Joints Characteristics of Dissimilar Materials Friction Welds (I)†

- Titanium/AISI 304L Stainless Steel -

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Abstract

The inadequate bend ductility of joints results from the combined effects of (FeNiCr)Ti intermetallic phase formation at the joint interface and the development of a locally-hardened region in titanium material immediately adjacent to the bondline. The poor bend testing properties of dissimilar joints are not associated with the residual stress generated during cooling. The plastic strain distribution in dissimilar joints corresponds well with the hardness distribution in as-welded joints.

Removal of the locally-hardened region in the titanium substrate via post-weld-heat-treatment markedly improves bend ductility and only marginally decreases tensile strength. The optimum mechanical properties are produced in joints post-weld-heat-treated at 500℃ for one hour. Longer holding times at 500℃ promote the formation of a thick intermetallic layer at the joint interface. When this occurs, fracture during tensile testing shifts from the titanium base material to the joint interface.

Provided that development of a locally-hardened region in the titanium substrate is counteracted without the formation of a thick intermetallic layer at the joint interface, friction joining can produce dissimilar titanium/AISI 304L stainless steel joints with satisfactory mechanical properties.

KEY WORDS: (Friction welding) (Joining of dissimilar materials) (Residual stress) (Plastic strain) (Hardness) (Intermetallic compound) (Post weld heat treatment)

1. Introduction

The tensile strength of dissimilar titanium/AISI 304L stainless steel joints was high and all test samples failed in titanium base material away from the joint interface[1]. However, during bend testing failed at the bondline region, at very low bend angle (≤ 10°).

In this paper, the cause of the poor bend ductility is elucidated and the bend ductility of the joints is improved while maintaining satisfactory tensile strength properties.

2. Modeling

2.1 Model

A flash is produced at the periphery of the completed joints when the friction welding is performed. It is considered that no flash influences on stress and strain generated in the completed joints. **Figure 1** shows the model, the coordinate system and the finite element grids. The thermal elastic-plastic analysis was carried out as the axisymmetric problem[2] (based on application of the Von Mises criterion).

2.2 Characteristics of residual stress and plastic strain

Based on the results of thermal elastic-plastic analisis, the characteristics of residual stress and plastic strain is shown.

2.2.1 Residual stress

Figure 2(a) shows the distributions of residual

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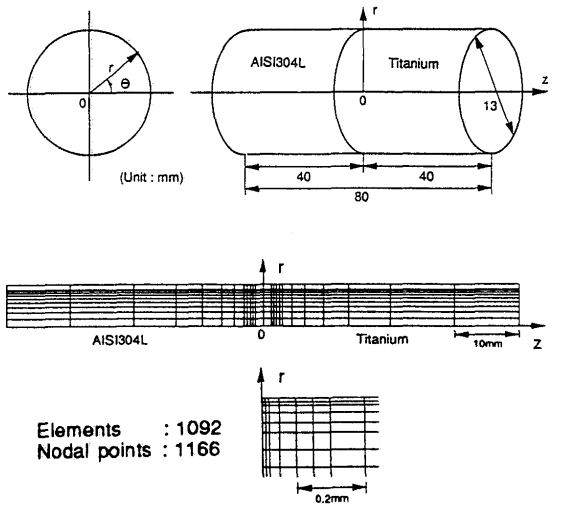


Fig.1 Component geometry and finite element grid.

stress components σ_r (radial direction), σ_θ (circumferential direction) and σ_z (perpendicular to the bondline), in the radial direction in titanium and stainless steel immediately adjacent to the bondline (the location z=±0.005mm).

σ_r and σ_θ are tensile along the bondline in stainless steel and are compressive in titanium substrate because the titanium substrate restricts shrinkage of the stainless steel whose linear expansion coefficient α is large[2]).

σ_z is tensile near the center of the component and becomes compressive near the component periphery. However, the absolute value is not so high (yield stress of titanium substrate is around 350(MPa)[2])).

The distribution of σ_z along the z-axis is shown.

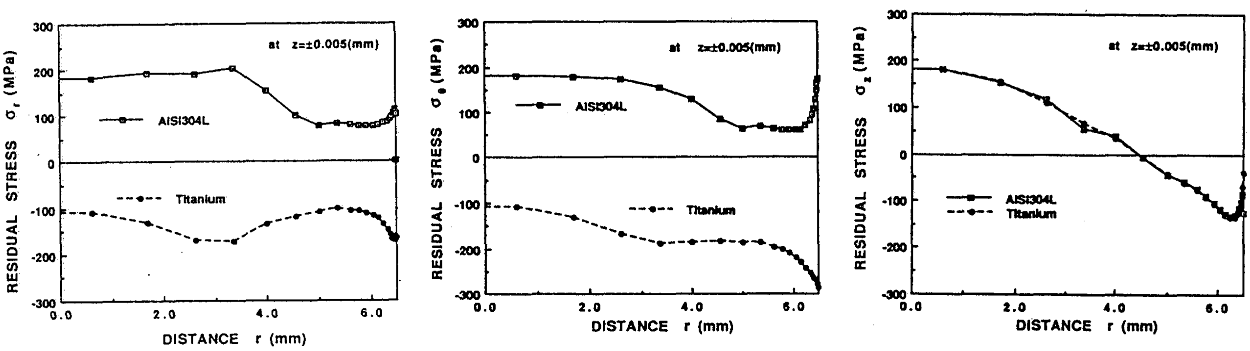
(a) The center of the component

Figure 3(a) shows the σ_z distribution in the axial direction at the center of the component (at r=0.6mm). σ_z is tensile in the titanium and stainless steel substrates immediately adjacent to the bondline and becomes compressive in regions far from the bondline.

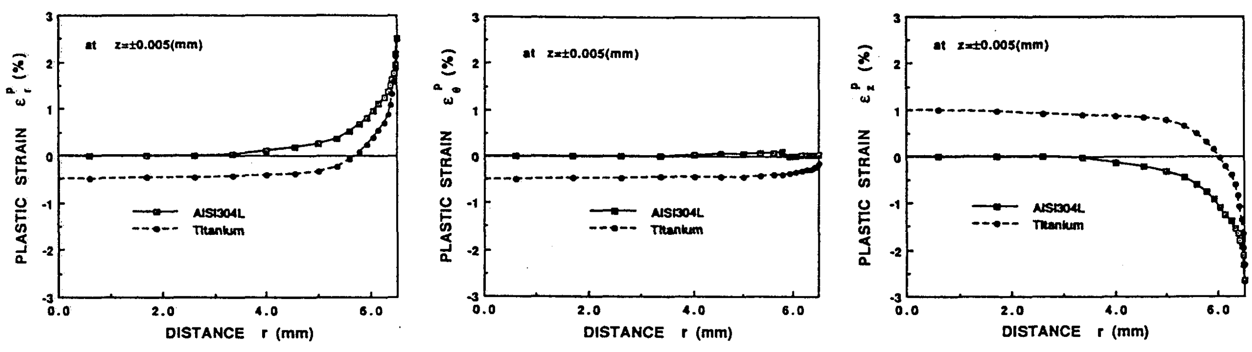
The maximum tensile stress $(\sigma_z)_{max}$ occurs in stainless steel close to the bondline region.

(b) The periphery of the component

Figure 3(a) shows the σ_z distribution in the axial direction at the component periphery (at r=6.495mm). σ_z is compressive in stainless steel close to the bondline and tensile in regions far from the bondline. In the titanium substrate, σ_z is tensile except in regions extremely close to the bondline.



(a) Residual stress



(b) Plastic strain

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

2.2.2 *Plastic strain*

Figure 2(b) shows the distributions of the plastic strain components $\varepsilon^p{}_r$ (radial direction), $\varepsilon^p{}_\theta$ (circumferential direction) and $\varepsilon^p{}_z$ (perpendicular to the bondline) in the radial direction, at the location z=±0.005mm. Considerable plastic strain, $\varepsilon^p{}_r$ and $\varepsilon^p{}_z$ are produced but $\varepsilon^p{}_z$ is produced to satisfy the condition of the volume constant. $\varepsilon^p{}_\theta$ is not so large.

Figure 3(b) shows the distribution of $\varepsilon^p{}_z$ in the axial direction at the center and the periphery of the component. $\varepsilon^p{}_z$ is only produced in titanium substrate at the center of the component (at r=0.6mm) and is concentrately produced in the narrower region at the periphery (at r=6.495mm) than that in stainless steel.

The mechanical condition is severer in titanium substrate than in stainless steel.

3. Consideration

3.1 Hardness

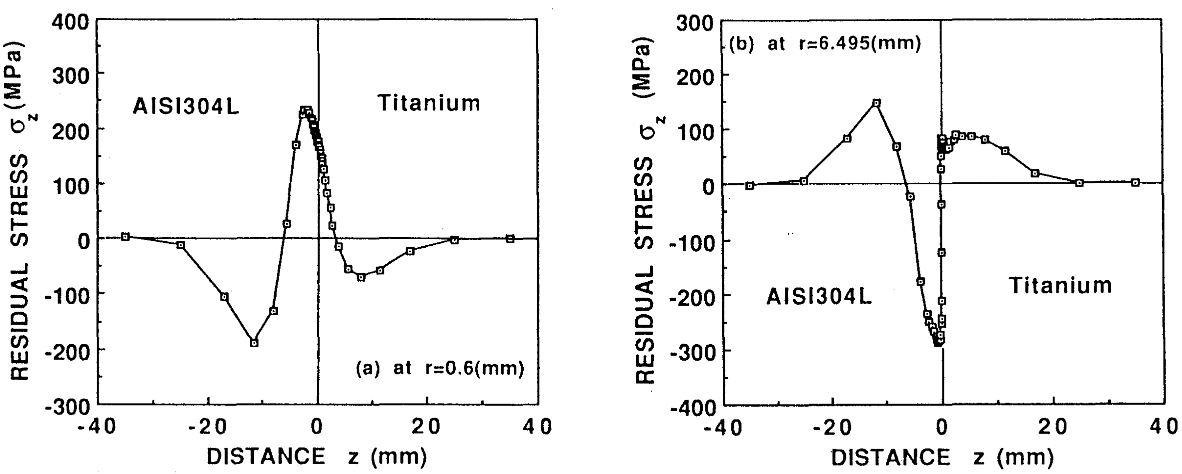
Figure 4 shows the hardness distribution measured at the 2(mm) inner part from the periphery of the completed component. Hardness of titanium substrate is 1.5 times harder than that of base material adjacent to the bondline.

On the other hand, it is apparent that $\varepsilon^p{}_z$ (see Fig.3(b)) is well corresponded to the distribution of hardness in as-welded joints.

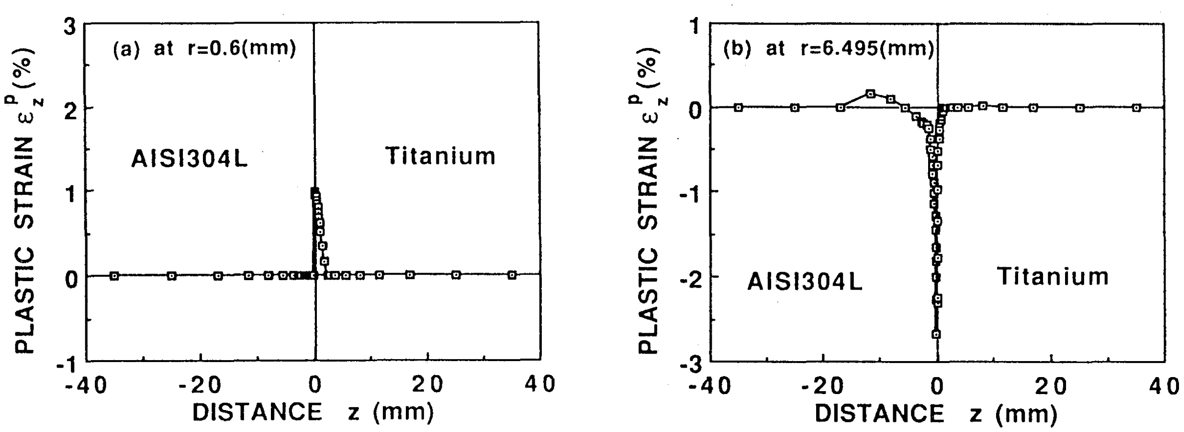
3.2 Joint strength and bend ductility

Considering the results of the tensile test, although tensile σ_z is generated in titanium material immediately adjacent to the bondline, the absolute value of σ_z is small (see Fig.2(a)).

Judging from hardness, it is considered that yield stress is higher by the strain hardening in the region adjacent to the bondline than in the base material. As a result, plasticity will initiate in the titanium base material during tensile testing and finally the whole cross-section will yield. This readily explains the location of test spcimen failure (in the titanium



(a) Residual stress



(b) Plastic strain

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

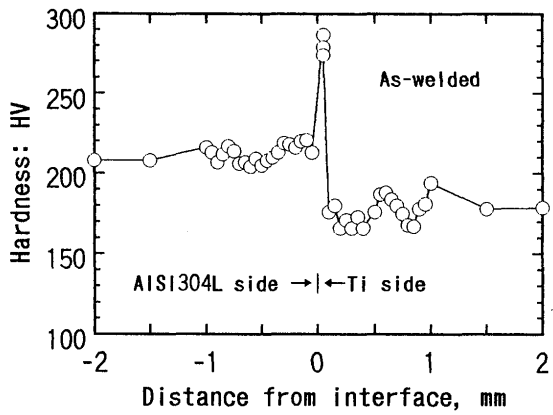


Fig.4 Hardness distribution across the dissimilar joint interface in an as-welded test specimen.

substrate), ductile failure in tensile test samples and the high tensile strength values found during mechanical testing.

Next, considering the result of the bend test, Fig.3(a) indicates that σ_Z is compressive or less tensile at the region adjacent to the bondline and that the influence of σ_Z on the bend strength and the poor ductility is small.

It is elucidated that the main cause of the high tensile strength and the poor bend property is the existence of the hardened region immediately adjacent to the bondline (the formation of the intermetallic compound layer and the development of a locally hardened region by strain hardening).

3.3 Improving the bend ductility

To remove the locally hardened region of the titanium material adjacent to the bondline, the post-weld-heat-treatment (PWHT) is carried out.

3.3.1 Hardness after the PWHT

Figure 5 shows the distribution of hardness after the PWHT according to the various conditions. After heating at 500°C and cooling down without holding, the hardened region adjacent to the bondline is reduced. However, as the temperature of the PWHT becomes high at 700-900°C, the titanium material adjacent to the bondline re-harden.

3.3.2 Tensile test after the PWHT

Figure 6 shows the tensile testing result after the PWHT. After heating at the temperature 500-600°C and cooling down without holding, the fracture occurs in the titanium base material (symbol O) keeping the same tensile strength as the as-welded joints. However, heating at the temperature higher than 700°C, the location of the fracture shifts from the titanium base material to the joint interface (symbol ●).

On the other hand, after heating at the temperature 500-600°C and cooling down after holding at the same temperature for 3.6ks, the fracture occurs in the titanium base material (symbol Δ). In this case, the tensile strength decreases by 10-20% compared with the tensile strength without holding. However, when the PWHT temperature is higher than 700°C, the location of the fracture shifts from the titanium base material to the joints interface (symbol ▲).

It is known that the tensile strength of the joint has a tendency to decrease because the intermetallic layer

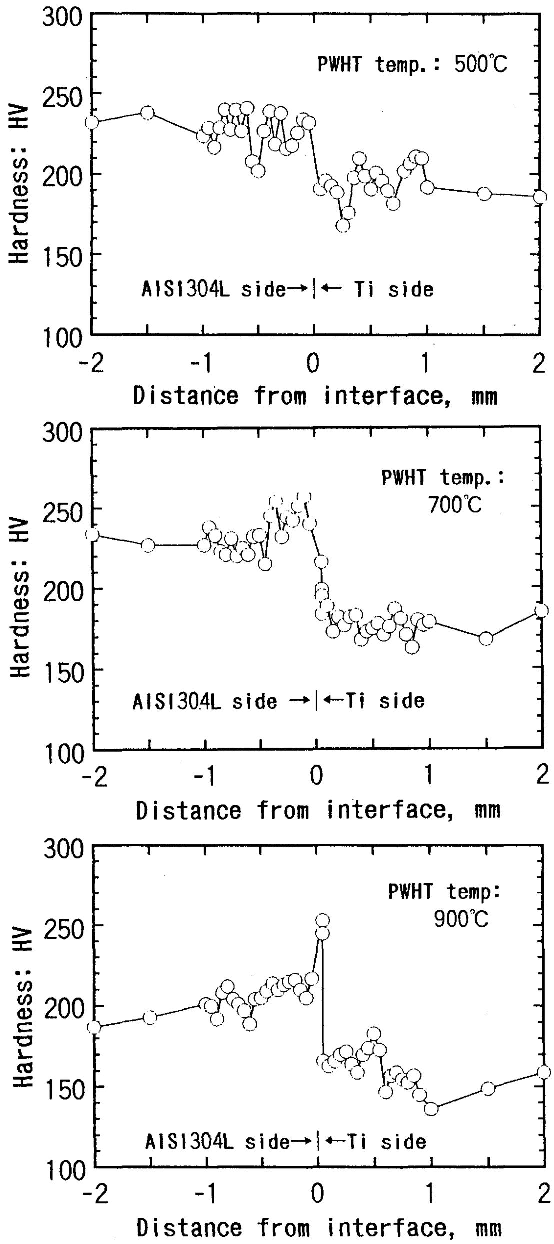


Fig.5 Hardness distribution across the dissimilar joint interface after the PWHT.

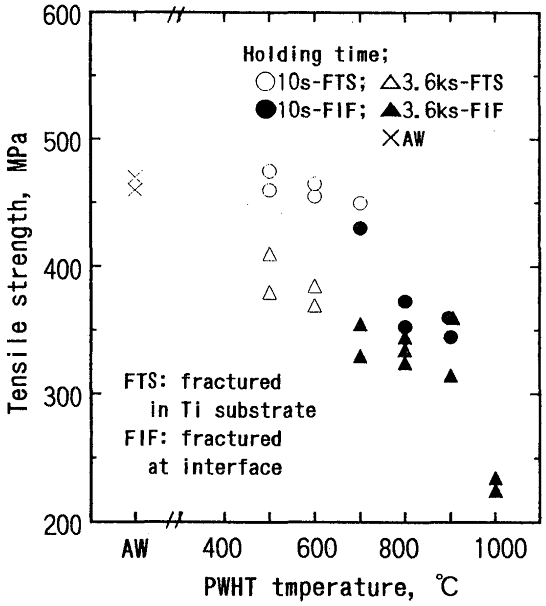


Fig.6 Effect of PWHT temperature on tensile strength.

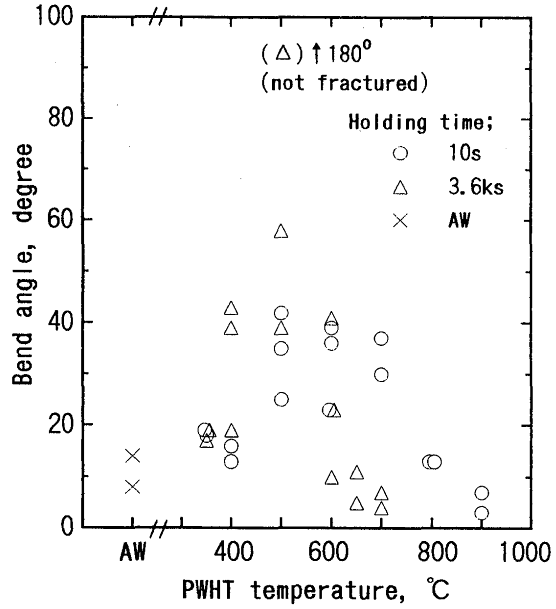


Fig.7 Effect of PWHT temperature on bend angle during three point bending.

largely grows as the holding time becomes longer. The fracture occurs in titanium base material below 600°C and at the joint interface higher than 600°C.

3.3.3 Bend test after the PWHT

Figure 7 shows the bend testing results after the PWHT. At the PWHT temperature 500°C without holding (symbol O), no fracture occurs at bend angle 20-40°. However, holding for 3.6ks at the same temperature (symbol Δ), no fracture occurs at the bend

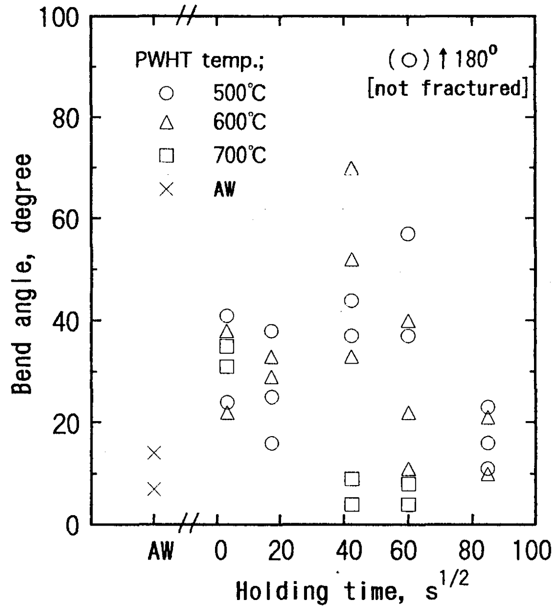


Fig.8 Effect of holding time in PWHT on bend angle during three point bending.

angle is over 40° even if in a certain case bent at 180° (symbol (Δ) in the figure).

Figure 8 shows the results of the holding time and the bend angle. The case of holding for 3.6ks at 500°C (symbol O) is the best, and the case of holding for 3.6ks and a half at 600°C (symbol Δ) can have a good result.

On the other hand, the effect of the relaxation of residual stress by the PWHT can not be expected. Because residual stress is newly generated during the cooling stage after the PWHT.

4. Conclusion

(1) The inadequate bend ductility of dissimilar titanium/AISI 304L stainless steel joints results from the combined effects of (FeNiCr)Ti intermetallic phase formation at the joint interface and the development of a locally-hardened region in titanium material immediately adjacent to the bondline. The poor bend testing properties of dissimilar joints are not associated with the residual stress generated during cooling following the friction welding operation.

(2) The plastic strain distribution in dissimilar joints corresponds well with the hardness distribution in as-welded joints.

(3) Removal of the locally-hardened region in the titanium substrate via PWHT markedly improves bend ductility and only marginally decreases tensile strength. The optimum mechanical properties are

produced in joints post-weld-heat-treated at 500 (°C) for 3.6 (ks). Longer holding times at 500 (°C) promote the formation of a thick intermetallic layer at the joint interface. When this occurs, fracture during tensile testing shifts from the titanium base material to the joint interface.

(4) Provided that development of a locally-hardened region in the titanium substrate is counteracted without the formation of a thick intermetallic layer at the joint interface, friction joining can produce dissimilar titanium/AISI 304L stainless steel joints with satisfactory mechanical properties.

Reference

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