	Experiment title: Design and durability of welded aircraft: measurement of residual strains in a 2024 VPPA weld	Experiment number: ME-516
Beamline: ID31	**Date of experiment**: from: 04/12/2002 to: 09/12/2002	**Date of report**: 19/06/03
Shifts:	**Local contact(s)**: Dr. Andy Fitch	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

L. Edwards*, S. Ganguly*, V. Stelmukh* and B. Nadri*

Department of Materials Engineering, The Open University, Walton Hall, Milton Keynes MK7 6AA

Introduction:

Research into weight saving, high performance material has long been a theme of aerospace engineering. Welding has been identified as an efficient and cost effective alternative to mechanical fastening for fabrication of future aircraft metallic members and components[1]. However, welding unlike mechanical fastening would lead to creation of a single load path and create local & global residual stress field which in turn will have profound influence on fatigue life. Hence it is vital to establish the relation between weld process variable, generation of residual stress and fatigue durability without which the optimum balance between the air-worthiness safety requirement and manufacturing cost reduction will not be achieved. In particular, the behaviour of fatigue cracks under the residual stress profile needs to be understood for reliable prediction of fatigue life necessary for damage tolerant design.

In a previous experiment (ME-281) carried out at beamline BM16 the same team measured detailed longitudinal and transverse strain maps on MIG welded Al 2024 amd Al 7150 samples. The same samples were then measured at the pulsed neutron source at ISIS to obtain transverse and normal strain directions. The full residual stress tensor was then calculated using a novel hybrid technique[3]. This work concerns Variable Polarity Plasma Arc (VPPA) welding which is thought to be superior to MIG welding in terms of microstructural performance and fatigue life. However, there has been little previous work on the residual stresses in VPPA welds. So in the present experiment, a VPPA welded coupon sample of Al2024 was measured in as welded and skimmed condition.. The detailed strain maps presented here were then used in conjunction with strain maps of normal and transverse directions measured at ENGIN diffractometer at the ISIS pulsed spallation neutron source to produce the full 3D stress tensor distribution.

Sample Description:

Two 11.8mm samples of Al2024-T351 was vertically welded along the rolling direction by VPPA welding process. The keyhole mode of operation results in high heat input and the plates were joined in a single pass. The initial coupon sample produced has a dimension of 400x280x11.8mm, which was then cut into two pieces of 240mm and 120mm length along the welding direction. The sample having dimension of 240x280x11.8mm was used to measure the residual strain. In order to find out the effect of machining another as-welded sample of similar dimension and origin was machined down to 7mm from 11.8mm in steps of 0.5mm from both sides. Stress free reference data were obtained from comb sample of dimension 3x3x11.8mm machined out from the central portion of the weld. Fig1. shows the sample and the stress free reference comb as machined out from the sample.

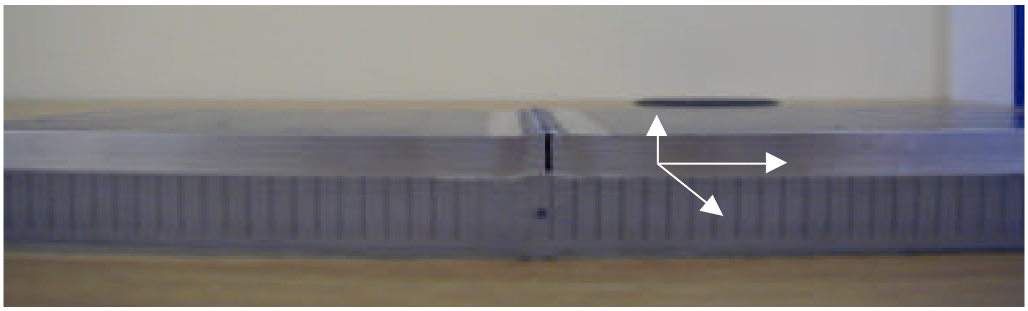


Fig 1. Stress free reference sample (comb) machined from the weld.

Experimental Details:

Synchrotron X-rays of energy 45 KeV were used in this experiment which corresponds to a wavelength(λ) of 0.275Å. Texture measurments obtained by EBSD experiment in SEM showed that the Al2024-T351 plate is not characrerised by any strong texture component (see Fig.2) . So the, <311> family of planes were selected for the experiment as there is adequate presence of this family of plane for all the three directions (Fig 2) and <311> family is the closest representative of the bulk[4].

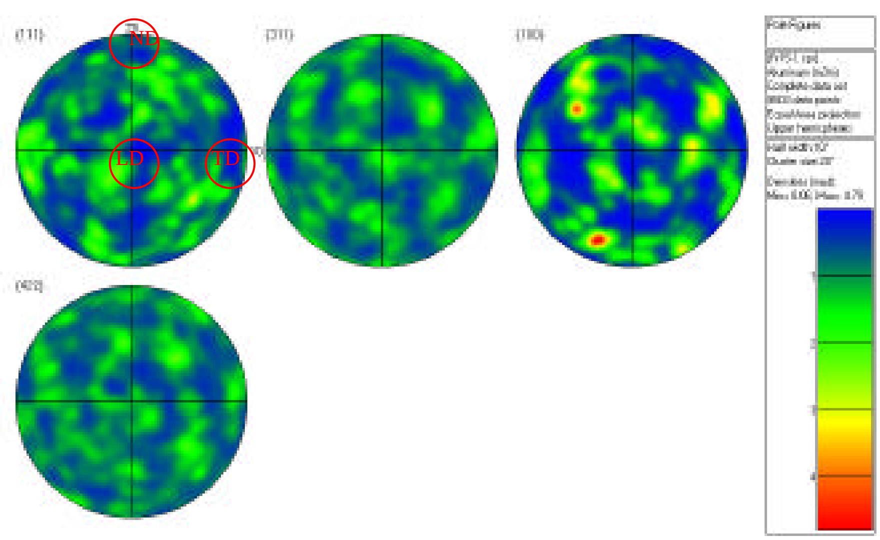
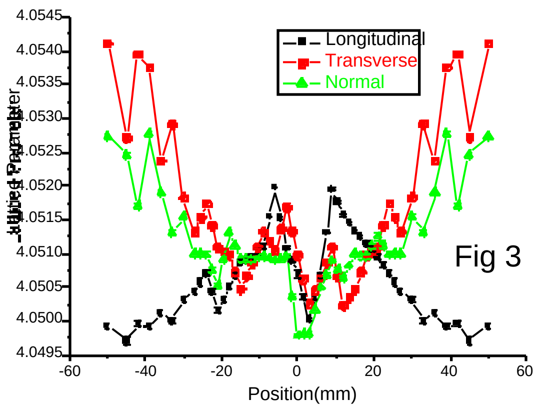


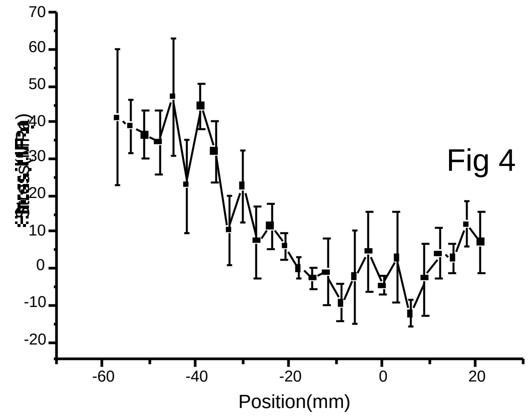
Fig 2. Pole figure obtained from the EBSD (The <311> & <422> family shows some intensity over all the three poles). The positions corresponding to longitudinal (LD), transverse (TD) and normal (ND) directions were shown over the first pole figure.

In the as welded plate, 5 through thickness lines were measured in the longitudinal & transverse strain directions (at +5, +3, 0, -3, -5 mm) whilst in the skimmed sample 7 through thickness lines (at +3,+2,+1,0,-1,-2,-3 mm) were measured in the same two principal strain directions. Stress free reference data were measured in the comb along 3 through thickness lines (+3, 0, -3) in all the three principal directions. A $\sin^2\psi$ measurement was carried out in the comb in the normal direction to determine the presence of any macro stress in that direction that had not been relieved by the comb production

Results:

Fig 3 shows the stress free reference variation as observed at ESRF. It can be seen that the transverse and normal directions vary in the same manner and differently from the longitudinal direction. Fig 4. shows the presence and variation of stress in normal direction determined from $\sin^2\psi$ analysis of the comb sample. The variation in the transverse direction is due to presence of intergranular stresses which are not relaxed in the comb sample. Fig 3 shows the peak width variation of the diffraction peaks in the principal strain directions showing that anisotropy in the plastic strain history is quite evident.





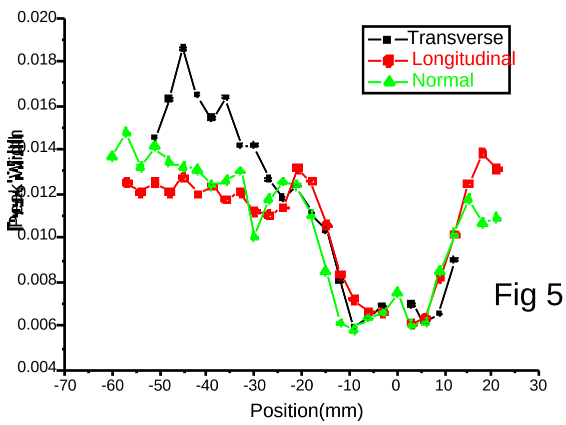


Fig 3. Variation of reference lattice spacing in the three principal directions

Fig 4. Presence of stress in the far field as observed in the $\sin^2$_ analysis of the comb

Fig 5. Peak width analysis of the cube showing the anisotropy in the plastic strain history of the 2024-T351 aluminium plate

The effect of these intergranular stresses particularly in the transverse direction on the final measured stresses has been removed by the direct calculation of strain from identical spatial locations on the comb sample-that is by using the comb measurments as a d_{ref} rather than a d_0. The stress measured by $\sin^2\psi$ analysis in the normal direction of the comb has also been used to correct the reference sample variation in all the three directions. The final calculated transverse strain from ESRF shows good agreement with that of measured by pulsed neutron source at ISIS despite of difference in gauge volume, geometry of reflection (Fig 6) showing that the effect of these intragranular streses has been removed.

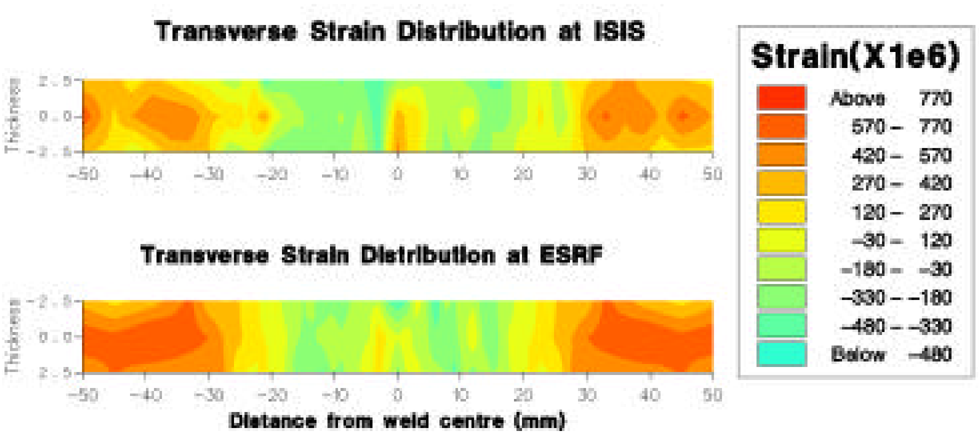


Fig 6. Transverse strain comparison at ISIS & ESRF. The strain values are corrected for d_0 measured at either source. Bi-linear interpolation is used to obtain the contour maps from several hundred strain values by Gsharp 3.1 software.

The longitudinal and transverse strain data obtained from ESRF is then used along with the normal strain data from ISIS to calculate the full residual stress tensor the Hooke's law. Fig 7. shows the 3D stress so produced.

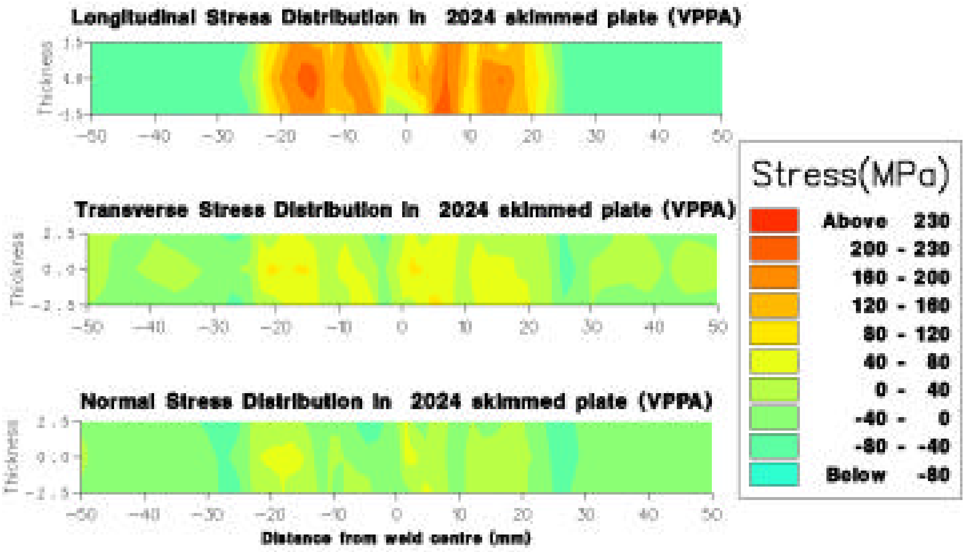


Fig 7. Three dimensional stress distribution in skimmed VPPA 2024-T351 weld.

The longitudinal stress distribution mimics the weld structure in the centre of the weld. The maximum stresses occur in the longitudinal dircetion and in the heat affected zone (HAZ) are characterized by a double peak shape. The maximum stress of 230MPa is also found in the HAZ.

Aspects of his work are being presented at two international conferences [5,6] and is currently being published in appropriate matreials engineering journals

References

1. **Mendez, P.F.,** *New Trends in Welding in the Aeronautic Industry. Proc.Conf"New trends for the manufacturing in the aeronautic industry", Inasmet, San Sebastian, Spain 24-25/5/ 2000: p. 21-38.*
2. **L. Edwards, V.S.., Stelmukh, J. R. Santisteban and S. Ganguly,** *Design and Durability of welded aircraft. ESRF report of Experiment ME-281: http://ftp.esrf.fr/pub/UserReports/21151_B.pdf*
3. **Stelmukh, V., Edwards, L., Santisteban, J. R., Ganguly S.,** *Weld Stress Mapping Using Neutron and Synchrotron X-ray Diffraction.* Materials Science Forum, 2002(404/407): p. 599-604.
4. **Daymond, M.R., et al.,** *Use of Rietveld refinement for elastic macrostrain determination and for evaluation of plastic strain history from diffraction spectra. Journal of Applied Physics, 1997. 82(4): p. 1554-1562.*
5. **Ganguly, S , Stelmukh, V., ,Fitzpatrick, M.E. and Edwards, L.** *A comparative study of residual strain in welded Al2024 alloy plate using neutron and synchrotron X-ray diffraction*presented at an *International Workshop on Hard Synchrotron X-rays for Texture and Strain Analysis* held at DESY, Hamburg, FRG, April 9-11 2003
6. **Ganguly, S**, **Stelmukh, V., ,Fitzpatrick, M.E. and Edwards, L**. *Use of neutron and synchrotron X-ray diffraction for non-destructive evaluation of weld residual stress in aluminium alloys* presented at MECASENS – the 2nd International Conference on Stress Measurement by Neutron and Synchrotron diffraction. held at Manchester on 8/9/2003 and to be Published in Journal of Neutron Research