In situ neutron diffraction measurements of temperature and stresses during friction stir welding of 6061-T6 aluminium alloy

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The evolution of temperature and thermal stresses during friction stir welding of Al6061-T6 was investigated by means of *in situ*, time resolved neutron diffraction technique. A method was developed to deconvolute the temperature and stress from the lattice spacing changes measured by neutron diffraction. The deep penetration capability of neutrons made it possible for the first time to obtain the temperature and thermal stresses inside a friction stir weld.

Keywords: Friction stir welding, Aluminum alloy, Thermal stress, Neutron diffraction

Introduction

Friction stir welding (FSW) is an innovative material joining process that enables the advantages of solid state joining for fabrication of continuous linear welds without bulk melting.[1] The process utilises a specially shaped tool that rotates and traverses along the joint line, creating heat that softens a column of material underneath the shoulder and around the pin. The softened material flows around the tool through extensive plastic deformation and is consolidated behind the tool to form a solid state continuous joint. The economical and technological benefits of FSW have been well established for Al alloys and other low melting temperature materials. There have been extensive efforts to apply FSW to high temperature materials and to extend the process as a material processing technology (friction stir processing) for property improvement.[2,3]

Fundamentally, FSW is a severe thermomechanical deformation process; it relies on extensive thermomechanical deformation to develop the metallurgical bonding. The key factors contributing to a successful friction stir welding operation are the temperature and stress distributions during the process, particularly the temperature and stresses near the rotating tool where the material is stirred and metallurgical bond is formed. There have been many studies on this important subject, both experimental and analytical based.[4–9] However, direct experimental measurement of the temperature and stress inside the stir zone has been extremely challenging, as the severe thermomechanical deformation associated with the process makes many measurement techniques impossible to apply.

The deep penetration capability of neutrons into most metallic materials makes neutron diffraction a unique and powerful tool for the investigation of their structures and properties.[10] Recently, a methodology has been developed that enables simultaneous measurements of the temperature and stress field using *in situ* time resolved neutron diffraction.[11]

This paper presents a direct *in situ* neutron diffraction experiment of the FSW process which reveals, for the first time, the temperature and thermal stresses in the stir zone of Al6061-T6 aluminium alloy weld.

Experimental

The *in situ* neutron diffraction measurements were performed at the Spectrometer for MAterials Research at Temperature and Stress (SMARTS)[12] of the Los Alamos Neutron Science Center (a pulsed neutron source). Due to the space confinement and other restrictions of the neutron source, a remotely operated portable FSW machine was built and used in this work. The FSW machine was mounted on the X-Y translation stage of SMARTS, as shown in Fig. 1. The neutron measurement was performed *in situ* – it was performed as the weld was being made.

Commercial 6061-T6 Al alloy plates (965 mm long, 178 mm wide, and 6·35 mm thick) were used in the experiment. An ~760 mm long bead on plate weld was made along the centreline of the plate. All welds were made with position control, at a constant welding speed of 0·42 mm s^{-1} and tool rotation speed of 156 rev min^{-1}. The diameter of the threaded pin and the tool shoulder was 6·35 and 25·4 mm respectively. The relatively slow welding speed enabled a neutron measurement time of over 30 min, which was sufficient

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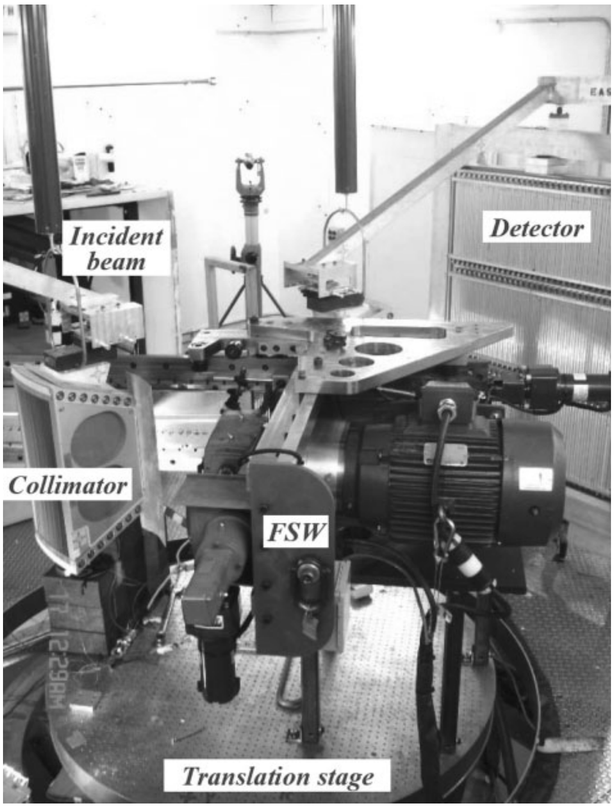
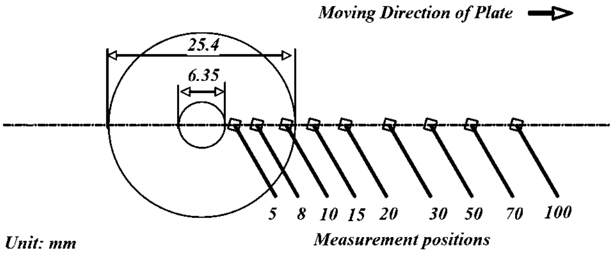


1 Experimental setup for *in situ* neutron diffraction measurement of FSW

to accurately determine the neutron diffraction peak position for stress and temperature measurements.

The *in situ* neutron diffraction study in this work required a completely different experimental approach from the conventional study of static problems such as weld residual stress measurements in the past. To overcome the neutron flux limitation of neutron source for *in situ* measurement of the temperature and thermal stresses during FSW, the neutron measurement was made in a specially arranged experimental setup, the so called Eulerian measurement reference frame. For a Eulerian measurement, the neutron scattering volume is fixed relative to the friction stir tool head; the Al plate traverses across the neutron scattering volume at a constant speed (the welding speed) as the Al plate moves relative to the tool head. The Eulerian measurement utilises the quasi-steady state phenomenon of the FSW process that extends the neutron collection time.

It is well established that the quasi-steady state condition in a FSW process is related to the motion of the welding tool relative to the material being welded.[13] The temperature change in the material in vicinity of the rotating tool is governed by the net energy between the heat generated by the welding heat source and the heat diffused away from the region. When the heat generated in FSW is balanced by the heat carried away by the cold material that continuously enters the weld region (no net energy gain/loss), the temperature field in the weld region reaches the quasi-steady state: to an Eulerian observer (the neutron scattering volume) that is fixed related to the welding tool, the temperature field is stationary, independent of time.[14] The stationary temperature and stress fields under the Eulerian measurement frame allows sufficient time to collect the diffracted neutrons under the same temperature and stress condition for the intended measurement.



2 Measurement positions: tool shoulder diameter is 25·4 mm; pin diameter is 6·35 mm

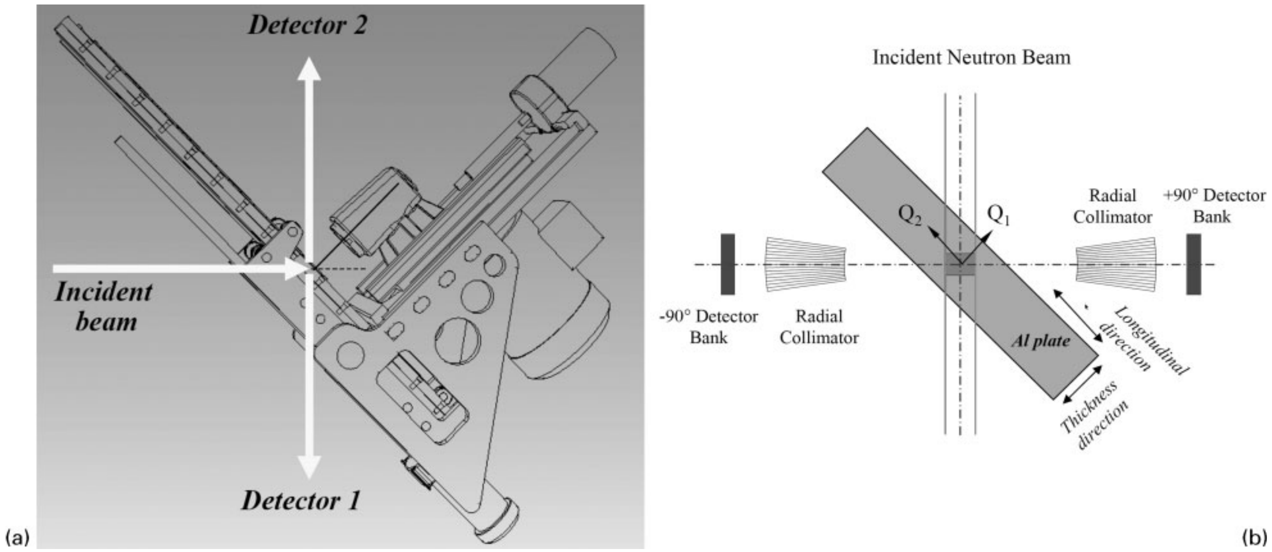
For each neutron experiment, a new Al plate was used to make full length weld, and the measurement position was predetermined and fixed relative to the welding tool head. In order to study the evolution of the temperature and stress as the material exits the friction stir processing region, all measurements were made along the weld centreline and behind the rotating tool. The measurements were made at 5, 8, 10, 15, 20, 30, 50, 70 and 100 mm from the rotating tool, as illustrated in Fig. 2. Three locations (5, 8, and 10 mm) were underneath the rotating shoulder. Repeated measurements were made at the 8 and 30 mm positions, which confirmed that the neutron measurement and the welding process were highly repeatable.

Neutron diffraction is a volume averaged measurement of interplanar spacing (d spacing) in a crystalline material based on the Bragg's law, from which the apparent lattice strains can be determined

$$\varepsilon = \frac{d}{d_{\rm o}} - 1 \tag{1}$$

where d is the d spacing under stress and temperature, and $d_{\rm o}$ is the stress free d spacing at a reference temperature. A unique advantage of the pulsed neutron source such as SMARTS is its ability to utilise diffraction patterns from multiple crystallographic lattice planes to define the lattice strain in a particular material direction.[10] The full pattern Rietveld refinement method[15] was employed to determine the d spacings. The Rietveld analysis makes use of the entire diffraction pattern by fitting all the diffraction peaks to a structural model of the material. Hence, the Rietveld approach allows accurate lattice spacing data with much shorter count times than is required to make individual peak refinements. The general structure analysis system (GSAS) computer code,[16] which was based on the Rietveld method, was used to determine the d spacings from the measured diffraction data.

To determine the temperature and thermal stress in the friction stir weld, it was necessary to measure the d spacings with their scattering vectors along the three orthogonal directions – longitudinal direction (LD), transverse direction (TD) and normal direction (ND) – of the plate. Figure 3 schematically depicts the horizontal arrangement of the FSW machine for simultaneous measurement of two lattice strain components (longitudinal and normal) by means of two opposing detectors at SMARTS. To measure the third (transverse) strain component, it was necessary to rotate the friction stir welding machine and the Al plate 90 degrees relative to the neutron detectors to the vertical



3 Schematic drawings showing orientation relationship for simultaneous longitudinal and normal lattice strain measurement: (a) – overview of FSW machine and its orientation to neutron instrument; (b) – beam arrangement and position of scattering volume in Al plate

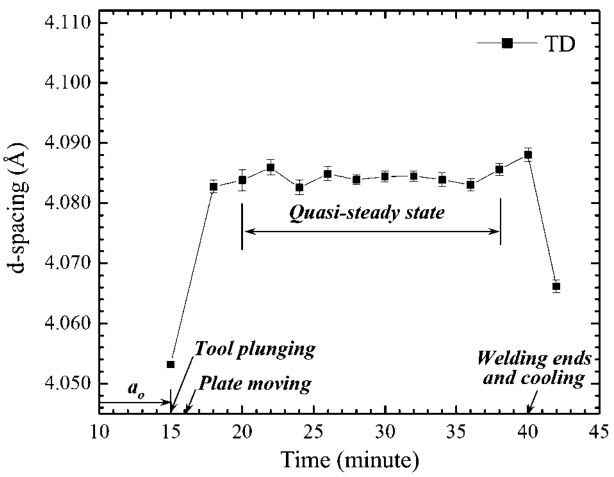
measurement position. The neutron scattering volume was $3\times2\times2$ mm, defined by the 3 mm wide radial collimator in front of the detector with a focal length of 3 mm along the beam direction and the 2×2 mm incident beam square slit. The neutron scattering volume was centred on the mid plane of the Al plate as shown in Fig. 3.

During the *in situ* measurement, the neutrons were continuously collected at a 2 min interval for a total of 30 min neutron collection time for each measurement position. The diffraction patterns obtained from the entire quasi-steady state period for a given measurement position were combined and used to determine the *d* spacing parameter at the specified measurement position.

Results and discussion

Quasi-steady state and changes of *d* spacing during friction stir welding

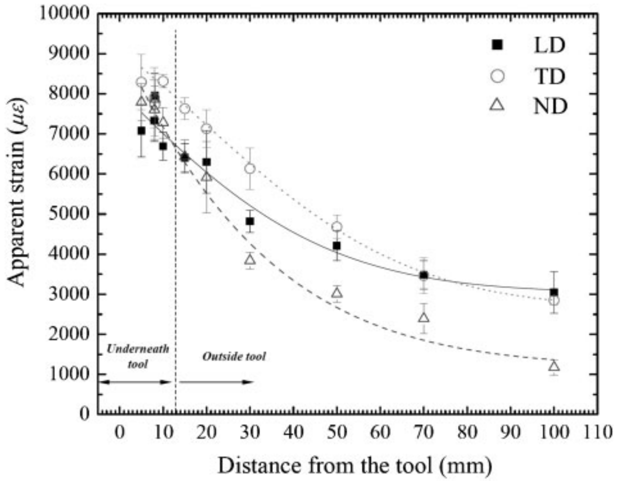
Figure 4 shows representative *d* spacing changes measured in a Eulerian experiment. The measurement position in this experiment was at 15 mm from the tool centre. As shown in Fig. 4, there was a drastic increase in *d* spacing for the first 3 min at the beginning of the experiment. This was associated with the initial transient stage of a FSW cycle in which the temperature begins to build up and the stress field to develop. After this initial transient, the *d* spacing remained relatively consistent for ~18 min, as labelled in the figure. This confirmed that the quasi-steady state condition was indeed achieved in the experiment. Thereafter, the *d* spacing increased further as the rotating tool approached to the end of the plate. Finally, the *d* spacing decreased after the welding was completed and the plate began to cool down.



4 Evolution of *d* spacing in transverse direction during neutron experiment at 15 mm position

The experimental confirmation of the existence of the quasi-steady state condition in our neutron experiment conducted is important. Neutron scattering studies have always been flux limited. Currently, no neutron source in the world is powerful enough to perform direct *in situ* measurement of the rapid temperature and stress transients during FSW and many other welding processes. In this regard, the quasi-steady state condition circumvented the limitation of the neutron flux for the intended *in situ* temperature and stress measurements.

Figure 5 shows the apparent lattice strain changes as a function of the distance from the tool centre. The three different *d* spacing curves correspond to the three orthogonal measurement directions (longitudinal, transverse and normal directions of the plate). In general, the *d* spacing values in all three directions are the highest at the 5 mm position (the position closest to the tool centre in this study), and they monotonically decrease from their respective highest values as the distance between the measurement position and the tool centre increases. This trend correlates to the expected temperature variation along the welding centreline – the highest thermal expansion caused by the highest temperature underneath the friction stir tool shoulder results in the largest increase in *d* spacing. Since the thermal expansion of the face centred cubic Al is isotropic (i.e. the same in all directions), the differences in *d* spacings



5 Variation of *d* spacings as function of distance from welding tool centre: LD – longitudinal direction; TD – transverse direction; ND – normal direction

along different directions are the result of thermal stresses, which can be used to determine the thermal stresses during welding, as further discussed in the next section.

Determination of stress and temperature from *d* spacing measurement

Unlike the case of residual stress measurement in a weld,[17–20] the lattice spacing changes in an *in situ* welding measurement includes both the elastic strain due to stress and the thermal strain due to temperature change. Therefore, it is necessary to separate the thermal strain from the elastic strain in the measured apparent lattice strain, in order to determine the temperature and the thermal stress during the welding process.

The apparent lattice strain measures the expansion or contraction of the lattice plane of a material. In a thermomechanical problem, the lattice strain includes the elastic strain ε^e due to stress and the thermal strain due to temperature change. The lattice strain also includes the contributions from the phase transformation, when a solid state phase transformation is accompanied by changes in the lattice plane spacing (such as the lattice strain caused by the precipitation process in Al6061). It is noted that, the coefficient of thermal expansion (CTE) often includes the phase transformation part. Following the approach in Ref. 11, the following equations are used to determine the temperature and the thermal stress from neutron diffraction measurement data

$$T = T_0 + \frac{1}{\alpha}\left[\frac{v}{1+v}(\varepsilon_x + \varepsilon_y) + \frac{1-v}{1+v}\varepsilon_z\right] - \frac{1-2v}{\alpha E}\sigma_z \qquad (2)$$

and

$$\sigma_i = \frac{E}{1+v}(\varepsilon_i - \varepsilon_z) + \sigma_z = \frac{E}{1+v}\frac{d_i - d_z}{d_0} + \sigma_z \quad i = x,y \qquad (3)$$

where T, σ and ε are the temperature, thermal stress and apparent lattice strains respectively. The subscripts x, y, z denote the longitudinal, transverse and normal direction of the Al weld plate. E, v and α are the elastic modulus, Poisson's ratio and thermal expansion coefficient.

It is noted that d_o in the equation (3) can be substituted by d_z for the determination of stress

$$\sigma_i = \frac{E}{1+v}\frac{d_i - d_z}{d_z} + \sigma_z \quad i = x,y \qquad (4)$$

Such substitution is reasonable, as the *d* spacing changes are very small in neutron diffraction measurement. By differentiating the equation (4), the uncertainty in stress calculation induced by using d_z instead of d_o can be estimated as

$$\frac{\Delta\sigma}{\sigma} = -\frac{\Delta d}{d} \qquad (5)$$

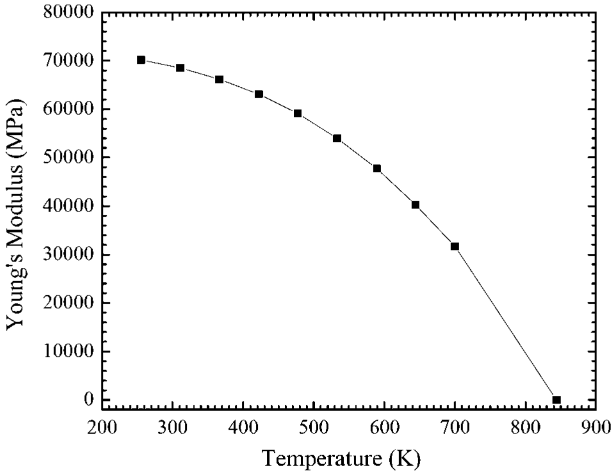
In this study, the measured *d* spacing of the stress free sample (d_o) was ~4·050 Å and the maximum *d* spacing during the welding was ~4·085 Å. The maximum error in stress calculation induced by the substitution of d_z for d_o is less than 0·9%.

It is important to recognise the advantages of using the equation (4) for stress calculation. Equation (3) requires the use of the stress free reference *d* spacing (d_0). However, the microstructure inhomogeneity and/or internal built-in stresses in many engineering materials generally preclude the determination of d_0 for neutron diffraction in many situations. By eliminating the need to know d_o *a priori*, equation (4) provides a realistic approach for *in situ* neutron diffraction measurement of the time dependent stress changes in a thermo–elasto–plastic deformation process.

For the thin Al plate used in this study, the thermal stresses in the plate are essentially two-dimensional.[21,22] Outside the rotating tool, the stress state is essentially plane stress (i.e. σ_z=0). Underneath the tool shoulder, the plane stress condition is no longer valid and the distribution of the normal stress (σ_z) is expected to be complicated. As first approximation, this study assumed that the normal stress was uniform and can be calculated from the forging force of the process and tool diameter. With an estimated forging force of 8500 N, and tool shoulder diameter of 25·4 mm, the nominal normal stress due to the forging force was −17 MPa. The temperature and the other two thermal stress components (longitudinal and transverse) can then be determined by the equations (2) and (4), using the *d* spacing data measured by neutron diffraction. The calculation of temperature and stresses requires the use of temperature dependent elastic modulus of Al6061, which are given in Fig. 6. Since both the Poisson's ratio and the thermal expansion coefficient are weak function of the temperature, constant values (α=2·45×10^{-5} 1/°C, v=0·345) from Refs. 23 and 24, were used in this study.

The temperature and thermal stress distribution along the weld centreline are shown in Figs. 7 and 8 respectively. The temperature monotonically decreases as the distance from the tool centre increases. The maximum temperature was underneath the tool shoulder and reached 635 K (362°C). Because of the relatively low rotational speed (156 rev $\min^{-1}$) in this study, the maximum temperature attained was at the low end of the temperature range reported in the literature.[3,25–27]

In calculating the temperature underneath the tool shoulder, assumption was made about the normal stress (σ_z). The contribution of the normal stress term in neutron temperature measurement can be estimated as

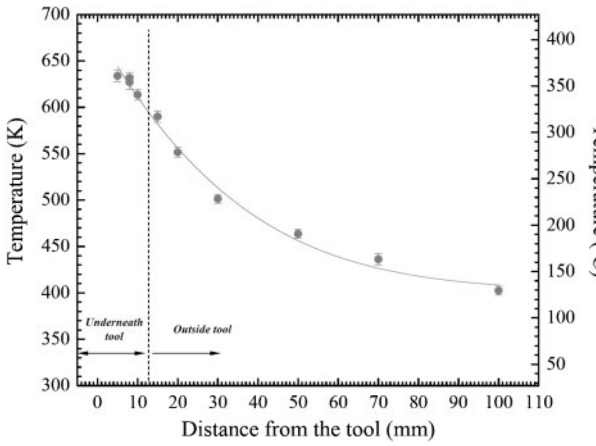


6 Elastic modulus of Al 6061 as function of temperature[13]

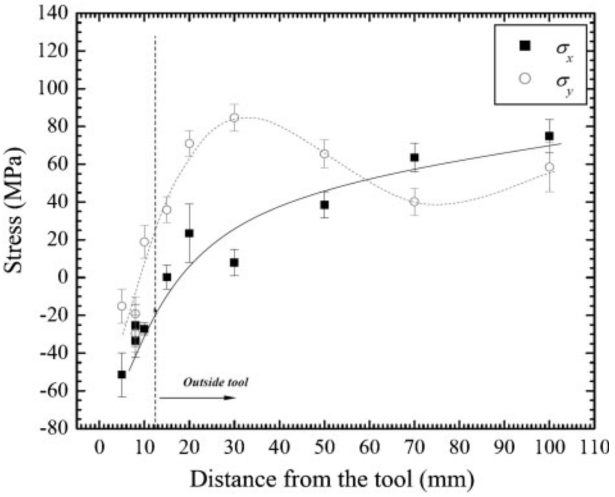
follows. According to the equation (2), a stress level of −17 MPa would cause a temperature change of about 5 K. At elevated temperatures, the material softens and its yield strength and the plastic flow stress decrease. The flow stress of Al6061 at 600 K is ~50 MPa.[13] As the stresses in the stir zone are bounded by its flow stress, the uncertainties in temperature measurement due to the lack of accurate normal stress information should be relatively small – they should be less than 15 K with 50 MPa flow stress.

As shown in Fig. 8, both the longitudinal and transverse stresses were largely in compression under the tool shoulder, due to the thermal expansion and the forging pressure from the tool shoulder. The longitudinal stress was more compressive than the transverse stress, which can be attributed to the elongated temperature field caused by the friction stir tool moving along the longitudinal direction of the plate. It is worth noting that the compressive longitudinal stress is in the range of the reported yield strength of Al6061 at 600 K.[13]

Outside the tool, the thermal stresses become tensile to balance the thermal contraction of the weld region as it cools down. In addition, the longitudinal stress becomes higher than the transverse stress when the distance from the tool centre is greater than 60 mm. At 100 mm from the tool centre, the tensile stresses reach 75 MPa in the longitudinal direction, and 60 MPa in the transverse direction. As the distance from the tool centre further increases, the temperature will further decrease and the stresses will eventually reach the residual stress levels reported in other studies.[28,29]



7 Temperature distribution along weld centreline behind tool as function of distance from tool centre



8 Thermal stress distribution along weld centreline behind tool as function of distance from tool centre: σ_x – longitudinal (LD) stress; σ_y – transverse (TD)

Conclusions

The temperature and thermal stresses during FSW of Al6061-T6 were investigated by the *in situ* neutron diffraction experiment. The deep penetration capability of neutrons made it possible for the first time to obtain the temperature and thermal stresses inside the friction stir weld. A method to deconvolute the temperature and stress from the measured neutron diffraction data was presented. The following conclusions can be drawn by the *in situ* neutron diffraction measurement for the FSW conditions used in this study.

1. The maximum temperature is underneath the tool shoulder, reaching 635 K.
2. Compressive thermal stresses develop in the vicinity of the rotating tool. The compressive stresses are not the same in different directions – the highest compressive stress is in the longitudinal direction, reaching the yield strength of Al6061 at the given temperature.
3. As the weld metal cools down from the processing region, the thermal stresses changes to tension. Higher tensile stresses develop along the longitudinal direction of the weld. As the weld metal cools down to room temperature, the magnitudes of the stress approach to those of residual stress determined in previous studies.

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References

1. W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Templesmith and C. J. Dawes: International Patent Application PCT/GB92/02203, UK Patent Application 9125978·8, December 1991, US Patent 5 460 317, 1995.
2. J. E. Gould, T. J. Lienert and Z. Feng: Recent developments in friction stir welding. Technical Paper No. 981875, 1998, Aerospace Manufacturing Technology, SAE International.
3. R. S. Mishra and Z. Y. Ma: *Mater. Sci. Eng. R*, 2005, **R50**, 1–78.
4. T. U. Seidel and A. P. Reynolds: *Sci. Tech. Weld. Join.*, 2003, **8**, 175–183.
5. Z. Feng and J. E. Gould: *J. Mater. Proc. Manuf. Sci.*, 1998, **7**, 185–194.
6. M. Z. H. Khandkar, J. A. Khan and A. P. Reynolds: *Sci. Tech. Weld. Join.*, 2003, **8**, 165–174.
7. G. Buffa, J. Hua, R. Shivpuri and L. Fratini: *Mater. Sci. Eng. A*, 2006, **A419**, 389–396.
8. P. A. Colegrove and H. R. Shercliff: *J. Mater. Proc. Tech.*, 2005, **169**, 320–327.
9. P. Heurtier, M. J. Jones, C. Desrayaud, J. H. Driver, F. Montheillet and D. Allehaux: *J. Mater. Proc. Tech.*, 2006, **171**, 348–357.
10. C. G. Winsor: 'Pulsed neutron scattering'; 1981, London, Taylor and Francis.
11. W. Woo, Z. Feng, X.-L. Wang, K. An, C. R. Hubbard, S. A David and H. Choo: *Appl. Phys. Lett.*, 2006, **88**, 261903.
12. M. A. M. Bourke, D. C. Dunand and E. Üstündag: *Appl. Phys.*, 2002, **74**, S1707–1709.
13. K. Masubuchi: 'Analysis of welded structures'; 1980, New York, Pergamon.
14. H. S. Carslaw and J. C. Jaeger: 'Conduction of heat in solids', 2nd edn; 1959, London, Oxford University Press.
15. H. M. Rietveld: *J. Appl. Cryst.*, 1969, **2**, (2), 65–71.
16. A. C. Larsen and R. B. von Dreele: 'General structure analysis system, GSAS', LAUR 86–748, 2004, Los Alamos National Laboratory.
17. X.-L. Wang, E. A. Payzant, B. Taljat, C. R. Hubbard, J. R. Keiser and M. J. Jirinec: *Mater. Sci. Eng. A*, 1997, **A232**, 31–38.
18. M. A. Sutton, A. P. Reynolds, D. Q. Wang and C. R. Hubbard: *J. Eng. Mater. Technol.*, 2002, **124**, 215.
19. W. Woo, H. Choo, D. W. Brown, Z. Feng, P. K. Liaw, S. A. David, C. R. Hubbard and M. A. M. Bourke: *Appl. Phys. Lett.*, 2005, **86**, 231902.
20. R. A. Owen, R. V. Preston, P. J. Withers, H. R. Shercliff and P. J. Webster: *Mater. Sci. Eng. A*, 2003, **A346**, 159–167.
21. Z. Feng, X.-L. Wang, S. A. David and P. S. Sklad: *Sci. Tech. Weld. Join.*, 2007, 12, in press.
22. V. Soundararajan, S. Zekovic and R. Kovacevic: *Int. J. Machine Tools Manuf.*, 2005, **45**, 1577–1587.
23. G. Simmons and H. Wang: 'Single crystal elastic constants and calculated aggregate properties'; 1971, Cambridge, MIT Press.
24. Y. S. Touloukian, R. K. Kirby, R. E. Taylor and P. D. Desai: 'Thermophysical properties of matter, thermal expansion, metallic elements and alloys'; 12, 1975, New York, IFI/Plenum.
25. P. J. Ditzel: Microstructure/property relationships in aluminum friction stir welds. Master's dissertation, The Ohio State University, Columbus, OH, USA, 1997.
26. J. C. Mcclure, Z. Feng, W. Tang, J. E. Gould, L. E. Murr and X. Guo: A thermal model of friction stir welding, Proc. 5th Int. Conf. on 'Trends in welding research', Pine Mountain, GA, USA, June 1998, ASM International.
27. A. P. Reynolds, W. Tang, Z. Khandkar, J. A. Khan and K. Lindner: *Sci. Tech. Weld. Join.*, 2005, **10**, 190–199.
28. X.-L. Wang, Z. Feng, S. A. David, S. Spooner and C. R. Hubbard: Neutron diffraction study of residual stress in friction stir welds, Proc. 6th Int. Conf. on 'Residual stresses', Oxford, UK, July 2000.
29. W. Woo, H. Choo, D. W. Brown, Z. Feng and P. K. Liaw: *Mater. Sci. Eng. A*, 2006, **A437**, 64–69.