively. Zinc vacuum-evaporated by a few μm on the faying surface was also used as insert-metal to examine the effects of the thickness of the zinc insert-metal on the diffusion welding.

The details of welding procedure employed in this investigation were the same as those reported in the previous paper1. The faying surfaces of the base metals and insert-metals were degreased by washing in acetone before welding. The welding chamber was evacuated to $10^{-5}$~$10^{-4}$ mmHg during welding. The bonding zone was heated with a high frequency induction heater. The temperature of the bonding zone was monitored with a chromel-alumel thermocouple penetration-welded at the point of 1 mm from the bonding interface on the side surface of titanium base metal. The welding pressure was applied with a hydraulic press. After the welding, the bonding zone was allowed to cool to 250°C in vacuum environment.

Testing procedures are summarized as follows. The etchant for the observation of microstructure was Kroll's reagent. X-ray diffraction analysis was performed by Cu-Kα radiation. The observation with a scanning electron microscopy (SEM) was carried out at the acceleration voltage of 20 kV. The distribution of element was also examined with an energy dispersive X-ray spectroscopy attached to SEM. The analysis with an electron probe X-ray microanalyzer (EPMA) was performed with an electron beam 2 μm in diameter. The tensile strength test was carried out with an Instron type machine at the deformation rate of 1 mm/min. Specimens for tensile strength test were prepared by machining joints after welding. The gauge length and diameter of the specimen were 36 mm and 8 mm, respectively.

3. Results and Discussions

3.1 Effects of Silver Insert-metal

Photo. 1 shows the microstructures of the bonding zones between titanium and aluminum welded with silver insert-metal. As shown in Photo. 1(a), for the joint welded at 500°C the insert-metal remained in the bonding zone and some parts of the insert-metal contained many precipitates. This insert-metal in the bonding zone will be called as residual insert-metal. Many precipitates were also observed in the aluminum base metal, as shown in Photo. 1(a). On the other hand, in the case of welding at 550°C or 600°C, an intermetallic compound layer was observed in the bonding zone, but a residual insert-metal or precipitate in the aluminum base metal was not observed, as shown in Photo. 1(b). In order to identify the intermetallic compound and precipitates, X-ray diffraction patterns obtained on the fractured surface of
the joint were analyzed. As shown in Fig. 1, for the joint welded at 500°C, the strong diffraction lines of Ag₃Al were observed on the fractured surfaces of both titanium and aluminum side. However, the diffraction lines of Al₃Ti which was an only intermetallic compound formed in joint welded without insert-metal were much weaker than those of Ag₃Al. As shown in Fig. 2, for the joint welded at 550°C, the diffraction lines of Ag₃Al were much weaker than those of Al₃Ti observed on the fractured surface of titanium side.

Fig. 1 X-ray diffraction patterns from the fractured surfaces of the joint welded with silver insert-metal. The welding conditions were 500°C, 60 min., and 0.1 kg/mm².

Fig. 2 X-ray diffraction patterns from the fractured surfaces of the joint welded with silver insert-metal. The welding conditions were 550°C, 10 min., and 0.1 kg/mm².

As shown in Fig. 3, the silver diffused chiefly into the aluminum base metal. The titanium or aluminum hardly diffused into the other base metal.

Fig. 3 EPM analysis for the distributions of titanium, aluminum, and silver in the bonding zone. The welding conditions were 550°C, 30 min., and 0.1 kg/mm².

Fig. 4 Variation of the tensile strength of joints with welding time at various welding temperatures and pressures. The joints were welded with silver insert-metal.

As shown in Fig. 4, the variation of the tensile strength of joint with welding time at various welding temperatures and pressures. The broken lines in Fig. 4 show the tensile strength of joints welded without insert-metal under the same condition as those indicated with the arrows. As shown in Fig. 4, the tensile strength of joints was increased by using the silver insert-metal at the welding temperature of
500°C～600°C. The joints subjected to the welding for more than 30 min. at 550°C or for more than 10 min. at 600°C, fractured at the aluminum base metals. In Fig. 4, in the case of welding at 600°C, a welding pressure with a hydraulic press was not applied but a pressure of about 0.01 kg/mm² is considered to be applied on the welding interface due to the weight of the base metal and atmospheric pressure transmitted through the pressing axis in the welding chamber.

The cross sectional microstructure of the fractured zone and the microstructure of the fractured surface were observed to investigate what factor was important for the mechanical properties of joint welded with silver insert-metal. Photo. 2(a) and (b) show the cross sectional microstructures of the fractured zone obtained from the joints welded at 500°C and 550°C, respectively. As shown in Photo. 2(a), the fracture of joint welded at 500°C occurred at the interface between the residual insert-metal and aluminum or titanium base metal (see also Photo. 3). The insert-metal was dissolved for the joint welded at 550°C, as shown in Photo. 2(b). In this case, the joint was fractured mainly at the interface between the intermetallic compound layer and aluminum base metal, but the regions where a piece of aluminum was stucked on titanium side were observed.

Photo. 2 Cross sectional microstructures for the fractured zones (titanium side) obtained from the joints welded with silver insert-metal.

Photo. 3 Scanning electron micrographs for the fractured surfaces obtained from the joint welded with silver insert-metal.

Photo. 3, the fractured surfaces of joints welded at 500°C were composed of two characteristic regions: one of them was region where the grooves caused by machining with a lathe were observed, and the other was region where no grooves was observed. According to the analysis with an energy dispersive X-ray spectroscopy on the fractured surface of titanium side, the concentration of silver was higher and that of titanium was lower in the latter region compared with the concentrations in the former region. As shown in Photo. 3, the fractured surface presented a terras-and-wall like fracture. These results indicate that in the former region the fracture occurred at the interface between the residual insert-metal and titanium base metal, and in the latter region at the interface between the residual insert-metal and aluminum base metal. Thus, in the case of welding at 500°C, the residual insert-metal existed in the bonding zone, and the bonding strength between the residual insert-metal and the base metals was not so strong for the joint to fracture at the base metal. For the joint welded at 550°C, many regions where a piece of aluminum was stucked were observed on the fractured surface of ti-
Effects of Insert-metals on Diffusion Welding

Titanium as shown in Photo. 4. As reported in the previous paper\textsuperscript{3}, for the joint welded without insert-metal, the region where a piece of aluminum was stucked was formed on the fractured surface of titanium along the microasperities caused by machining with a lathe. This fact indicates that the joining process proceeds preferentially in the regions where the oxide film of aluminum is disrupted by the microasperities on the faying surface of titanium. On the other hand, as shown in Photo. 4, for the joint welded with silver insert-metal, the region had no connection with the microasperity of titanium faying surface. This fact indicates that the harmful effects of aluminum oxide film on the joining process can be reduced by the use of silver insert-metal. Therefore, the tensile strength of the joint welded at 550°C was remarkably improved by the use of silver insert-metal.

3.2 Effects of Zinc Insert-metal

Photo. 5 shows the microstructures of a bonding zone in the joint welded with zinc insert-metal which is a sheet of foil 50\,\mu m thick. As shown in Photo. 5(a), a thick intermetallic compound layer was formed and the thickness of the layer varied largely. Furthermore, as shown in Photo. 5(b), many voids were observed in the aluminum close to the bonding interface. It is considered that these voids were originated from the bubbles of zinc vapour formed in the liquid region where the aluminum base metal was alloyed with zinc. In order to suppress the formation of these voids, diffusion welding was carried out at 400°C so as to reduce the vapour pressure of zinc. However, in this case the joint strength was very low and the microstructure of bonding zone can not be observed.

A zinc vacuum-evaporated by a few \mu m on the faying surface was used as an insert-metal to investigate the effects of the thickness of insert-metal on the formation of the intermetallic compound layer and voids. As shown in Photo. 6, in the joint welded with vacuum-evaporated zinc insert-metal, the thickness of the intermetallic compound layer was reduced, but the voids were formed in the same manner as those in a joint welded with foil insert-metal. No difference in the microstructure of the bonding zone was observed whether the zinc was evaporated on the faying surface of aluminum or titanium.

In order to identify the intermetallic compound formed in the joint welded with zinc insert-metal,
X-ray diffraction patterns obtained on the fractured surfaces of the joint was analyzed. As shown in Fig. 5, the diffraction lines of Al₆Ti and TiZn₅ were observed inclusive of those of titanium, aluminum, and zinc. This result indicates that the intermetallic compound layer in the joint welded with zinc insert-metal with zinc insert-metal, the fracture occurred at the intermetallic compound layer, interface between the intermetallic compound layer and base metals, and voids. This fact indicates that the tensile strength of joint welded with zinc insert-metal was reduced by the formation of the intermetallic compound layer and void in the bonding zone.

4. Conclusive Remarks

In this investigation, the effects of insert-metals on the diffusion welding process and mechanical properties of the joint between aluminum and titanium was investigated. Silver and zinc were selected as an insert-metal using the results reported in the previous paper. The effects of the insert-metals on diffusion welding were investigated by the observation of microstructures in the bonding zone, cross section of fractured zone, and fractured surface, X-ray analysis, and analysis with EPMA. The mechanical properties
was evaluated by a tensile strength test. The results obtained are summarized as follows.

1) The tensile strength of the joint between aluminum and titanium was increased by using the silver insert-metal. The joint subjected to the diffusion-welding with the silver insert-metal for more than 30 min. at 550°C or for more than 10 min. at 600°C fractured at the aluminum base material.

2) In the case of welding at 500°C with silver insert-metal, the insert-metal remained in the bonding zone and the bonding strength between this insert-metal and the base metals was lower than the strength of aluminum base metal. On the other hand, for the joint welded at 550°C or 600°C, the silver insert-metal was dissolved by the aluminum base metal. In the bonding zone where the aluminum base metal was alloyed with silver, a localized region of low flow stress or liquid was formed. The destruction of the oxide film on the aluminum faying surface which inhibited the bonding between titanium and aluminum was promoted by the formation of this region. Therefore, the joint welded with the silver insert-metal at 550°C or 600°C had a enough tensile strength to fracture at the aluminum base metal.

3) The intermetallic compounds of Ag₅Al and Al₃Ti were formed in the bonding zone of the joint welded with silver insert-metal.

4) For the joint welded with zinc insert-metal, a thick intermetallic compound layer and many voids were formed in the bonding zone. The tensile strength of the joint welded with zinc insert-metal was not necessarily stronger than that of the joint welded without insert-metal and the reproducibility of the tensile strength was quite poor, because of the formation of these intermetallic compound layer and voids.

5) The intermetallic compounds of Al₃Ti and TiZn₃ were formed in the bonding zone of the joint welded with zinc insert-metal.

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