ESRF	**Experiment title:** Development of BM16 and ID11 for Strain Scanning – Second Phase	**Experiment number**: ME-103
Beamline **BM16/ID31** **ID11**	**Date of experiment**: from: November 2000 to: November 2002	**Date of report**: 26/02/03
Shifts: 60,60	**Local contact(s)**: A N Fitch, G B M Vaughan, A Terry, J Wright, F Fauth	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

***P J Webster, *D J Hughes, *G Mills**

Institute for Materials Research, University of Salford, Manchester, M5 4WT, UK

***P J Withers, *R A Owen, *J Peng, *A Steuwer, *M Preuss, *J Fonseca, *M Peel, *B Nadri, *S McDonald**

Manchester Materials Science Centre, University of Manchester and UMIST, M1 7HS, UK

***A M Korsunsky, *K James, *M Jensen, *R Cho, *B Halfacre, *J Tuck, *S Achtioui, *S Chhann**

Department of Engineering Science, University of Oxford, Oxford, OX1 3PJ, UK

Report:

The proposal was a combined application from a consortium of three University groups to enable them to continue and to extend, in collaboration with beam-line staff, the development of instruments BM16 and ID11 as strain scanners. The proposers had begun strain scanning at ESRF in 1996 and were allocated a number of standard beam-time awards up to 1998. During this time they were able to identify the potential of the technique and to make a number of advances. In 1998 they were awarded their first Long-Term proposal, HS-674, and this enabled significant developments to be started. This second phase allocation, ME-103, awarded in 2000, has enabled these developments to be substantially advanced and for a wide range of samples, treatments and engineering materials to be studied. Materials engineering research is now firmly established at the ESRF.

Technical developments

The principal technical objectives were to: establish a strain scanning environment on ID11 similar to that already installed on BM16; to improve positioning, surface location and gauge resolution; to produce beam-line linking software for analysis programmes so that novice and expert alike may perform near real-time data analysis.

All the technical objectives were achieved. A prototype scanning translator facility is now available on ID11 that can be readily assembled so that the benefits of the exceedingly fast rates of data acquisition can be realised. This is of particular benefit when using small gauge sizes for high spatial resolution or when multiple point mapping of large samples is required. The provision of positioning and surface location facilities, using fixed theodolites, has improved the positioning accuracy. Additionally, on BM16 (ID31) the incorporation of a CCTV camera attached to the theodolite has speeded up and improved the setting-up procedures. Dead-times have been reduced by a combination of software and hardware developments. These improvements are particularly beneficial for the higher flux undulator machines where counting times are substantially shorter and dead-times are proportionately more significant. New beam-line linking software for our analysis programmes has been produced so that efficient near real-time analysis of data can now be performed. It has been used by both experienced and new users and has transformed experimentation procedures. Processed data can now be displayed within minutes of its collection enabling data quality to be evaluated almost immediately and for measuring parameters, such as counting times and scan matrices, to be changed where necessary. Programmes have been developed to allow the optimisation of measurement matricies in complex samples and further increase the experimental efficiency.

BM16/ID31

In 2002 the BM16 diffractometer (maximum energy 40 KeV), and its strain scanning facilities, was transferred to the undulator source ID31 (maximum energy 60 KeV). After a short interval for re-commissioning strain scanning re-commenced. The higher beam energy permits sample thicknesses to be increased by about a factor x3, and the increased flux has typically increased counting rates by a factor of about x5. In combination the two factors have substantially increased the speed of measurement and the range of engineering materials, and component sizes, that can be studied using the instrument.

ID11/ID31

The two instruments ID11 and ID31 can now be considered to be at the robust prototype stage as strain scanners. The next stage will be to standardise and refine the systems, to improve and to speed up sample mounting and positioning accuracy and to optimise counting efficiency.

Scientific and Engineering Measurements

The principal scientific and engineering objectives were to: maintain our lead in the high resolution measurement of strain in engineering materials, particularly lightweight materials of interest to the transport industry; to underpin composite micromechanics with new data on the individual fibre scale; to study near-surface stresses; to study ferroelectrics and piezoelectrics; to undertake dynamic measurements in-situ.

All the principal scientific and engineering objectives outlined in the proposal, except the studies of ferroelectrics and piezoelectrics studies were attained. Additional measurements were focused instead on extending the capacity to study the heavier structurally important engineering materials, steels and nickel superalloys, making use of the higher energies available at ID11 and ID31.

List of experiments performed

The following studies have been performed, both as part of the development programme and because of their materials engineering significance:

BM16/ID31

1. Ti-6Al-4V – Line profiles across bent bars used in conjunction with polycrystalline modelling
2. Ti-6Al-4V – Line profiles across two welds – important aspects of mechanical load transfer and phase interaction identified and highlighted
3. Aluminium alloy cracked sample – strain maps collected through the sample at different depths
4. Residual stress measurements on low-distortion aluminium alloy welds
5. Full strain map around a 4% cold-expanded hole
6. In-situ compression loading of a high volume fraction MMC
7. Ti-6Al-4V – In-situ loading studies
8. Ti-6Al-4V – Line profiles across laser bent samples
9. Aluminium alloy MIG welded bars - Line profiles across bars
10. Strain mapping of cracks grown from a cold-expanded hole
11. Stresses in the vicinity of impact damage
12. High resolution mapping of stresses in the vicinity of a crack
13. Measurement of stress around a cold-expanded hole
14. Stresses in Al TIG welds
15. Friction stir welds in Al Alloys

ID11

16. Aluminium alloy casting – Through-thickness profile
17. AlSiC – Line profiles across bent bars
18. Studies of the (100) superlattice reflection in inertia welded superalloys
19. Residual strain measurements of a MMC blade/ring sample
20. In-situ strain mapping of a fatigued Ti-6Al-4V/SCS-6 sample
21. High-resolution area mapping of a worn US railway rail
22. Ti-6Al-4V – Line profiles across bent bars
23. Ni alloy weld - Line profiles across weld
24. Residual stress measurements on 2XXX, 5XXX and 7XXX aluminium alloy friction-stir welds
25. Influence of post weld heat treatment on residual stresses
26. Residual stresses in induction hardened gears
27. Stresses in Ti/SiC Single Fibre composites
28. Stresses in damaged monolayer composites
29. $\gamma\gamma'$ phase mapping across Ni superalloy friction welds
30. Residual stresses in worn UK railway rails
31. Fibre bridging of cracks in multiply composites
32. Linear friction welds in Ti-alloys
33. In-situ compression loading of a high volume fraction (70%) MMC
34. Crack tip strain field in the matrix of an Al-SiC composite

Summary

Experiments have been performed on a range of typical engineering materials, components and processed samples. The materials include: titanium alloys, nickel-based superalloys and composites as used respectively for blades and discs in the inlet and hot stages of aero-engines; a range of aluminium alloys and composites as used in aircraft structures and fast surface transport; steels as used in construction. High residual strain fields have been mapped in railway rails; around expanded holes; through surfaces; around crack tips. Residual stress fields generated by welding, including MIG, TIG, friction stir, linear friction and low-distortion welds have been studied. Dynamic in-situ measurements have been used to study crack growth phenomena. The studies and results have been of intrinsic engineering research value and have been used to develop the synchrotron X-ray strain scanning techniques, hardware and software.

Highlighted examples

High-resolution area mapping of a worn US railway rail (6) [I8, H3]

Many of the various mechanisms of rail fracture are related to the relationship between defects and the residual stress field in a rail. Typically a rail fracture is the result of a progressive defect, the propagation of which is related to the inherent residual stresses in the rail. The residual stresses are generated first as a result of the manufacturing processes that may include hot-rolling, roller-straightening and head hardening. Then, in-service, the running surfaces are subjected to repeated rolling contact stresses. There will also be wear caused by sliding friction near the running band and at the gauge corner side of the head when contact is made by the wheel flange. Additionally the head may also be ground periodically as a maintenance procedure to restore the correct rail profile, to remove small surface cracks and to move the wheel-rail contact position across the head in order to extend the rail life. Figure 1 shows high spatial resolution maps of the residual stress fields in a section of worn US rail derived from strain measurements made on a rectangular matrix at over 6000 points. The ‘banana’- and ‘T’-shaped tensile central regions are characteristic of many transverse and vertical railhead residual stress patterns respectively. Both patterns have asymmetrical pointed features that extend towards features of physical discontinuity at the surface. These are the regions at which fatigue cracks are most likely to start and then propagate. The maps should enable engineers to better understand the failure mechanisms and to determine the optimum rail maintenance and replacement schedules for safe and economic operation.

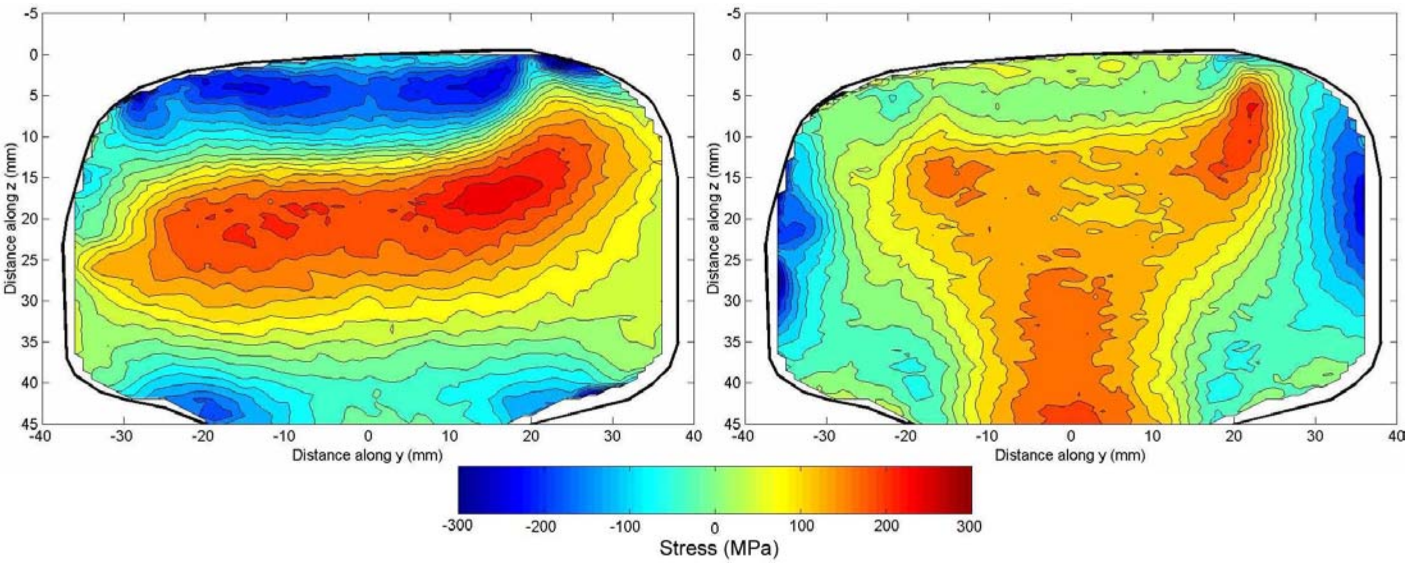

Figure 1. High-resolution transverse (left) and vertical (right) residual stress maps of a 4 mm thick heavily worn US rail section (6) [18, H3]

Quantitative analysis of the crack tip strain field in the matrix of an Al-SiC composite (34)

The sample was in the form of a 100x14x10 mm^3 bar machined from a rolled plate of powder metallurgy route Al 2124-matrix particulate composite with 17 vol% of SiC. A 6 mm deep slot approximately 0.1 mm wide was electric discharge machined perpendicular to the longest dimension to represent a planar crack with a straight front. The specimen was subjected to four-point bending *in-situ* using a portable bending rig. A beam spot size of 0.5x0.5 mm on the specimen was used, at a wavelength of 0.176 Å. The 311 peak was chosen since it is known to be the least sensitive to intergranular stress effects and representative of the average engineering strain in the sampling volume. The pattern was collected by a scintillation detector mounted on the arm of a KUMA diffractometer behind two sets of secondary collimating slits. The matrix direct strain in the crack opening direction was calculated on the basis of the 311 peak position. Away from the crack tip four point bending results in the non-singular strain profile varying linearly from tension and into compression across the bar. Near the crack tip this variation is superimposed on the *K*-field. Figure 2a shows a map of the K-field obtained by subtracting the linearly varying bending strain from the measured map. Figure 2b shows the corresponding LEFM prediction of the near tip strain field corresponding to the stress intensity factor value of K = 28 MPa√m. This value of K was chosen by least squares fitting of the predicted profile to the map in figure 2a. The result allows an interesting observation to be made on the

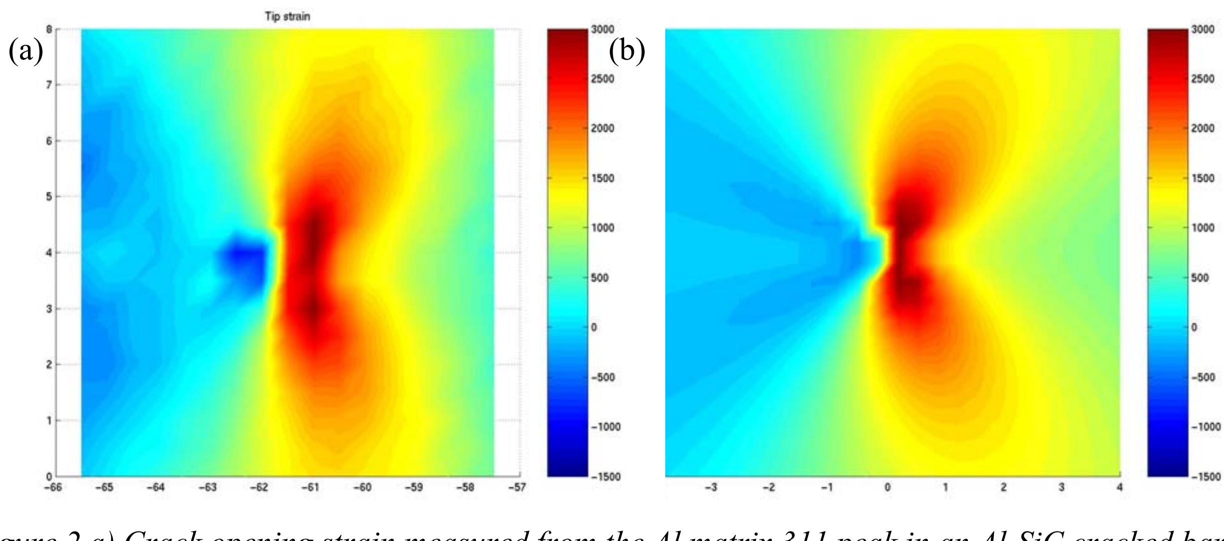

Figure 2 a) Crack opening strain measured from the Al matrix 311 peak in an Al-SiC cracked bar, b) LEFM K-field predicition, K = 28 MPa√m subject of micromechanics of how the strain is partitioned between the matrix and reinforcement at crack tip. The quality of the agreement between the prediction and the experiment is apparent, suggesting that even in the presence of reinforcement the strain distribution within the matrix phase obeys the LEFM predictions.

In-situ strain mapping of a fatigued Ti-6Al-4V/SCS-6 sample (20) [23]

In fibre-reinforced materials, fibre bridging can play an important role in fatigue crack resistance. Crack tip shielding has been extensively modelled but is difficult to measure experimentally. In this study we made the first measurements of fibre bridging deep within a fatigue-cracked sample. The stress field in the matrix and fibres in shown in figure 3 for a fatigue crack grown under tension-tension in conditions leading to bridging fibres in the wake. The results are an average over all the fibres through thickness. Of particular interest is the level of tensile strain in the fibres bridging the crack and the distance from the crack over which the fibres return to their continuum value. The data have been compared with finite element predictions of the crack tip shielding brought about by the bridging fibres. They have shown that the observed interfacial shear sliding strength (proportional to the gradient of fibre stress) in the vicinity of the bridging zone appears to be significantly lower after fatigue cycling than is measured further from the crack plane or in fibre fragmentation testing. This means that the fibre stress is high over a broader region away from the crack. This change in the interfacial shear stress for sliding in the forward-reverse sliding region under fatigue needs to be taken into account in the predictive models. Note how the matrix stress peaks at the crack tip, while the stress in the fibres peaks in the crack wake. This project also incorporated radiography and tomography imaging (ID19) in order to carry out in-situ damage characterisation of mechanically tested samples.

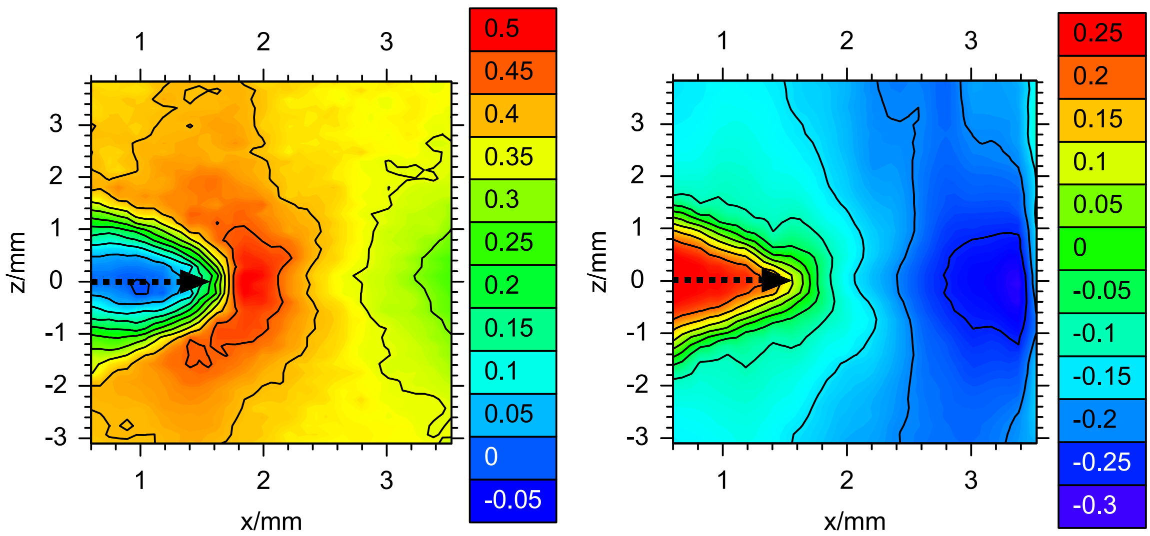

Figure 3. a) Matrix and b) fibre strain (in %) distribution in the vicinity of a 1.6 mm fatigue crack grown from a 0.6 mm notch under K_{max} loading in an 8 ply 4 mm wide sample (20) [23]

ESRF Medium Term Scientific Programme for the Period 2002-2006

FaME38 – Support Facility for Materials Engineering at ILL-ESRF

Materials engineering is now part of the medium term programmes of ILL and ESRF. The joint FaME38 programme, initiated by the ME-103 proposers and materials engineering researchers from four other UK institutions, with a grant from EPSRC and matching support from ILL-ESRF, began in December 2001. It has a laboratory with a co-ordinate measuring machine (CMM) for precise sample shape measuring, standard mounting equipment, and a scan simulator to optimise scanning procedures off-line. Support is provided to all engineering users to prepare proposals and experiments, and for data processing and analysis. It is anticipated that this provision will both widen the engineering user base and substantially increase the efficiency of beam-time utilisation. FaME38 has now taken over the further development of the knowledge gained during ME-103. ME-103 was a crucial element in initiating FaME38 which supports the Materials Engineering programme of the ESRF.

Publications

Publications related to ME-103 are listed below. Of the 23 published papers fourteen [1-4, 8, 11-13, 16, 18-21, 23] could be broadly classified as being concerned with materials engineering specific investigations and the remaining nine [5-7, 9-10, 14-15, 17, 22] with synchrotron X-ray strain scanning, its development and potential. One of the latter [5] was awarded the prize for the 'Best paper in Strain in 2001' and another [17] was the keynote presentation to the 6th European Conference on Residual Stresses in Coimbra, Portugal. A further seven are to be published, or have been submitted, and others are in preparation. Four contributions have been made as book chapters and aspects of the work have contributed to Highlights and Annual Reports. Six students have been awarded PhD or MSc degrees and others have started their doctorate programmes.

Journals and Published Conferences

1. *R A Owen, P J Withers and P J Webster:* 'Synchrotron stress measurements of laser formed aluminium alloy sheet'. Proceedings ICRS6, Oxford 2000, IoM Communications Ltd, 82-89 (2000).
2. *P J Webster, G Mills, P A Browne, D J Hughes and T M Holden:* 'Residual stress around a cold-expanded hole'. Proceedings ICRS6, Oxford 2000, IoM Communications Ltd, 125-132 (2000).
3. *P J Webster, W P Kang, D J Hughes and P J Withers:* 'High resolution synchrotron area strain mapping of a double-V weld'. Proceedings ICRS6, Oxford 2000, IoM Communications Ltd, 743-750 (2000).
4. *P J Webster, D J Hughes, W P Kang, P A Browne, L Djapic Oosterkamp, P J Withers and G M Vaughan:* 'Synchrotron X-ray residual strain scanning of a friction stir weld'. J Strain Analysis **36** 61-70 (2001).

5*. *P J Withers and P J Webster:* 'Neutron and synchrotron X-ray strain scanning'. Strain **37** 19-33 (2001).

6. *P J Webster, D J Hughes, P J Withers and A N Fitch:* 'Synchrotron strain scanning on BM16 at ESRF'. MECA-SENS 2000 – Proceedings of Conference on Stress Evaluation with Neutrons and Synchrotron Radiation, Reims, France, December 2000. J Neutron Research **9** 93-98 (2001).
7. *M R Daymond and A M Korsunsky:* 'Determination of macroscopic plastic strain by analysis of multiple diffraction peaks'. Journal of the Physical Society of Japan **70**(A) 545 (2001).
8. *D J Hughes, P J Webster, N Ananthaviravakumar, G Mills, N W Bonner, A Se and S Norburn:* 'Quenching stresses – Measurement and Prediction'. Proceedings of the SEM Annual Conference on Experimental and Applied Mechanics, Portland, Oregon, USA, June 2001, 674-677 (2001).
9. *P J Webster:* 'The Status and Future of Residual Stress Analysis and the VAMAS TWA20 Project'. Proceedings of the International Symposium on Advances in Neutron Scattering Research, Tokai, Japan, 2000. J. Phys. Soc. Jpn. **70** Suppl. A 504-508 (2001).
10. *P J Withers:* 'Monitoring Strain & Damage by Neutron and Synchrotron Beams'. Jointly in Mat. Sci & Technology, **17**, 759-765, (2001) and Adv. Eng. Materials, **3**, and 453-460, (2001).
11. *M V R S Jensen, D Dye, K E James, A M Korsunsky, S M Roberts and R C Reed:* 'Residual stresses in a welded superalloy disc: characterization using synchrotron diffraction and numerical process modelling'. Met. and Mats. Trans. A-Physical Metallurgy and Materials Science **33** 2921-2931 (2002).
12. *A M Korsunsky, M R Daymond, and K E Wells:* 'The correlation between plastic strain and anisotropy strain in aluminium alloy polycrystals'. Materials Science and Engineering A – Structural Materials, Properties, Microstructure and Processing **334** 41-48 (2002).
13. *M Preuss, G J Baxter and P J Withers:* 'Inertia Welding Nickel-based Superalloy. Part I: Metallurgical Development'. Metal. & Mater. Trans, **33A**, 3115-25 (2002).
14. *Korsunsky, A.M. and K.E. James:* 'Advanced strain analysis by high energy synchrotron X-ray diffraction'. Proceedings of the 6th European Conference on Residual Stresses, ECRS6, Coimbra, Portugal, July 2002, Materials Science Forum, **404-407**, 329-334 (2002).
15. *P J Webster and W P Kang:* 'Optimisation of data collection and processing for efficient strain scanning'. J Neutron Research, **10,** 93-110, (2002).
16. *P J Webster, N Ananthaviravakumar, D J Hughes, G Mills, R V Preston, H R Shercliff, P J Withers:* 'Measurements and modelling of residual stress in a TIG weld'. Applied Physics **A 74** S1421-S1422 (2002).

17. *P J Withers, M Preuss, P J Webster, D J Hughes, A M Korsunsky:* 'Residual strain measurement by synchrotron diffraction'. Proceedings of the 6th European Conference on Residual Stresses, ECRS6, Coimbra, Portugal, July 2002, Materials Science Forum, **404-407**,1-12 (2002).
18. *P J Webster, D J Hughes, G Mills and G B M Vaughan:* 'Synchrotron X-ray measurements of residual stress in a worn railway rail'. Proceedings of the 6th European Conference on Residual Stresses, ECRS6, Coimbra, Portugal, July 2002, Materials Science Forum, **404-407**, 767-772 (2002).
19. *D J Buttle, N Collett, P J Webster, D J Hughes and G Mills:* 'A comparison of MAPS and synchrotron X-ray methods: Stresses measured in railway rail sections'. Proceedings of the 6th European Conference on Residual Stresses, ECRS6, Coimbra, Portugal, July 2002, Materials Science Forum, **404-407**, 881-886 (2002).
20. *M J Peel, M Preuss, A Steuwer, M Turksi, P J Withers:* 'The Evaluation of the Mechanical Properties of AA5083 Friction Stir Welds by Electronic Speckle Pattern Interferometry', 6th International Conference on Trends in Welding Research, Gatlinburg, April 2002, Georgia, USA.
21. *R A Owen, R V Preston, P J Withers, H R Shercliff and P J Webster:* 'Neutron and Synchrotron Measurements of Residual Strain in an Aluminium Alloy TIG Weld'. Mat. Sci. Eng., **A346**, 159-167 (2003).
22. *A M Korsunsky, K E James and M R Daymond:* 'Intergranular stresses in polycrystalline fatigue: diffraction measurement and self-consistent modelling'. Engineering Fracture Mechanics, **70**, (2003).
23. *M Preuss, G Rauchs, T Doel, A Steuwer, P Bowen, and P J Withers:* 'Measurements of Fibre Bridging during Fatigue Crack Growth in Ti/SiC Fibre Metal Matrix Composites'. Acta Materialia, **51**,1045-1057, (2003).

****Awarded the 'Fylde Electronics' Prize for the 'Best paper in 2001 Strain'***

To be published or submitted

A1. *Joe Kelleher, David Buttle, Judith Shackleton, Peter J Webster, Darren J Hughes, Philip J Withers and Paul Mummery:* 'The effects of service lifetime and wear on the residual stress in railway rails'. Proceedings of 6th International Conference on Engineering Structural Integrity Assessment, ESIA6, Manchester October 2002. FESI – UK Forum for Engineering Structural Integrity.
A2. *M Preuss, G J Baxter, P J Withers:* 'Inertia Welding of Nickel Base Superalloys for Aerospace Application'. International Conference on The Microstructure and Performance of joints in High-Temperature Alloys, London, UK, November 2002 To be published in Science and Technology of Welding and Joining.
A3. *M Preuss, J W L Pang, G J Baxter and P J Withers:* 'Inertia welding nickel-based superalloy. Part II: Residual Stress Development'. (Submitted to Metal. Trans A 2001).
A4. *M J Peel, A Steuwer, M Preuss, P J Withers:* 'Microstructure, Mechanical Properties and Residual Stresses as a Function of Welding Speed in Aluminium AA5083 Friction Stir Welds'. Acta Mat. (Submitted, 2003).
A5. *D Stefanescu, A Steuwer, R A Owen, B Nadri, L Edwards, M E Fitzpatrick, and P J Withers:* 'Elastic strains around cracked cold expanded fastener holes measured using the synchrotron X-ray diffraction technique'. (To be submitted, 2003).
A6. *R V Preston, D Hughes, H Shercliff, S Smith, P J Webster, and P J Withers:* 'A comparison between finite element predictions and synchrotron x-ray measurements of strain in an Al TIG weld'. Met. Trans. (To be submitted, 2003).
A7. *M Preuss, J Quinta da Fonseca, L Wang, P J Withers and S Bray:* 'Bulk residual stresses in linear friction welded IMI550'. Abstract submitted to International Ti Conference, Hamburg, July 2003.

Book Chapters

B1. *P J Withers:* 'Residual Stresses: Measurement by Diffraction'. in 'Encyclopedia of Materials: Science & Technology', Editors,.K.H.J. Buschow, et al., Pergamon, Oxford, 8158-8170 (2001).
B2. *P J Withers and H K D H Bhadeshia:* 'Residual Stress – I: Measurement Techniques'. Mat. Sci. Tech., **17**, 355-365, (2001).
B3. *P J Withers:* 'Use of Synchrotron X-ray Radiation for Stress Measurement'. in 'Analysis of Residual Stress by Diffraction using Neutron and Synchrotron Radiation', Editors, M.E. Fitzpatrick and A. Lodini, Taylor & Francis, London, 170-189 (2003.

B4. *P J Webster:* ‘Strain Mapping’. in ‘Analysis of Residual Stress by Diffraction using Neutron and Synchrotron Radiation’. Editors, M E Fitzpatrick and A Lodini, 209-218 (2003).

Theses

T1. *P A Browne:* ‘Determination of residual stress in engineering components using diffraction techniques’. PhD Thesis, University of Salford (2001).
T2. *Z Chen:* ‘Determination of residual stresses using synchrotron X-ray techniques’. MSc Thesis, University of Salford (2001).
T3. *R V Preston:* ‘Modelling of Residual Stresses in Welded Aluminium Alloys’, PhD Thesis, Cambridge University, (2001).
T4. *K E James:* ‘The effect of residual stresses on the deformation of polycrystals’, PhD Thesis, University of Newcastle upon Tyne (2001).
T5. *R A Owen:* ‘Synchrotron Strain Mapping: Aerospace Applications’, PhD Thesis, University of Manchester (2002).
T6. *N Ananthaviravakumar:* ‘Investigation of residual stresses in engineering components using neutron and synchrotron X-ray diffraction techniques’, PhD Thesis, University of Salford (2002).

Highlights and Annual Reports

H1. *P J Webster et al:* ESRF Highlights, Materials, ‘Friction Stir-welding’, 68-69, (2000).
H2. *A M Korsunsky et al:* SRS Annual Report, Materials and Engineering, ‘Illuminating the origins of material strength’, 14-15, (2002).
H3. *P J Webster et al:* ESRF Highlights, Industrial and Applied Research, ‘Residual Stresses in Railway Rails – The FaME38 Project’, 92, (2002).