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Joint Characteristics of Dissimilar Materials Friction Welds (II) †

- In the Case of Titanium/Aluminium Welds -

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Abstract

The dominant factors determining the joint characteristics (strength, ductility and so on) in titanium and aluminium friction welds were investigated variously from the mechanical and metallurgical points of view.

The mechanical factors were not the main factors determining the characteristics of the joints, as residual stress and plastic strain generated by the friction welding were not so large. It was found that the main factors dominating the characteristics of the joint were the metallurgical, that is the thickness of the intermetallic compound layer produced at the interface. The critical thickness of the intermetallic compound layer was about 5 μm. When this kind of the joint is used in a high temperature environment, the working temperature and time should be sufficiently noted. When the working time became long, the characteristics of the joints were largely decreased as the thickness of the intermetallic compound layer increased.

KEY WORDS: (Friction welding) (Dissimilar materials) (Mechanical properties) (Residual stress) (Plastic strain) (Intermetallic compound) (Aluminium) (Titanium) (FEM)

1. Introduction

In recent times, working conditions of various industrial components have become severer and severer. Accordingly, structural materials with functions, which could not have been considered originally, have appeared in the form of dissimilar materials. Using friction welding, which is one of the solid state bonding processes, the perfect components can be obtained as combinations of nonferrous metals, which could not be obtained by fusion welding. A series of the studies has been performed[1-3] so as to investigate the applicability for structural materials.

The present paper deals with the friction welding of titanium (Ti) and aluminium (Al). The joint characteristics (strength, ductility and so on) in Ti/Al friction welded are investigated and evaluated variously from the mechanical and metallurgical points of view. Then, the dominant factor determining the joint characteristics is elucidated.

2. Condition of Friction Welding and Mechanical Properties

Tensile, bending and hardness tests were performed on friction welds made under various conditions. Perfect components were bent at a bending angle of 90° (max.) in the bending test and the initiation of fracture at the bonded surface was examined. When the fracture occurred, the bending angle was measured.

Test specimens of diameter 13^{ϕ}(mm) for tensile and bending tests were used. According to the results, the location of the fracture was all in the base metals. In 90° bending tests, a good joint without a fracture was obtained (see **Fig. 6**). **Table 1** shows the conditions of friction welding.

Generally it is known that the strength of the joint decreases because intermetallic compounds are produced at the joints interface during welding. However, in the friction welding tests described above, tensile strength was high and bending ductility was good. So, Vickers hardness tests near the interface of friction welds were conducted. **Figure 1** shows the hardness distributions.

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Titanium tends to soften adjacent to the interface. In aluminium, although there is not so large difference, hardness at the interface seems to be a little higher than that of the aluminium base metal. According to the results, it is seen that the layer of the intermetallic compound adjacent to the interface is extremely thin.

3. Influence of Residual Stress and Plastic Strain on the Joint Characteristics

Noting residual stress and plastic strain generated by friction welding[4], the influence of these on the joint characteristics is described.

3.1 Residual stress

Figure 2(a) shows the distributions of the residual stress components σ_r (radial direction), σ_θ (circumferential direction) and σ_z (perpendicular to the bondline) in the radial direction, in material immediately adjacent to the bondline (at the location z= ±0.005(mm)).

In friction welding, the Al substrate for which the linear expansion coefficient α is large (α of Al is a little over two times[5] as much as that of Ti) and temperature T is high becomes tensile, the Ti substrate becomes compressive. So, components σ_r and σ_θ are tensile in the substrate whose αT is large and compressive in the substrate whose αT is small.

Although αT of the Al substrate is large compared with αT of the Ti substrate[4], the absolute value of σ_r and σ_θ generated in the Al substrate are smaller than in the Ti substrate. This is because yield stress, σ_Y, of the Al substrate is smaller than σ_Y of the Ti substrate[5]. These results indicate that the magnitude and distribution of produced residual stress should be discussed not as an elastic problem but as an elastic-plastic problem in the combination of the materials.

In σ_z distribution in the axial direction, the absolute value is small except at the periphery. This is because the main cause of residual stress generation is the difference of shrinkage in the radial direction owing to a temperature gradient in the axial direction. Characteristics of σ_z in the axial direction (z-axis) which largely influences the mechanical properties of the joints will be considered below.

Figure 3(a) shows the σ_z distribution in the axial direction near the centerline of the component (at r=0.6(mm)) and in the axial direction at the welded component periphery (at r=6.495(mm)).

For the σ_z distribution in the axial direction near the centerline of the component, in the Al substrate, σ_z is tensile near the bondline and becomes compressive in the regions far from the bondline. On the contrary in the Ti substrate, σ_z is compressive in the whole region except immediately adjacent to the bondline. Although a temperature gradient in the axial direction cannot be recognized for three seconds after friction welding[4], in the Ti substrate, large compressive stress is generated because a temperature gradient in the axial direction restrains shrinkage of the material near the bondline including the Al substrate.

Table 1 Friction welding conditions.

Rotational speed (1/s)	26
Friction pressure (MPa)	50
Friction time (s)	2
Forging pressure (MPa)	100
Forging time (s)	6
Faying surface	#240

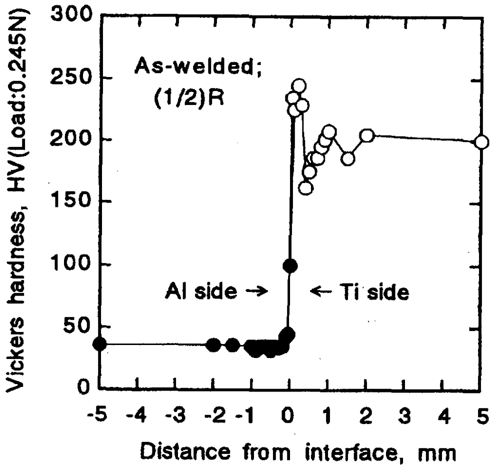
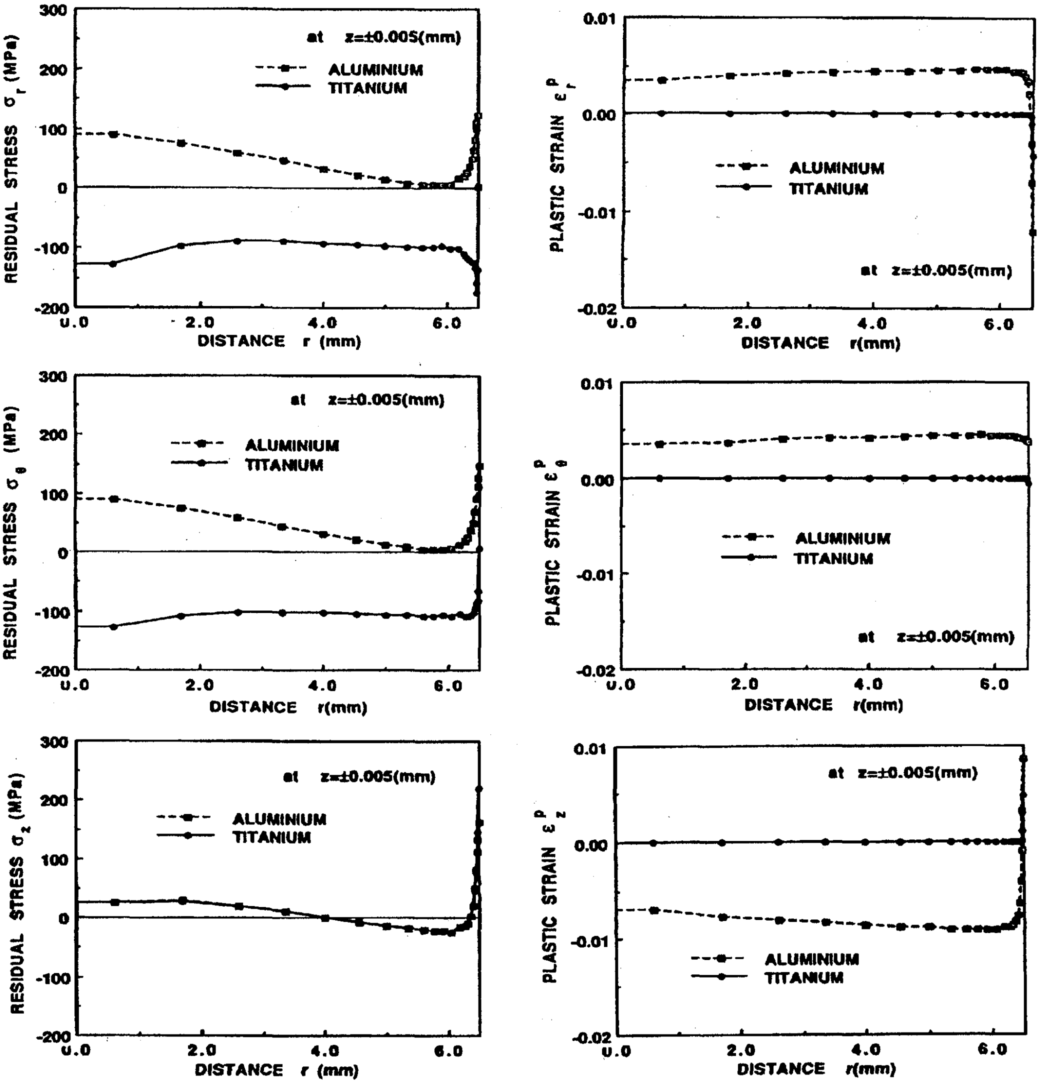


Fig.1 Hardness distribution of as-welded joints.

On the other hand, for the σ_z distribution in the axial direction at the welded component periphery, in the Al substrate, σ_z is compressive close to the bondline and tensile in the regions far from the bondline. In the Ti substrate, σ_z is tensile in the whole region. σ_z is largely compressive in the Al substrate whose αT is large because stiffness at the periphery is smaller than stiffness at the center of the component. Therefore, the Ti substrate cannot restrain the shrinkage of the Al substrate.

3.2 Plastic stain

Figure 2(b) shows the distributions of the plastic strain components ε_r^P (radial direction), ε_θ^P (circumferential direction) and ε_z^P (perpendicular to the bondline) in the radial direction, in material immediately adjacent to the bondline (at the location z= ±0.005(mm)).



(a) Residual stress.

(b) Plastic strain.

Fig.2 Residual stress and plastic strain distributions in radial direction immediately adjacent to the bondline.

Considerable plastic strain is generated in the Al substrate and ε_z^p is largely generated compared with ε_r^p and ε_θ^p. From the temperature distribution, large minus plastic strain ε_z^p perpendicular to the bondline is generated, not because of the severity of the mechanical restraint condition but to satisfy the condition of the volume constant.

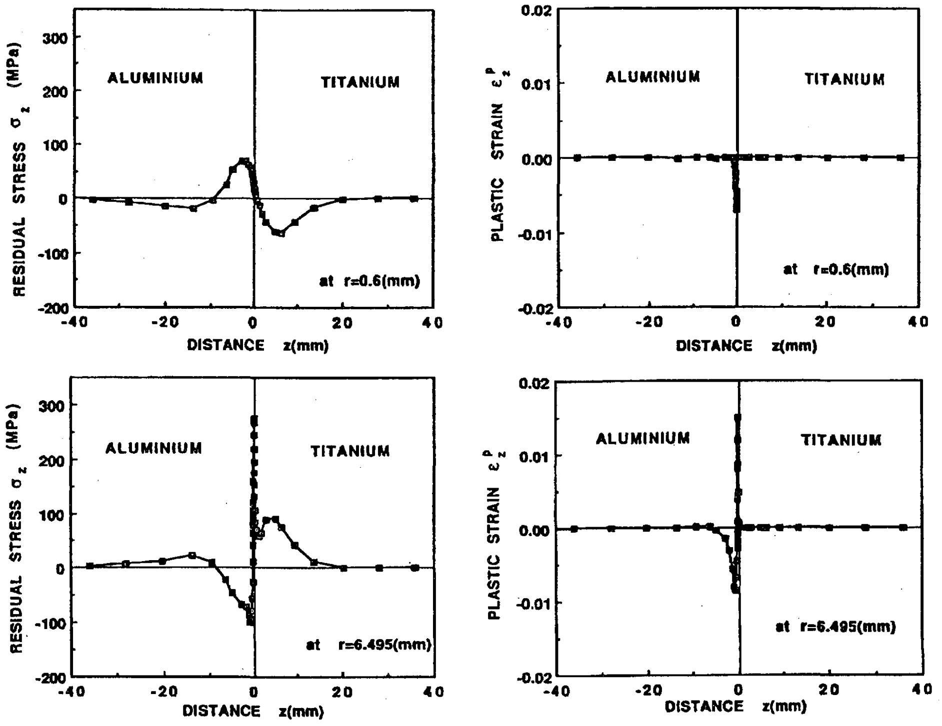
Figure 3(b) shows the distribution of ε_z^p in the axial direction near the center (at r=0.6(mm)) and at the periphery (at r=6.495(mm)) of the friction welded component. ε_z^p is concentrated in the Al substrate, but ε_z^p is hardly generated in the Ti substrate.

Residual stress and plastic strain generated in friction welding is not so large. So, it is considered that residual stress and plastic strain do not dominate the mechanical properties of friction-welded joints.

Next, the influences of the thickness of the intermetallic compound layer produced at the interface on the mechanical properties of the joints are investigated.

4. Thickness of the Intermetallic Compound Layer and Mechanical Characteristics

Noting the thickness of the intermetallic compound layer produced at the interface, the dominant factor of the joints properties is investigated. Controlling the thickness of the intermetallic compound layer by post heat treatment, the influence of the intermetallic compound layer thickness on the mechanical properties is investigated.



(a) Residual stress.

(b) Plastic strain.

Fig.3 Residual stress and plastic strain distributions in axial direction at center and periphery of component.

4.1 The thickness of the intermetallic compound layer

The bending tests were carried out on the friction welded specimens and holding times were variously changed, with the maximum temperature of the post heat treatment held constant (400, 500, 600 (°C)). **Figure 4** shows the results of the bending test.

Fracture occurred at the interface above the maximum heating temperature 600(°C), and holding time 10(H). Although in the case when the holding time was 10(H), the fracture occurred at a bend angle of 30 degree, the fracture occurred at the interface in all cases when the holding time is over 10H. So, the thickness of the intermetallic compound layer was measured using a light microscope for the post heat treated specimen whose holding time is variously changed. The results are shown in **Fig. 5**.

The intermetallic compound layer thickness becomes thicker as the holding time is longer. Therefore, the reason why the tensile strength or the bending ductility of friction welded joints is good is due

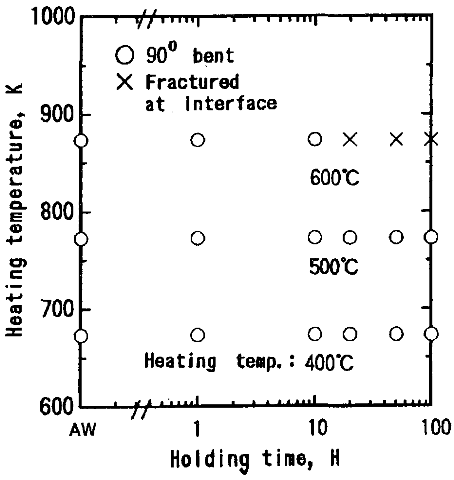


Fig.4 Effect of heating temperature and holding time on joint bend angle.

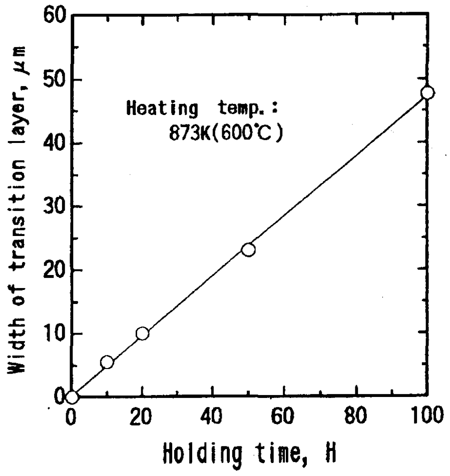


Fig.5 Effect of holding time at 600(°C) on width of transition layer.

to the intermetallic compound layer thickness which is extremely thin because the joining is instantaneously finished in friction welding. So, the tensile, bending and hardness tests are carried out after controlling the intermetallic compound layer thickness by post heat treatment.

4.2 Mechanical properties of post heat treated specimen

Figure 6 shows the results of the tensile and bending tests carried out on the post heat treated specimens in which holding times were variously changed with the maximum heating temperature 600(°C). According to the results, if holding time is within around 10(H), the Al substrate is fractured in all specimens. Although the tensile strength (Fig. 6(a)) is lowered a little, the bending ductility (Fig. 6(b)) is good.

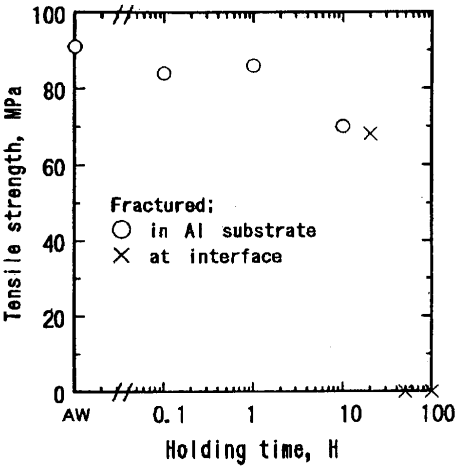
Figure 7 shows the results of the test in which the hardness is measured at the interface and at ±50μm from the interface for the post heat treated specimen.

It is known that although the hardness of aluminium (sign ○) and titanium (sign △) are constant irrespective of the holding time, the hardness at the interface (sign ×) rapidly increases when the holding time exceeds 10(H).

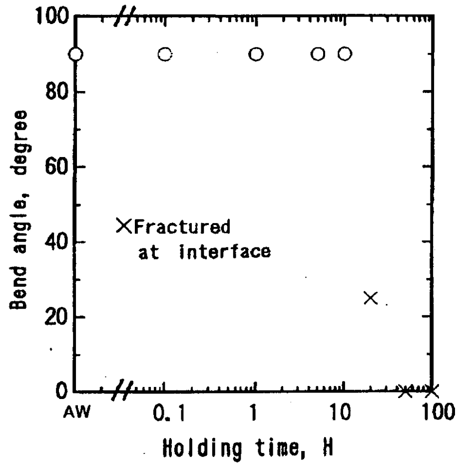
5. Dominant Factor of the Joint Characteristics

Dominant factors of the mechanical properties of the joints were variously investigated from the mechanical and metallurgical points of view. It was elucidated that the dominant factors of the joints were not residual stress and plastic strain but were the metallurgical. It was found that the main factor dominating the characteristics of the joints was the thickness of the intermetallic compound layer produced at the interface. According to the observation by light microscope, the intermetallic compound is mainly Al_3Ti. Al_3Ti is produced in the extremely narrow region adjacent to the interface of the Al substrate.

The mechanical properties of the joints were investigated by controlling the thickness of the intermetallic compound through heat treatment (Fig. 4, Fig. 6 and Fig. 7). According to the results, it was found that the critical thickness of the intermetallic compound which determines the tensile strength and the bending ductility was about 5μm. Moreover, as the thickness of the intermetallic compound layer became thicker as the holding time became longer (Fig.5), the working temperature and times should be sufficiently noted when this kind of the joint is employed for high temperature environments. If the working time becomes long, the mechanical properties of the joint are largely reduced as the thickness of the intermetallic compound layer increased.



(a) Joint tensile strength.



(b) Joint bend angle.

Fig.6 Effect of holding time at 600(°C) on tensile strength and bend angle.

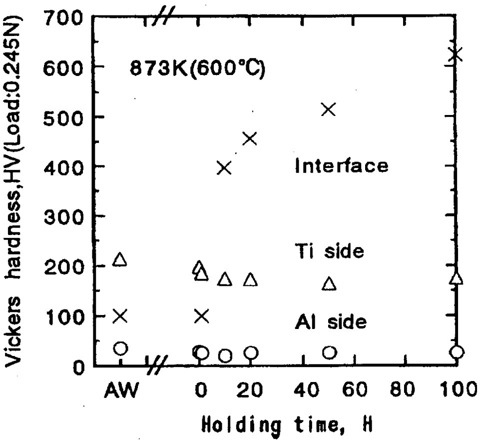


Fig.7 Relation between holding time at 600(°C) and Vickers hardness.

6. Conclusion

The dominant factors determining the joint characteristics (strength, ductility and so on) in titanium and aluminium friction welds were investigated variously from the mechanical and metallurgical points of view.

The obtained main results were as follows.

(1) The mechanical factors are not the main factors dominating the characteristics of the joint, as residual stress and plastic strain generated during the friction welding are not so large.

(2) It is found that the main factor, which determines the characteristics of the joint, is the thickness of the intermetallic compound layer produced at the interface.

(3) The critical thickness of the intermetallic compound layer was about 5 μm.

(4) When this kind of joint is used in high temperature environments, the working temperature and times should be sufficiently noted. If the working time becomes long, the characteristics of the joint are largely reduced as the thickness of the intermetallic compound layer increases.

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