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Characterisation of Residual Stress and Plastic Strain in AISI304L Stainless Steel/Titanium Friction Welds†

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Abstract

In order to elucidate the characteristics of residual stress and plastic strain produced by AISI304L stainless steel to titanium friction welding operation, detailed FEM modelling was carried out. Heat transfer into a narrow zone, $z = \pm 20$ mm on either side of the bondline promotes residual stress and plastic strain formation. The peak temperature occurs in the AISI304L substrate. Adjacent to the bondline, σ_r (radial component of residual stress) and σ_θ (circumferential component) are tensile in the higher thermal expansion substrate (AISI304L) and are compressive in the substrate with the lowest thermal expansion (titanium). The σ_z (axial component) which markedly affects joint strength properties is tensile near the center of the component (where the stiffness is large) and is compressive at the periphery of the component, in material far from the bondline, σ_z is compressive near the center of the component and is tensile at the joint periphery. In particular, σ_z is tensile in the titanium substrate, except in regions extremely close to the bondline at the periphery of the component. Plastic strain components, εp_r (radial component) and εp_z (axial component) are large. However, εp_z is not the result of the severity of mechanical deformation applied during friction welding, it exists to satisfy the constant volume requirement. εp_θ (circumferential component) is small. Mechanical deformation of the titanium substrate is more sever than in the AISI304L stainless steel. The plastic strain distribution in the axial direction corresponds well with hardness distribution in finished joints.

KEY WORDS: (Dissimilar materials joint) (Friction welding) (Residual stress) (Plastic strain) (FEM modelling) (Titanium) (Stainless steel)

1. Introduction

Although the residual stress and plastic strain produced as a result of dissimilar friction welding will have a large influence on final joint strength, no research has been published concerning residual stress and plastic strain formation in dissimilar friction welding operations. In the present study, friction welding of AISI304L stainless steel and titanium is numerically-modelled using a thermal elastic-plastic analysis via FEM. The distributions of residual stress and plastic strain produced by the dissimilar friction welding operation are characterised and their production mechanisms are described.

2. FEM Modelling

Figure 1 shows the temperature dependency of the thermophysical constants (density, thermal expansion coefficient, thermal conductivity, specific heat) and mechanical properties (Young's modulus, yield stress, ultimate strength) of titanium and AISI304L stainless steel. Although, axial shortening occurs at the joint interface during friction welding, this is not important with regard to residual stress generation since titanium has extremely low strength at temperatures above 800°C (see Fig.1). Also, only plastic deformation results from the forging stage during friction welding. Residual stress is only generated in the cooling cycle from 800°C to the room temperature.

Figure 2 shows the component geometry, the coordinate system and the grid employed in the present study. During FEM modelling, the dissimilar friction welding process was examined using an axisymmetric, thermal elastic-plastic analysis (it was analysed by applying the Von Mises' criterion). During FEM analysis isoparametric four-node finite element were

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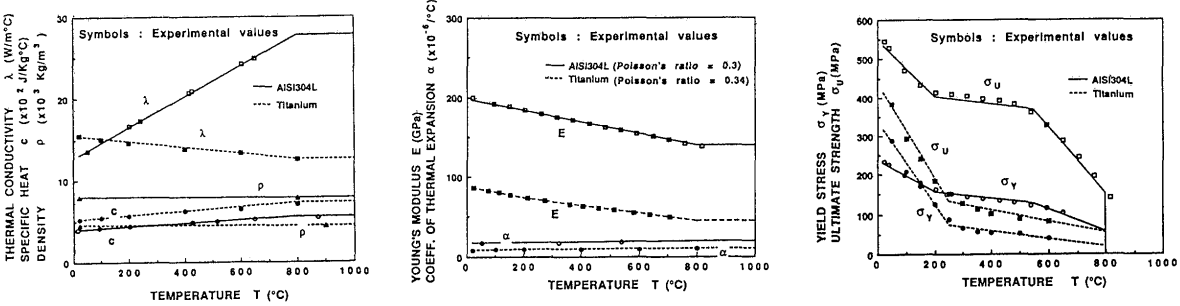


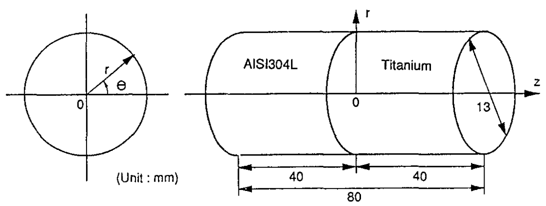
Fig.1 Thermophysical constants and mechanical properties.

examined, the total number of elements was 1092 and the total number of nodal points was 1166.

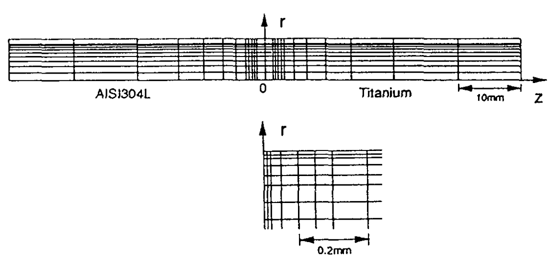
3. Results of FEM modelling

3.1 Temperature Distribution

The thermal cycle produced by the friction welding operation was estimated using a unsteady-state, axisymmetric, thermal conduction FEM analysis. The heat generated[1], q, during friction welding was 1.364 kJ/s. This energy was generated in a three second friction welding period and the temperature distribution produced in the z-direction, at the component centerline is shown in **Fig.3**. Heat diffuses into the AISI304L and titanium substrates to a distance of z = ±20 mm on either side of the bondline. **Figure 4** shows the temperature distribution at the location z = ±3 mm. Because the thermal conductivity of titanium is less than that of AISI304L, the temperature profiles produced in both substrates are different. The peak temperature attained in the AISI304L substrate is about 100°C higher than in the titanium substrate.



(a) Component geometry and coordinate system



(b) Grid

Fig.2 Component geometry and finite element grid.

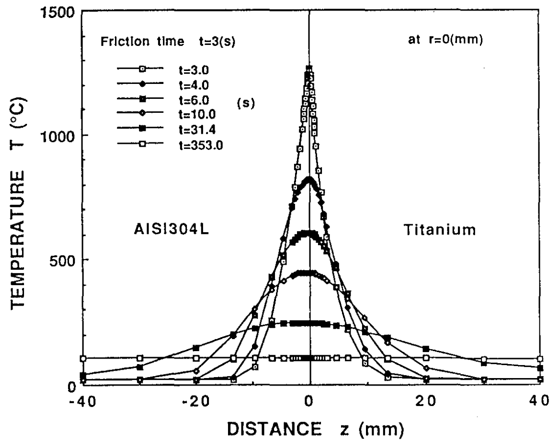


Fig.3 Temperature distribution during cooling following friction welding.

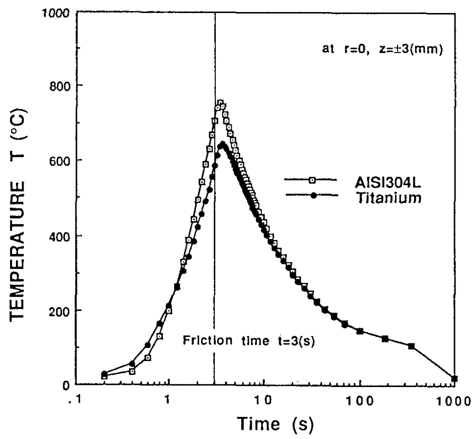
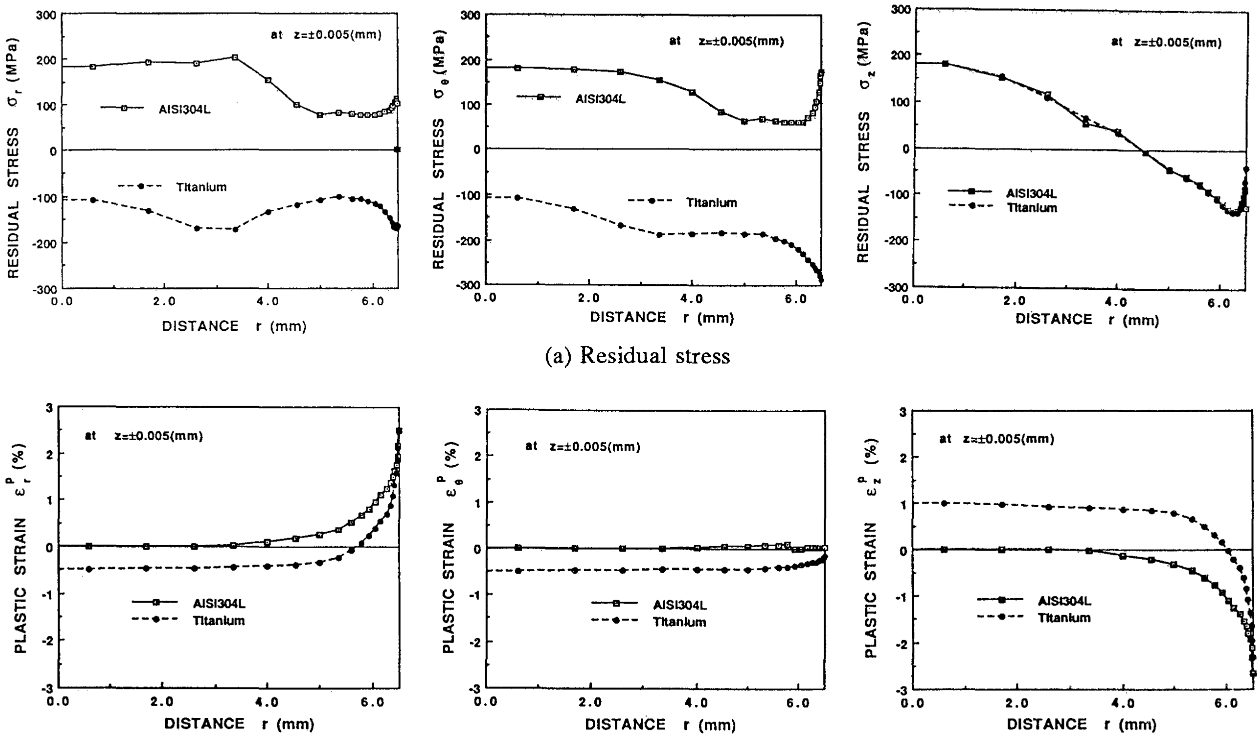


Fig.4 Heating and cooling cycles during dissimilar friction welding.



(a) Residual stress

(b) Plastic strain

Fig.5 Residual stress and plastic strain distribution in the radial direction at the immediately adjacent to the bondline.

3.2 Residual Stress

Figure 5(a) shows the radial distribution of the residual stress components: σ_r (radial direction), σ_θ (circumferential direction) and σ_z (perpendicular to the bondline) in material immediately adjacent to the bondline (at the location z = ±0.005 mm).

σ_r and σ_θ are both tensile in the AISI304L substrate and are both compressive in the titanium substrate. σ_r and σ_θ are tensile in the highest thermal expansion base material (AISI304L) since the titanium substrate restricts shrinkage of AISI304L during the cooling cycle following the friction welding operation. σ_z is tensile in the central region of the component, where the stiffness is large, and is compressive at the component periphery.

Since σ_z largely determines the dissimilar joint strength, the σ_z distribution in the z-direction is examined in detail in the present paper.

(a) Feature of σ_z at the center of the component

Figure 6(a) shows the σ_z distribution in the axial direction at the center of component (r = 0.6 mm). σ_z is tensile in the titanium and AISI304L substrates, (in material immediately adjacent to the bondline) and is compressive in regions far from the bondline. This occurs because of the increased stiffness and since shrinkage is restricted by lower temperature titanium and AISI304L base materials. In this connection, the formation of compressive stress in regions far from the bondline is a characteristic feature of dissimilar friction welded joints; this occurs as a direct result of the temperature gradient in the z-direction.

The maximum tensile stress $(\sigma_z)_{max}$ occurs in AISI304L material close to the bondline region (see Fig.4). This result can be explained as follows. It is apparent from the temperature distribution in Fig. 3, that the $(\sigma_z)_{max}$ value will be produced in the material that has the highest temperature. However, in dissimilar joining, the stiffness of titanium immediately adjacent to the bondline is less than that of AISI304L, since the Young's modulus of titanium is less than that of AISI304L. Also, the temperature in AISI304L material close to the bondline is about 100 °C higher than in the titanium substrate (see Fig.4). Because of this, shrinkage is delayed and $(\sigma_z)_{max}$ occurs in AISI304L material adjacent to the bondline. The location of $(\sigma_z)_{max}$ is consequently in the higher temperature substrate and this is a characteristic feature of dissimilar friction welding operations.

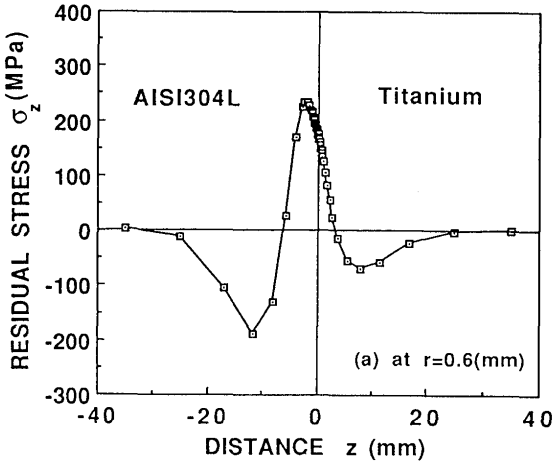
(b) Feature of σ_z at the periphery of the component

Figure 6(b) shows the σ_z distribution in the axial direction at the component periphery (r = 6.495 mm).

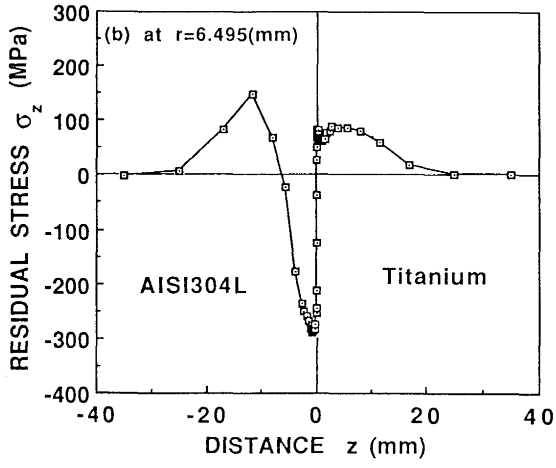
σ_z is compressive in AISI304L material adjacent to the bondline and is tensile in regions far from the bondline. σ_z is compressive in AISI304L base material because titanium at the periphery of the component has limited stiffness and cannot restrict shrinkage of the AISI304L substrate. In the titanium substrate, σ_z is tensile, except in regions extremely close to the bondline.

3.3 Plastic strain

Figure 5(b) shows the distribution of plastic strain components, $\varepsilon^p{}_r$ (radial direction), $\varepsilon^p{}_\theta$ (circumferential direction) and $\varepsilon^p{}_z$ (perpendicular to the bondline) at the location, z = ± 0.005 mm.



(a) at the center



(b) at the periphery

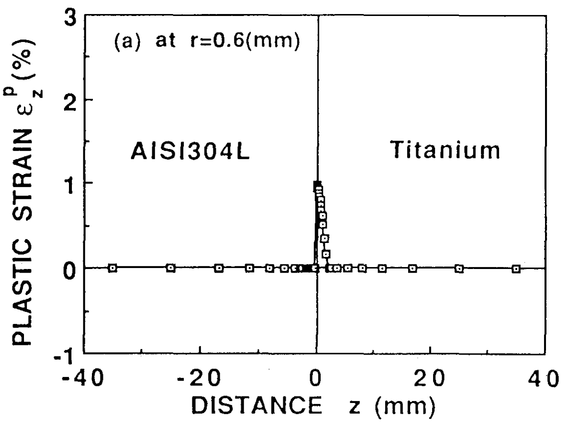
Fig.6 Residual stress distribution in the axial direction at the center and periphery of the component.

Based on these results, considerable plastic strain is produced in the radial direction and perpendicular to the bondline. However, plastic strain component of perpendicular to the bondline, $\varepsilon^p{}_z$, is not the result of the severity of the mechanical deformation. It is produced to satisfy the condition for constant volume in the system. The amount of plastic strain is much less in the circumferential direction. Severe plastic strain is produced in the titanium substrate close to the bondline. It is well-understood that mechanical deformation of the titanium substrate is much more sever than that in the AISI304L substrate.

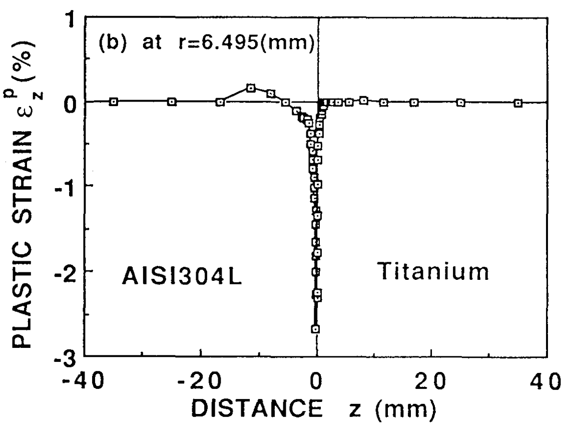
Figure 7 shows the distribution of $\varepsilon^p{}_z$ in the z-direction. Much of the plastic strain resulting from the dissimilar friction welding operation is concentrated in titanium material immediately adjacent to the bondline.

3.4 Hardness and Plastic Strain

A detailed metallurgical investigation confirmed[2] that (FeNiCr)Ti intermetallics were formed at the



(a) at the center



(b) at the periphery

Fig.7 Plastic strain distribution in the axial direction at the center and periphery of the component.

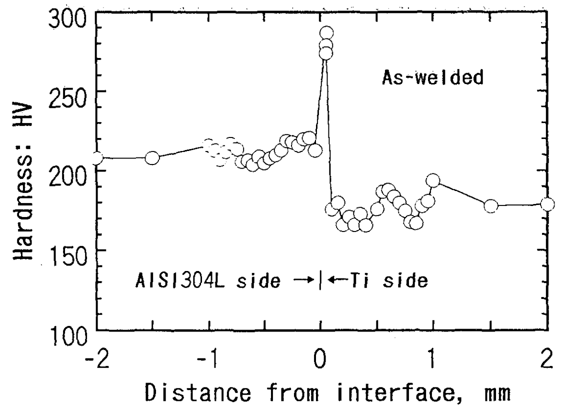


Fig.8 Hardness distribution across the dissimilar joint interface in an as-welded test specimen.

bondline region of AISI304L stainless steel/titanium friction welds and that a 125μm wide hardened layer formed in titanium material immediately adjacent to the bondline. **Figure 8** shows the hardness distribution across dissimilar joint interface. The narrow region immediately adjacent to the bondline (in the titanium substrate) had a hardness which was 1.5 times higher than in the bulk titanium base material.

This hardening effect in the titanium substrate corresponds well the plastic strain distribution in the axial direction (see Fig.7).

4. Conclusion

Detailed FEM modelling of residual stress and plastic strain generation during dissimilar friction welds between AISI304L stainless steel and titanium substrates was carried out. The principal conclusions of this study comprise:

(1) Heat transfer into a narrow zone, z = ±20 mm on either side of the bondline and promotes residual stress and plastic strain formation. The peak temperature occurs in the AISI304L substrate.

(2) Adjacent to the bondline, σ_r (radial component) and σ_θ (circumferential component) are tensile in the higher thermal expansion substrate (AISI304L), and are compressive in the substrate which has the lowest thermal expansion coefficient (titanium). σ_z is tensile near the central region of the component (where the stiffness is large) and is compressive at the periphery of the component.

(3) The σ_z distribution in the axial direction, in material far from the bondline, indicates that σ_z is compressive close to the center of the component and is tensile at the component periphery. In particular, σ_z is tensile in the titanium substrate, except in regions extremely close to the bondline at the periphery of the component.

(4) The plastic strain is the largest perpendicular to the bondline and in the radial direction. However, the plastic strain component perpendicular to the bondline is not produced by severity of mechanical deformation applied during friction welding, it occurs to satisfy the constant volume condition. The circumferential plastic strain component is small.

(5) Severe plastic strain is produced in titanium material close to the bondline. This particular region in the titanium substrate has a hardness 1.5 times higher than in the bulk base material. The present study confirmed that the mechanical deformation of the titanium base material is much more severe than in the AISI304L stainless steel substrate.

(6) The plastic strain distribution in the axial corresponds well with the hardness distribution across the dissimilar weld.

Reference

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2) A. Fuji, T.H. North, K. Ameyama and M. Futamata: Material science and technology, 3(1992), 219.