Available online at www.sciencedirect.com

Physica B 385–386 (2006) 904–907

PHYSICA B

www.elsevier.com/locate/physb

Investigation of reference samples for residual strain measurements in a welded specimen by neutron and synchrotron X-ray diffraction

A. Paradowska[a,*], T.R. Finlayson[b], J.W.H. Price[a], R. Ibrahim[a], A. Steuwer[c], M. Ripley[d]

[a] *Mechanical Engineering Department, Monash University, Vic. 3800, Australia*
[b] *School of Physics, Monash University, Vic. 3800, Australia*
[c] *FaME38 at the ESRF-ILL, France*
[d] *Materials and Engineering Sciences, ANSTO, Lucas Heights, NSW 2234, Australia*

Abstract

In this research, both neutron and synchrotron X-ray diffraction techniques have been used to investigate variations in measured *d* spacing in two reference samples. The reference "stress-free" samples, a set of cubes and a comb sample, were produced using electro-discharge machining (EDM) to obtain a macro-strain-relieved condition. It is shown that there is a variation in microstructure across the parent metal, heat-affected zone (HAZ) and weld metal. A study of the issues in using the cubes and comb sample to provide reference d_0 values for the measurement of residual stress in welding is presented.

PACS: 61.12.Ld; 81.20.Vj; 29.20.Lq

Keywords: Welding; Residual strain/stress; Stress-free reference; Neutron diffraction; Synchrotron X-ray diffraction

---

1. Introduction

There are various ways of measuring or estimating residual strains and stresses [1–5], based on direct measurements or using numerical techniques. Neutron and synchrotron diffraction are outstanding in their ability to obtain residual stresses non-destructively within the subsurface and interior of the components [6–8]. The techniques determine the residual strain/stress field based on Bragg's law which provides a lattice spacing, *d*, averaged over a certain measurement volume [1].

The measurements of residual strain using diffraction techniques relies critically on the determination of a change in lattice parameter relative to a (known) reference or "strain-free" lattice parameter, d_0. Obtaining a precise reference lattice parameter is an important part of any diffraction-based, residual strain/stress experiment [8,9]. Pseudo-strain [10] means the difference between the *d* spacing measured at a particular point and the average *d* spacing, d_{ave}, across all measurements made at positions throughout the specimen.

Special care is needed in dealing with welds (alloys) where one can expect a change in stress-free lattice spacing due to composition and/or microstructural variations. Experimental measurements have already shown that the local d_0 values change with position [7–9] near weldments. However, some researchers reported [11] that for some alloys there is "little or no difference between the heat affected zone (HAZ) and base metal" in spatial resolution of strain measurements.

In this paper, we report on the results of strain measurements using both neutron and synchrotron X-ray diffraction (SD) of the weld produced by the flux-cored arc welding (FCAW) process in low carbon steel. The differences between the experimental procedures of SD and neutron diffraction (ND) are significant as discussed below. This means that the pseudo-strain measurements could be different for the two techniques.

---

[*] Corresponding author. Tel.: +61 3 9905 1716; fax: +61 3 9905 3122.
E-mail address: anna.paradowska@eng.monash.edu.au (A. Paradowska).

0921-4526/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.physb.2006.05.245

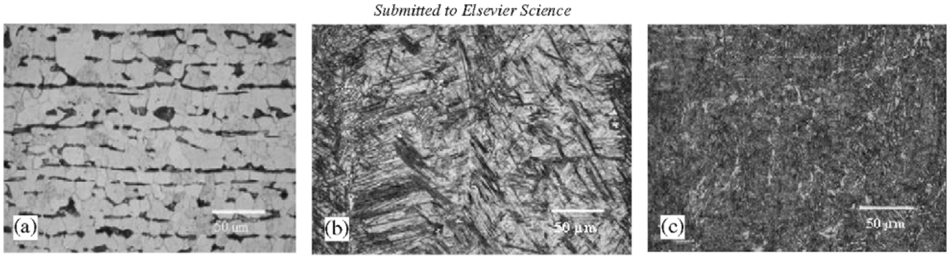

Fig. 1. Optical micrographs through welded section: (a) parent metal (ferrite and pearlite), (b) weld metal (martensite & bainite), and (c) HAZ (predominantly bainite).

2. Experimental procedure

2.1. Material properties and welding procedure

The parent material used in this study was a low-carbon steel [12]. The dimensions of the plates were $200 \times 100 \times 12\,\text{mm}^3$. The typical microstructures of the parent material, weld metal and HAZ are shown in Fig. 1. The welds were produced by the FCAW process. The welding procedure and materials properties are described in more detail elsewhere [13,14].

2.2. Manufacture of "stress-free" reference samples

To establish the "stress-free" lattice parameter, d_0, two samples (a) a cube (Fig. 2a) and (b) a comb (Fig. 2b) were produced using electro-discharge machining (EDM) with a wire diameter of 0.2 mm. Sample (a) was assembled from eight small ($2 \times 2 \times 2\,\text{mm}^3$) cuboids which had been cut from the parent metal. Sample (b), the comb, was made from a transverse section cut from a long weldment in order to establish the difference between the parent metal, HAZ and weld metal. Assuming a symmetric weld, one-half only of the specimen was wire-cut to form two rows of sixteen $2 \times 2\,\text{mm}^2$ teeth.

3. Residual strain determination

3.1. Neutron diffraction

ND measurements were done on The Australian Strain Scanner (TASS) at ANSTO, Australia. The same measurement parameters were used for both specimens. The neutron wavelength used was 1.40 Å. Measurements were made using the α-Fe (1 1 2) reflection, at the detector angle, 2θ, of approximately 73.5°.

Counting times were determined by the accuracy required for the measurements. Counts were collected until the peak was clearly defined. For each data point for d_0 parameter measurements this required count times of approximately 60 min using $1.5 \times 1.5 \times 2\,\text{mm}^3$ slits. For sample (a) the gauge volume was positioned in the centre of the set of cubes. For the comb one set of measurements was made along the transverse line (Fig. 2b) from $x = 0$ (centre of the weld) to $x = 32\,\text{mm}$. The centre of the gauge volume was positioned 1.5 mm below the top surface and in the centre of the "tooth". A second set of comb measurements was done along the weld centreline down through the plate thickness (Fig. 2b) from $z = -1.5\,\text{mm}$ (in the weld) to $z = 4.5\,\text{mm}$ (parent metal below the weld) in four steps of 1.5 mm.

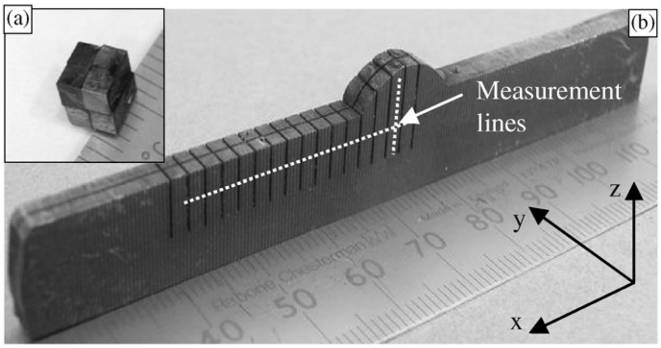

Fig. 2. The specimens (a) set of cuboids and (b) comb used to find "stress free" parameter d_0.

3.2. Synchrotron X-ray diffraction

SD was used to measure the transverse and normal directions in the comb reference specimen. The experiments were carried out on beam line ID15A at the European Synchrotron Research Facility (ESRF), in Grenoble, France. The energy dispersive method [15] was used with an energy range of approximately 50–180 keV. This method is useful for fast strain mapping and in the experimental set-up two detectors, vertical and horizontal, were used to measure strains in transverse x and normal z directions simultaneously. The high energy (small wavelength) of the incident beam drives the diffraction peak to a very low angle. Measurements were made using the α-Fe (1 1 2) reflection, at a fixed detector angle, 2θ, of approximately 5.2°. The incident beam was set in the y-direction. The small diffraction angle results in elongation in a gauge volume along the y-direction (Fig. 2). The incident beam slits were set at $50 \times 50\,\mu\text{m}^2$ and centred at a depth of 1.5 mm from the plate surface, in the middle of the teeth.

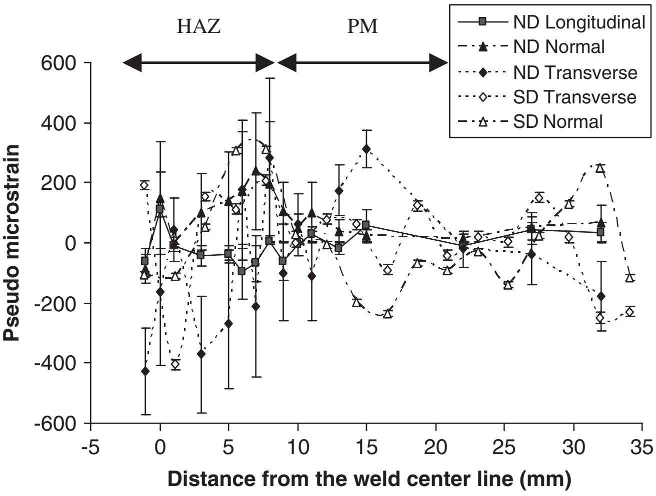

Fig. 3. Pseudo-strain measured by ND and SD across the weld.

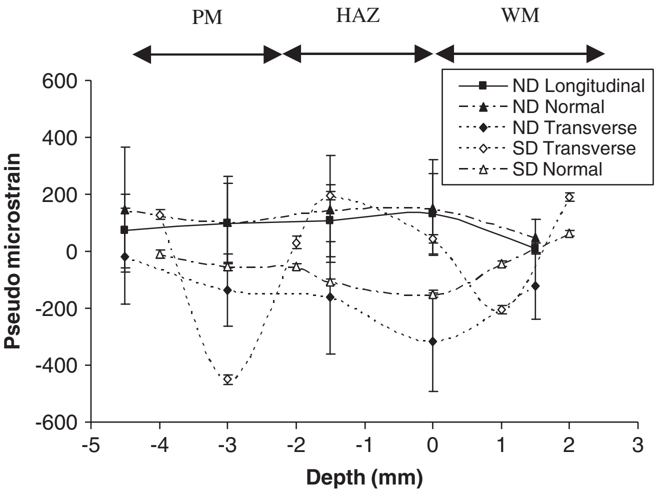

Fig. 4. Pseudo-strain measured by ND and SD through the thickness.

4. Results

The comparison of pseudo-strain values for ND and SD across the weld and through the thickness are shown in Figs. 3 and 4, respectively. The pseudo-strain was calculated from the average strain from all ND and SD measurements.

The average stress-free lattice parameters and statistical errors for ND in each microstructural region are given in Table 1. The errors are calculated assuming normal statistics (one divided by the square root of counts in the peak).

5. Discussion and conclusion

Table 1
ND measured stress-free lattice parameters

Specimen	Area of measurements	Local average d_0 (Å)	Statistically calculated error (Å)
Cuboid	Parent metal (PM)	1.18605	0.00007
Comb	Parent metal (PM)	1.18607	0.00007
	Heat affected zone (HAZ)	1.18600	0.00009
	Weld metal (WM)	1.18601	0.00009

Strain profiles are reported using ND and SD for a comb and ND measurements for a set of cubes cut from a welded specimen were tested. The ND and SD data are in agreement in the magnitude of pseudo-strain variation in the normal and transverse directions (Figs. 3 and 4).

Despite the change in microstructure, the results show that the measured lattice spacing of the α-Fe matrix does not change across the comb sample in the HAZ, parent and weld metal. Examining the raw data, there is an effect of intensity and thus on the counting statistics, due to microstructural changes, but an average d_0 can still be used to calculate the residual strain. In ND in the weld and HAZ the decreased intensity resulted in an increase in statistical error of the order of ±200 microstrain. For SD measurements there was a small statistical error (±15 microstrain) but the gauge volume is very sensitive to the position.

The ND measurements of local d_0 (Table 1) show that average differences between the weld metal, HAZ and parent metal are less than 0.0001 Å (±85 microstrain).

The manufacturing process of the comb is expensive and time consuming. This set of results suggests there is no significant effect on d_0 results due to microstructure and texture in the welded area and cubes from the parent metal are satisfactory as a d_0 specimen for ND at least.

Further investigation using various diffraction techniques are envisaged.

Acknowledgements

The authors would like to acknowledge beam line scientists and support for measurements at the Australian Nuclear Science and Technology Organisation (ANSTO), Australia and European Synchrotron Research Facility (ESRF), France. This work was conducted with the assistance of an Australian Research Council grant supported by the Welding Technology Institute of Australia (WTIA). The authors also thank the Australian Institute of Nuclear Science and Engineering (AINSE) for financial assistance (award nos. 04050, 04198 and 05053) to enable measurements on TASS to be conducted. A.P. acknowledges the receipt of an AINSE Postgraduate Research Award.

References

[1] P.J. Withers, H.K. Bhadeshia, Mat. Sci. Tech. 17 (2001) 355.
[2] P.J. Withers, H.K. Bhadeshia, Mat. Sci. Tech. 17 (2001) 366.

[3] J. Jang, D. Son, Y.H. Lee, Y. Choi, D. Kwon, Scrip. Mater. 48 (2003) 743.

[4] M. Duquennoy, M. Ouaftouh, M.L. Qian, F. Jenot, M. Ourak, NDT&E Inter. 34 (2001) 355.

[5] R.A. Owen, R.V. Preston, P.J. Withers, H.R. Shercliff, P.J. Webster, Mater. Sci. Eng. A 346 (2003) 159.

[6] P.J. Withers, M. Preuss, P.J. Webster, D.J. Hughes, A.M. Korsunsky, Mater. Sci. Forum 404–407 (2002) 1.

[7] G.A. Webster, R.C. Wimpory, J. Neutron Res. 9 (2001) 281.

[8] P.J. Webster, N. Ananthaviravakumar, D.J. Hughes, G. Mills, V. Preston, H.R. Shercliff, P.J. Withers, App. Phys. A 74 (2002) 1421.

[9] D.J. Hughes, M.N. James, D.G. Hatting, P.J. Webster, J. Neutron Res. 11 (2003) 289.

[10] D.-Q. Wang, J.R. Santisteban, L. Edwards, Nucl. Instrum. Methods A 460 (2001) 381.

[11] L. Edwards, P.J. Bouchard, M. Dutta, D.Q. Wang, J.R. Santisteban, S. Hiller, M.E. Fitzpatrick, Int. J. Press. Vess. Pip. 82 (2005) 289.

[12] AS/NZS 3678:1996.Grade 250.

[13] A. Paradowska, J.W.H. Price, R. Ibrahim, T. Finlayson, C. Curfs, Proceedings of fourth Australasian Conference on Applied Mechanics (2005) 775.

[14] A. Paradowska, J.W.H. Price, R. Ibrahim, T.R. Finlayson, J. Mater. Process Tech. 164–165 (2005) 1099.

[15] A. Steuwer, J.R. Santisteban, J. Marrow, P.J. Withers, T. Buslaps, J. Appl. Cryst. 37 (2004) 883.