Key Engineering Materials Vols. 385-387 (2008) pp 517-520
online at http://www.scientific.net

Online available since 2008/Jul/02

A study of residual stresses in Al/SiC$_p$ linear friction weldment by energy-dispersive neutron diffraction

Tea-Sung Jun[1, a], Fabio Rotundo[2, b], Lorella Ceschini[2, c], Alexander M. Korsunsky[1, d]

[1]Department of Engineering Science, University of Oxford, Parks Rd, Oxford OX1 3PJ, UK

[2]SMETEC, University of Bologna, Viale Risorgimento 4, I-40136 Bologna, Italy

[a]tea.jun@eng.ox.ac.uk, [b]fabio.rotundo@studio.unibo.it, [c]ceschini@bomet.fci.unibo.it, [d]alexander.korsunsky@eng.ox.ac.uk

Keywords: residual stress, linear friction welding, metal matrix composite, neutron diffraction, eigenstrain

Abstract. Linear friction welding (LFW) is a solid state joining process for bonding of two flat-edged, complex geometry components through relative reciprocating motion under axial (compressive) forces. Although the proof of principle has been obtained some time ago, recently a number of studies have been published aimed at optimising the joining operations to obtain best joint strength and reduced distortion and residual stress. The present paper is devoted to the study of linear friction welds between components made from aluminium alloy 2124 matrix composite (AMC) reinforced with 25vol% particulate silicon carbide (SiC$_p$). Neutron diffraction was used to measure interplanar lattice spacings in the matrix and reinforcement, and to deduce residual elastic strains and stresses as a function of distance from the bond line. Significant asymmetry is observed in the residual stress distribution within the two components being joined, that may be associated with the difference in the microstructure and texture.

Introduction

Aluminium matrix composites (AMCs) form a class of attractive light-weight materials possessing a good combination of high stiffness and strength. The incorporation of stiff and hard (usually ceramic) reinforcement in the form of fibres or particles leads to a significant increase in the overall elastic modulus. Strength is also improved due to a variety of mechanisms, including grain refinement, creation of additional obstacles to dislocation movement, etc. Based on these advantages over conventional base alloys, AMCs have recently been considered for application in aerospace, motor sport and automotive industries [1]. However, a significant limitation to industrial application of AMC's arises from the problems arising in conventional fusion welding methods, such as segregation and degradation of the reinforcement phase. Consequently, friction welding processes (friction stir welding or linear friction welding) is seen as a promising candidate for joining AMCs materials, since no melting is involved and the formation of brittle solidification products is reduced [2-3]. In the case of friction stir welding, additional difficulty arises because of the significant tool wear caused by the presence of highly abrasive ceramic particles within the bulk of material. In the case of linear friction welding, published studies of the process has been limited to components of relatively simple geometry, e.g. jet engine blades to discs.

Linear Friction Welding (LFW) is a solid state joining process in which the bonding of two flat edged, complex geometry components is completed with their relative reciprocating motion under axial compressive force. During the process, significant heat is generated by friction at the component interface, resulting in continued plastification and the displacement of plastically deformed material [4-5]. After fusion and cooling down from the processing temperature some misfit strains (eigenstrains) are generated, and the attendant process of elastic re-equilibration ultimately results in the generation of residual stresses.

Residual stresses in AMC's exist on a variety of scales, from microscopic (at the characteristic length scale of alloy crystallites and diameters of particles or fibres) to macroscopic, associated with the overall deformation and/or thermal history of the entire sample or component [6]. It is crucially important for industrial applications to develop improved understanding of these residual stresses in order to modify and control them by deformation and thermal processing, and to be able to predict their performance in service.

Among a variety of residual stress measurements, neutron diffraction from pulsed sources provides a particularly attractive approach for truly non-destructive spatial mapping of residual elastic strains. Pulsed sources are particularly well-suited for energy-dispersive diffraction experiments due to the fact that the neutrons are created over a wide energy range, and their wavelength (energy) is easily determined by the time-of-flight (TOF) technique. Although LFW has seen significant development over the last decade, little or no data on residual stress characterisation has been published. Publications found in the literature focused in particular on joining of titanium alloys for application in the aircraft engine manufacturing industry [4]. In the present study residual stress measurements by neutron diffraction have been carried out on AMC linear friction weldments.

Experimental and data analysis

The material used in this research was an aluminium alloy matrix composite AMC225xe, high quality aerospace grade aluminium alloy reinforced with 25% by volume of ultra-fine particles of silicon carbide, manufactured by Aerospace Metal Composites Ltd (Farnborough, UK). The matrix material was aluminium alloy AA2124, with the nominal composition (in wt %): Cu – 3.8, Mn – 0.5, Mg – 1.4, Zn < 0.25, Al balance. Reinforcement consisted of fine (<3μm) particles of SiC. Composite was produced by the powder route consisting of mixing, followed by de-gassing and consolidation by hot iso-static pressing, and extrusion. The addition of finely dispersed reinforcement provides significant improvement in stiffness (E_{Al} = 73GPa, E_{SiC} = 415GPa, E_{comp} = 115GPa) and strength (composite σ_Y of 487MPa, UTS of 690MPa) without an appreciable change in density (ρ_{Al}=2.78gcm^{-3}, ρ_{SiC}=3.22gcm^{-3}).

Figure 1 illustrates the linear reciprocal motion of the welding process and dimensions of each component. Initial settings for the process corresponded to the amplitude of 2mm, frequency of 50Hz, the compressive welding force perpendicular to the weld line of 100kN and the burn-off of 2mm. The variation of welding parameters as a function of time is shown in Figure 2. The frictional heat generated by reciprocal motion under pressure softens the material in the vicinity of the weld interface, thus leading to plastification of the interface. Interface rubbing removes the oxide layer and creates fresh surfaces suitable for bonding, creating large extrusions known as “flash” of different shape depending on the material(s) being bonded and extruded. In the present linear friction welding process the total upset was 9.37mm. The heat affected zone extends from the bond line into the bulk of material.

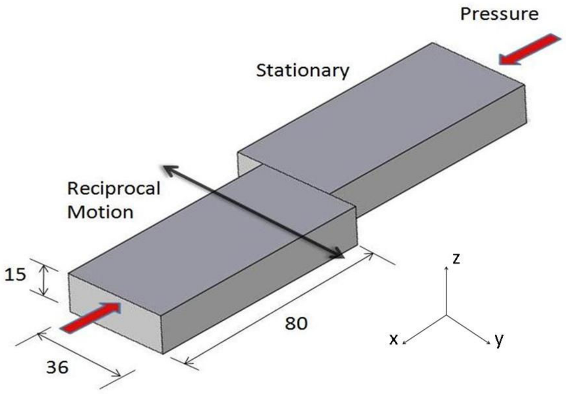

Fig. 1. Schematic of the linear friction welding process

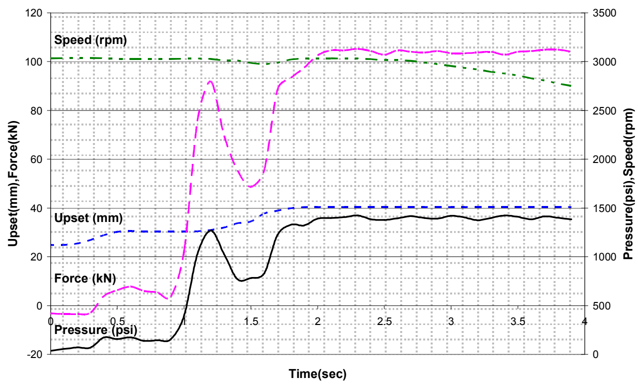

Fig. 2. Variation of the weld parameters with time

Neutron diffraction measurements were carried out on the ENGIN-X instrument (ISIS, Rutherford Appleton Laboratory, UK). Figures 3 and 4 show the schematic diagram of the ENGIN-X diffractometer and the illustration of the experimental setup, respectively. The diffraction patterns were collected as time-of-flight data by two detectors mounted perpendicularly to the incident beam. The results are converted into lattice *d*-spacing by combining the de Broglie’s equation ($\lambda = h/mv = ht/mL$) and Bragg’s equation ($\lambda = 2d_{hkl}\sin\theta_B$):

$$d_{hkl} = \frac{ht}{(2mL\sin\theta_B)}, \quad (1)$$

where $2\theta_B$ is the neutron scattering angle, d_{hkl} is the lattice spacing between the family of planes with *hkl* Miller indices, λ the neutron wavelength, h Planck's constant, m neutron mass, L the flight path, t the time-of-flight of the neutron and v its velocity. The elastic strain is determined from the change in the atomic interplanar distances d_{hkl}, as compared with the value d^0_{hkl} measured in the unstressed (or reference) condition, $\varepsilon_{hkl} = \left(d_{hkl} - d^0_{hkl}\right)/ d^0_{hkl}$ [7]. In the absence of reference strain-free samples, the unstrained lattice parameters d^0_{hkl} were obtained from pattern collected by placing the beam at the very corner of the plate, which was assumed to carry no or little residual macroscopic strain. A different reference was used for each half of the component, due to the fact that different parts came from slightly different production routes. The reference at central point (x=0) was taken to be the average value of the two far-field references.

The data analysis was carried out on the entire diffraction spectra obtained at each measurement position, using the Open Genie software for the display and analysis of data from the neutron scattering instruments at the ISIS facility [8]. The stresses of Al and SiC in the component were computed using Hooke's low for triaxial stress, i.e.,

$$\sigma_{xx} = \frac{\mathrm{E}}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{xx} + \nu\left(\varepsilon_{yy} + \varepsilon_{zz}\right)\right] \quad (2)$$

$$\sigma_{yy} = \frac{\mathrm{E}}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{yy} + \nu\left(\varepsilon_{xx} + \varepsilon_{zz}\right)\right] \quad (3)$$

$$\sigma_{zz} = \frac{\mathrm{E}}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{zz} + \nu\left(\varepsilon_{yy} + \varepsilon_{xx}\right)\right] \quad (4)$$

Finally, macroscopic residual stresses were computed using the rule of mixtures:

$$\sigma_{Macro} = f\sigma^{SiC}_{tot} + (1-f)\sigma^{Al}_{tot} = 0.25\sigma^{SiC}_{tot} + 0.75\sigma^{Al}_{tot} \quad (5)$$

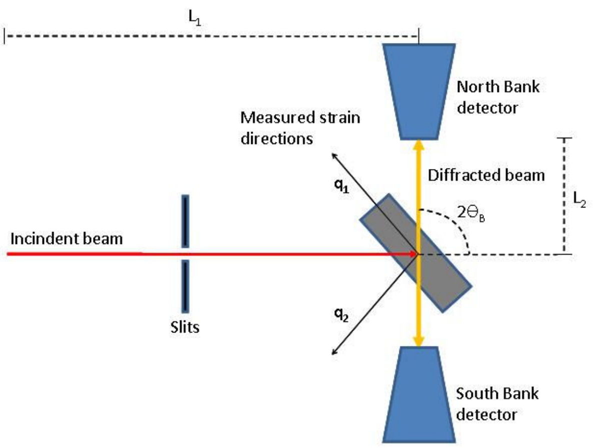

Fig. 3. Schematic of the ENGIN-X diffractometer at ISIS

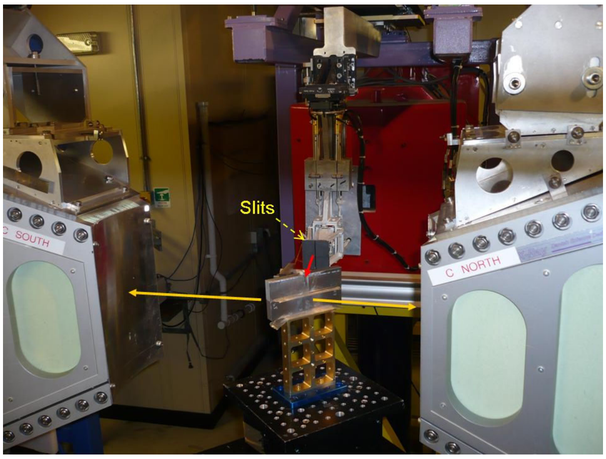

Fig. 4. Illustration of the experimental setup at ISIS

Results and discussion

Figure 5 and 6 shows the computed stress distributions as a function of the x position across the bond line for Al alloy matrix and SiC reinforcement respectively, for three components: x, normal to the bond plane (longitudinal), y, along the bond line (transverse), and z, through the thickness. Figure 7 shows the macroscopic residual stress variation computed using the rule-of-mixtures, equation (5). It is interesting to note that significant asymmetry of residual stress is observed across the bond line. It is surmised that this asymmetry may be associated with the presence of different texture in the two pieces being joined. Since aluminium alloy crystals possess a relatively low level of elastic anisotropy, the presence of texture has little effect on macroscopic strain computation from diffraction patterns. However, texture may be expected to exert significant influence over plastic flow, resulting in different strength of the components being joined, that serves as the primary cause of residual stress asymmetry in weldments. Further experimental investigation of bulk texture is envisaged to verify this hypothesis.

Compared with previous LFW studies involving Ti [4] and Ni [9] alloys that have relatively higher thermal resistance, larger amounts of plastic flow are observed in Al-based materials. It is noted that *y*-strain is tensile in weld zone and compressive in the heat affected zone, while the spatial variation trend for the *z*-strain component is opposite to that for the *y*-strain.

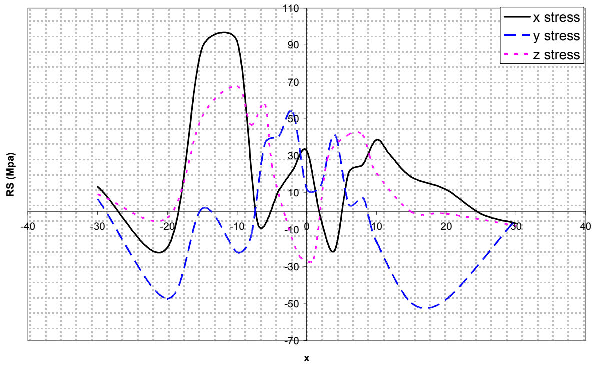

Fig. 5. Stress (Al) as a function of *x*-axis position

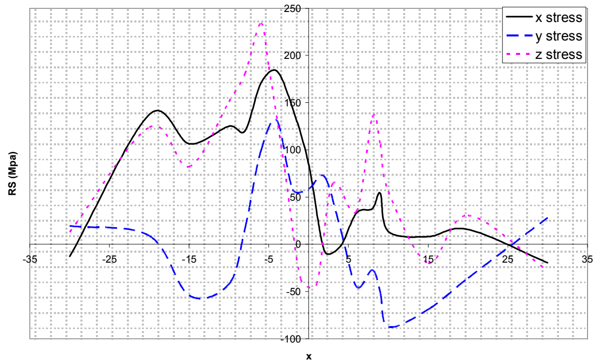

Fig. 6. Stress (SiC) as a function of *x*-axis position

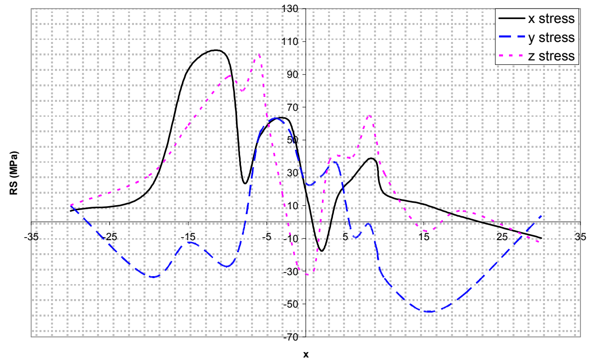

Fig. 7. Residual macroscopic stress (AlSiC) as a function of *x*-axis position

Conclusion

The study described in this paper was devoted to the analysis of residual stresses in linear friction weldments between aluminium alloy matrix – SiC particulate reinforced composite material. It has been demonstrated that neutron diffraction provides a powerful means of evaluating the residual stress variation around LFW joints. Modelling of macroscopic residual stress using inverse eigenstrain modelling should be carried out in order to improve process characterisation. The observed asymmetry of residual stress is likely to be associated with the difference in the microstructure and texture of the two components.

References

[1] S. Xu, S. Chardonnet, G. Savini, S.Y. Zhang, W.J.J. Voster and A.M. Korsunsky: Mater. Sci. Forum 571-572 (2008), p.277-282

[2] H. Uzun: Materials and Design 28 (2007) p.1440-1446

[3] J.A. Wert: Scripta Materialia 49(2003) p.607-612

[4] M.R. Daymond and N.W. Bonner: Physica B 325 (2003) p.130-137

[5] P. Wanjara, M. Jahazi: Metallurgical and Material Transactions A 36A (2005) p.2149-2164

[6] A.M. Korsunsky and K.E. Wells: Matls. Sci. Forum 321-323 (2000) p.218-223

[7] J.R. Santisteban, M.R. Daymond, J.A. James, L. Edwards: J. Appl. Cryst. 39 (2006) p.812-825

[8] F.A. Akeroyd, R.L. Ashworth, S.D. Johnston, J.M. Martin, C.M. Moreton-Smith and D.S. Sivia: OPEN GENIE User Manual

[9] M. Preuss, J. Quinta da Fonseca, A. Steuwer, L. Wang, P.J. Withers, S. Bray: J. Neutron Research 12(1-3) (2004) p.165-173