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Procedia Structural Integrity 13 (2018) 517–522

Structural Integrity Procedia

www.elsevier.com/locate/procedia

ECF22 - Loading and Environmental effects on Structural Integrity

Neutron diffraction and neutron imaging residual strain measurements on offshore wind monopole weldments

Anaïs Jacob[a,*], Ali Mehmanparast[a], Joe Kelleher[b], Genoveva Burca[b]

[a]Cranfield University, Bedfordshire MK430AL, UK

[b]Rutherford Appleton Laboratory, ISIS-STFC Facility, Chilton, OX11 0QX, UK

Abstract

Residual stress measurement is of fundamental interest in order to estimate the service life of engineering components and structures subjected to various loading conditions operating in different environments. Destructive and non-destructive techniques are used for the evaluation of residual stresses. Neutron diffraction, as a non-destructive technique, is widely used to measure the elastic strain component of a specific atomic plane from which residual stresses can be calculated. Neutron imaging is an alternative technique which enables residual stresses to be measured through strain mapping of the area of interest. In this study, neutron diffraction measurements were performed in conjunction with neutron imaging to evaluate residual strains in a compact tension, C(T), specimen extracted from a welded plate made of S355 structural steel. Neutron diffraction and imaging are two complementary techniques which have been employed in this work by performing measurements on the Engin-X and newly developed IMAT instruments, respectively, at the Rutherford Appleton Laboratory. Neutron diffraction residual strain measurements in all three directions were conducted within the Heat Affected Zone (HAZ) of the weld area whereas longitudinal residual strains were measured using the neutron imaging technique. A comparison of the neutron diffraction and neutron imaging preliminary results has shown that neutron imaging can provide acceptable measure of residual strains compared to those of obtained from neutron diffraction. The results have been discussed in terms of the possible sources of error encountered in each measurement technique and the accuracy of each technique against the other.

Peer-review under responsibility of the ECF22 organizers.

Keywords: Residual stresses; welded joints; neutron diffraction; neutron imaging.

1. Introduction

Welded joints are widely used in the offshore renewable energy sector to support offshore wind turbines. Indeed the renewable energy sector,, particularly offshore wind, is growing exponentially as the use of efficient sources of clean energy is globally encouraged to meet the greenhouse gas emissions reduction targets and the increasing world energy demand. Offshore wind industry uses monopiles as the most popular foundation type, widely used in shallow water. Offshore wind turbine monopiles are made of thick structural steel plates welded together in longitudinal

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Peer-review under responsibility of the ECF22 organizers.
10.1016/j.prostr.2018.12.085

direction to form "cans" after a cold-rolling and bending process. The full-length monopile is subsequently fabricated after circumferential welding of the individual cans.

Nomenclature

hkl	Miller indices defining the lattice planes
λ	Wavelength of the characteristic rays
d_{hkl}	Lattice interplanar spacing of the crystal
$d_{0,hkl}$	Lattice interplanar spacing of the strain-free sample
θ	Incidence angle
ε_{hkl}	Residual strain corresponding to the hkl plane
C(T)	Compact Tension specimen geometry
TOF	Time of Flight
BM	Base Metal
WM	Weld Metal
HAZ	Heat Affected Zone

During this fabrication process, a significant amount of residual stress is expected to be stored in monopiles. Residual stresses have a substantial influence on the structural integrity and fatigue life of the components, as discussed by Nelson (1982), Lawrence, Burk, and Yung (1982) and Baumgartner (2016). To measure residual stresses, various techniques can be employed which are generally categorised as destructive (such as contour or hole drilling), as discussed by Kandil et al. (2001), and non-destructive (such as X-ray diffraction or neutron diffraction), as presented by Ruud (1982). In order to accurately characterize the service life of offshore wind monopole welded structures, residual stresses should be measured and quantified. The focus of this study is use the neutron diffraction and imaging techniques to measure locked-in residual strains (hence stresses) in compact tension, C(T), specimens extracted from monopole weldments.

2. Specimen design and extraction

The material used in this study is EN-10225:09 S355 G10+M, which is widely used in the fabrication of offshore wind turbine monopiles as explained in the standard from Det Norske Veritas AS (2009). Multi-pass submerged arc welding (SAW) technique was conducted on double V-grooved hot-rolled plates of 90 mm thickness with no post-weld heat treatment (PWHT) in order to replicate real-life conditions of offshore wind monopile structures. In order to visualize the weld region and heat affected zone (HAZ) on the welded plate, polishing and etching using 10% Nital solution, as shown in Fig. 1.

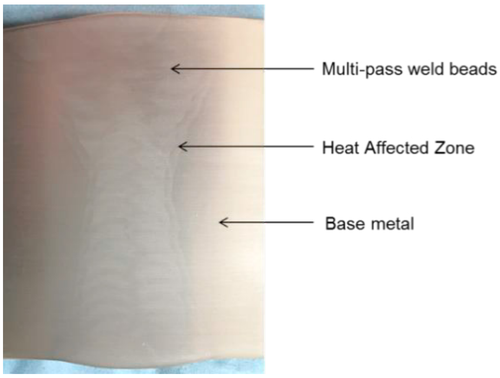

Fig. 1. Cross-weld extracted slice after polishing and etching of the surface

C(T) specimens, that are usually used to characterize the fatigue crack growth behaviour of materials, have been machined from 16 mm thick slices extracted from the welded plate with the notch tip located within the HAZ as shown in Fig. 2.

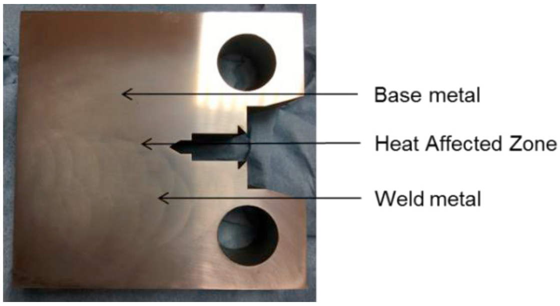

Fig. 2. C(T) specimen extracted from the welded slice

It is also worth noting that a thin 4 mm slice was also extracted in order to draw out small cubes of 3 mm^3 for d_0 measurements along the crack path required for the neutron diffraction data analysis as explained below.

3. Test procedure

In the present study, residual strains (hence stresses) have been measured on one of the extracted C(T) samples using neutron diffraction and neutron imaging techniques on the Engin-X and IMAT instruments, respectively, at the Rutherford Appleton Laboratory. Neutron diffraction measurements provided the residual strains in all three directions while neutron imaging only gives the longitudinal residual strains in the chosen experimental conditions. Note that the measurements have been performed before pre-fatigue cracking in the C(T) specimen.

3.1. Neutron diffraction measurements

At Time-of-Flight (TOF) instruments, such as Engin-X, the neutron speed is measured while the angle of scattering is fixed. When a crystalline material is illuminated by a neutron beam of wavelength λ, the diffractometers measure the atomic interplanar spacing and a diffraction pattern is observed, in which the lattice deformation is measured following the Bragg's law, as presented by IAEA International Atomic Energy Agency (2003) and Pynn (2009):

$$n\lambda = 2d_{hkl} \sin\theta \tag{1}$$

where n is a constant, λ is the wavelength of the characteristic rays, hkl are the miller indices defining the lattice plane, d_{hkl} is the lattice interplanar spacing and θ is the incidence angle.

Residual strains can then be calculated using the following equation:

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} \tag{2}$$

where ε_{hkl} is the residual strain corresponding to the hkl plane, d_{hkl} is the lattice interplanar spacing of the crystal measured and $d_{0,hkl}$ is the lattice interplanar spacing of the strain free specimen.

In neutron diffraction analysis, the error in the strain measurements is also calculated as follow:

$$\varepsilon_{err} = \sqrt{\frac{d_{err}^2}{d^2} + \frac{d_{0,err}^2}{d_0^2}} \tag{3}$$

The test set up for neutron diffraction measurements is presented in Fig. 3. A gauge volume of 2×2×2 mm^3 was used to measure residual strains at the mid-height and mid-thickness of the C(T) sample. A rotation of the sample by 90 has been achieved in order to obtain residual strains in all three directions (i.e. Transverse, Longitudinal and Normal).

Fig. 3. Neutron diffraction experimental set up on Engin-X

3.2. Neutron imaging measurements

In this project, neutron imaging technique wasused to produce radiographies of the samples where images were directly produced by transmitting a neutron beam through a specimen onto a Microchannel Plates (MCP) detector, the principle that is described by Tremsin et al. (2015). In neuron transmission, the experimental set-up is such that the Bragg's angle is equal to 180° as shown in Fig. 4.

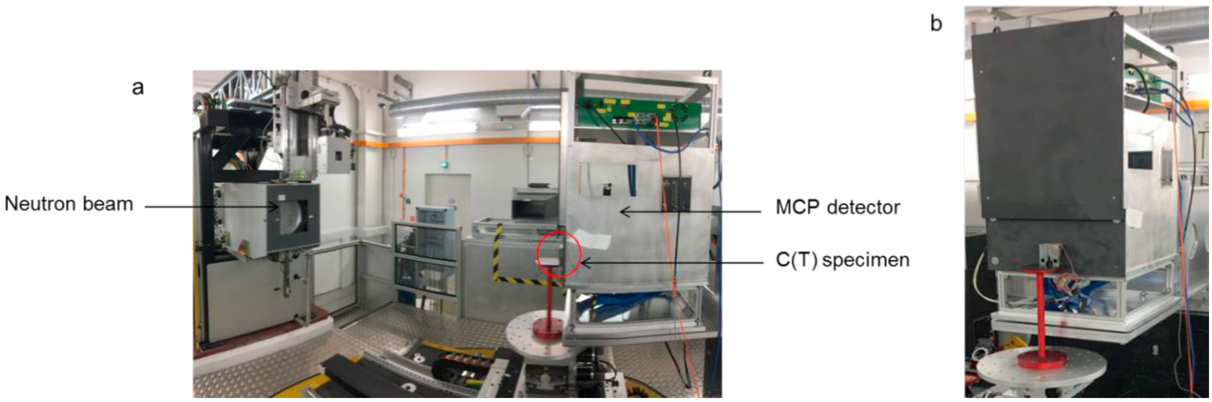

Fig. 4. (a) Neutron imaging experimental set up on IMAT; (b) C(T) specimen in front of the MCP detector

The C(T) sample was tested on IMAT and a sensitivity analysis has been performed with respect to the d_0 values chosen. The following cases have been compared:

- d_0 values taken from neutron diffraction measurements
- A single d_0 value taken as the average of the neutron imaging measurements within the HAZ
- A single d_0 value taken from the strain balance through thickness in longitudinal direction
- A single d_0 value taken from the corner of the sample as described in Fig. 5.

It is also worth noting that the corners taken for the d_0 measurements are not the actual corners of the sample, due to the size of the MCP detector, only a portion of the sample can be imaged

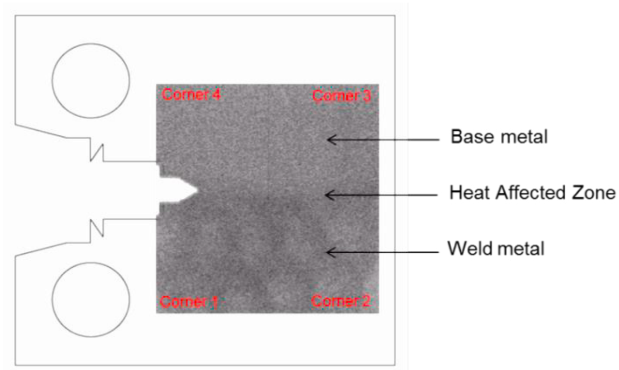

Fig. 5. Neutron radiography of the C(T) sample and the d_0 location with respect to the BM, HAZ and WM

4. Experimental results and discussion

The residual strain measured using neutron diffraction and neutron imaging techniques in through thickness direction are presented and compared in Fig. 6. Indeed, neutron imaging is a volumetric measurement applied on a plane to measure residual strains in a direction normal to the plane orientation, while neutron diffraction provides residual strains along two directions (i.e. strains in all three directions can be generated by rotating the sample) at a specific point. It can be seen in this figure that the neutron imaging residual strain results, generated using different d_0 assumptions, follow the same trend. Moreover, the location of the corner for the d_0 value seems to influence the analysis. Corner 2 may include non-strain free conditions as it is located within the weld while d_0 values taken from corners 3 and 4 provide similar values as they are located within the base metal. Finally seen in this figure is that the residual strain (hence residual stress) trends fall on top of each other when d_0 value is taken as the average of the neutron imaging data in the HAZ region and in the case where d_0 value comes from the strain balance of the same region in through thickness direction. The results obtained from these two cases agree well with those analyses based on d_0 values at corners 1, 3 and 4 and all of these results are in good agreement with neutron diffraction result stress measurements on the C(T) specimens.

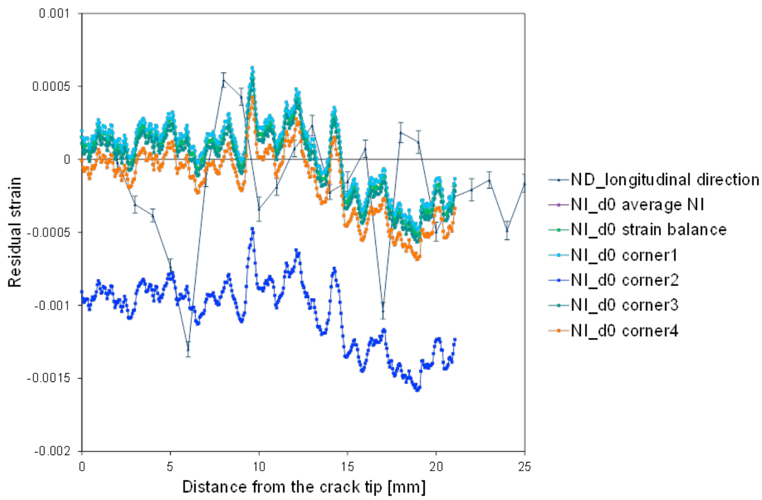

Fig. 6. Residual strains within the HAZ using neutron diffraction and neutron imaging techniques with different d_0

5. Conclusion

This study has shown a comparison of the neutron diffraction and neutron imaging measurements on a C(T) sample extracted from offshore wind monopole weldments. Moreover, a sensitivity analysis has been conducted in neutron imaging data analysis and the results have shown that:

- The location of the corner in the neutron imaging radiography for the single d_0 value influences the residual strain results
- Cases where d_0 value corresponds to the average of the neutron imaging results and d_0 value taken as the strain balance in through thickness direction give similar results which are in good agreement with the residual strain results obtained by employing d_0 values at corners 1, 3 and 4, and also the results obtained from neutron diffraction measurements

Acknowledgements

This work was supported by grant EP/L016303/1 for Cranfield University and the University of Oxford, Centre for Doctoral Training in Renewable Energy Marine Structures - REMS (http://www.rems-cdt.ac.uk/) from the UK Engineering and Physical Sciences Research Council (EPSRC). Furthermore, the financial support through ISIS facility development studentship is greatly acknowledged.

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