Institution: The Open University

Unit of Assessment: B13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: Neutron diffraction strain measurement for industry

1. Summary of the impact

Our research has enhanced neutron diffraction instruments worldwide for strain measurements on industrial engineering components, moving the technique from a scientific to an engineering tool. We led the £3.5m consortium which designed and built the world's first neutron diffractometer optimised for engineering measurements (ENGIN-X at the UK ISIS neutron source). The Strain Scanning Software (SScanSS) we developed for experiment visualization, simulation and control vastly improved the utility of the instrument to execute engineering residual stress measurements in complex structures and is now adopted at eight facilities worldwide. Numerous multinational companies including General Motors, John Deere, Airbus, Tata Steel and Pacific Rail Engineering have used the methods from our research to support their development programmes.

2. Underpinning research

1993–2004: Edwards (Senior Lecturer / Reader, left the OU 2011) recognised the potential demand for non-destructive measurements of residual stress. He was joint lead (with Withers, Cambridge) on the EU PREMIS programme that constructed the ENGIN diffractometer at ISIS. Edwards then led the consortium that designed and built the £3.5m ENGIN-X instrument, the world's first dedicated engineering neutron diffractometer, at ISIS. The new ENGIN-X instrument achieved a factor of 10 increase in performance over ENGIN, enabling production of residual strain data at a rate that made it a practical engineering tool [3.1].

2001: Edwards (Reader) observed that providing an optimised and dedicated instrument was not in itself sufficient because setting up and controlling a residual stress experiment consumed an unacceptable amount of expensive beam time.

2004–07: James (Research Fellow, appointed to permanent position 2006) developed an experiment planning and automation system (SScanSS) to optimise beam-based research measurements. The SScanSS system adds a virtual model of the sample, derived from CAD or laser scanning data, to a kinematic model of the instrument to create a virtual laboratory. The virtual laboratory is integrated with the instrument and metrology hardware and is used to plan, simulate, optimise and execute residual stress measurements [3.2].

2008–12: James (Research Fellow) introduced processed neutron and X-ray tomography data to provide an alternative source of virtual sample model for the SScanSS system, in addition to CAD or laser scan surface data, so making it possible to place diffraction measurements (routinely and automatically) on hidden internal features of a sample in order to identify material composition or residual stress [3.3, 3.4].

2009–13: In 2007 a number of drivers led to the proposal to build the world's first combined imaging and diffraction instrument, 'IMAT', at ISIS. These drivers included the increased use of imaging as an engineering tool, the continued oversubscription of ENGIN-X, the advent of new energy selective methods and the opportunity to offer the combined image guided diffraction methods described above on one instrument. **James** (Research Fellow) and **Fitzpatrick** (Professor) conducted research underpinning the new £10m instrument currently under construction. Comprehensive simulation of neutron optics and data reduction processes were carried out (OU) to prove the concept and to optimise components. In particular, OU research led to improvements in the signal-to-noise ratio in the instrument image data by redesigning the neutron guide [3.5].

3. References to the research

3.1 **Journal article.** Santisteban, J. R., Daymond, M. R., James, J. A. and Edwards. L. (2006) 'ENGIN-X: a third generation neutron strain scanner', *J. Appl. Cryst.*, vol. 39, pp. 812–825, DOI: 10.1107/S0021889806042245

3.2 **Journal article.** James, J.A. and Edwards, L. (2007) 'Application of robot kinematics methods to the simulation and control of neutron beam line positioning systems', *Nuclear Instruments and Methods in Physics Research A*, vol. 571, no. 3, pp. 709–718, DOI: 10.1016/j.nima.2006.11.033

3.3 **Journal article.** van Langh, R., James, J., Burca, G., Kockelmann, W., Zhang, S.-Y., Lehmann, E., Estermanne, M. and Pappot, A. (2011) 'New insights into alloy compositions: studying Renaissance bronze statuettes by combined neutron imaging and neutron diffraction techniques', *J. Anal. At. Spectrom*, vol. 26, pp. 949–958, DOI: 10.1039/C0JA00243G

3.4 **Journal article.** Pierret, S., Evans, A., Paradowska, A. M., Kaestner, A., James, J., Etter, T. and Van Swygenhoven, H. (2012) 'Combining neutron diffraction and imaging for residual strain measurements in a single crystal turbine blade', *Journal of Non-Destructive Techniques & Evaluation (NDT&E) International*, vol. 45, pp. 39–45, DOI: 10.1016/j.ndteint.2011.08.009 **Listed in REF2.**

3.5 **Journal article**. Burca, G., Kockelmann, W., James, J. A. and Fitzpatrick. M.E. (2013) 'Modelling of an imaging beamline at the ISIS pulsed neutron source', *Journal of Instrumentation*, vol. 8, P10001, DOI: 10.1088/1748-0221/8/10/P10001 **Listed in REF2.**

4. Details of the impact

The Director of the UK's ISIS Neutron Facility has said: '*While the term 'world leading' is over-used … the OU–ISIS technique developments have been leading the world. And within the resulting research outcomes there continue to be numerous examples that have significant technical and financial impact on industry*' [5.1].

The ability for industry to undertake reliable, accurate and speedy non-destructive residual stress measurements has two essential requirements suitable hardware (instrumentation) and effective experimental methods. Open University research has delivered solutions that satisfy both of these requirements.

The OU led the consortium to design and build the £3.5m ENGIN-X instrument [3.1] at ISIS which was the world's first dedicated <u>engineering</u> neutron diffractometer. It was designed to measure large, intact, industrial components so that companies would have directly relevant data for the solution of their problems. Since 2011, the impact of this instrument on industry has increased, with beamtime being <u>awarded directly to UK-based companies</u> through the ICR&D (Industrial Collaborative R&D) scheme for projects demonstrating <u>economic benefit</u>. Companies that have benefited from this scheme include Rolls-Royce, EDF Energy, TWI, the Train Consortium (RSSB, ATOC, Lucchini, Siemens), AREVA, BorgWarner, Tata Steel, and Airbus [5.2].

We continue to advance both hardware and experimental methods for residual stress measurement; for example our recent work on new methodologies and instrumentation for combining imaging and diffraction techniques [3.4]. The Director of ISIS has written: '*This work has made major contributions that underpin both the machine design and the experimental methodology for the £10M IMAT instrument currently under construction at ISIS'* [5.3].

The impact of the OU's SScanSS optimisation and control methodology in terms of improving accuracy, reducing set-up times, enabling otherwise impractical measurements and offering QA to safety critical industrial users, such as the nuclear sector, is attested by its use at (currently) eight international facilities:

2005: The Oak Ridge National Laboratory (ORNL, USA) provides financial support for further development
2007: Installed at ORNL

2010: Modified and installed at the ANSTO (Australian Nuclear Science and Technology Organisation) OPAL research reactor

2011: Modified and installed at the DIAMOND synchrotron source (UK)

2012: Modified and installed at the Spallation Neutron Source (USA)

2012: Modified and installed at the FRM-II research reactor (Germany)

2012: Modified and installed at Chalk River Laboratories research reactor (Canada).

2013: Modified and installed at NECSA research reactor (South Africa).

In summary, '*It has changed the way that residual stress measurements using neutron diffraction are made worldwide*.' [5.1].

For example, the Head of the Bragg Institute, (ANSTO, Australia) writes: '*The SScanSS software and associated methods are routinely used on our strain scanner (KOWARI), where they are an invaluable tool, enabling engineering residual stress measurements on large and complex shape samples from academic and industrial users such as, TWI Ltd., Pacific Rail Engineering Ltd., Hardchrome Ltd, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Defence Science and Technology Organisation (DSTO) and the Institute of Railway Technology*.' [5.4].

By improving the capacity for measuring residual stress at most of the world's major facilities our research has impacted on a large number of industrial development programs. For example, the Group Leader of the Diffraction and Thermophysical Properties Group at Oak Ridge National Laboratory describes how major industrial users such as John Deere and General Motors referred to SScanSS at a recent User meeting at Oak Ridge: '*The use of the data and the accuracy in position were critical for John Deere to achieve major improvement and replace very expensive 'build and test' research programs with validated computer modelling*'; and General Motors attest that '*the use of the metrology equipment and SScanSS software were critical in their study [of hydrogen storage tubes intended for hydrogen storage in vehicle]*'. [5.5].

Further, referring to a multi-year study of the dissimilar metal welds joining the pressure vessel and primary coolant piping in nuclear power plant conducted by the US Electric Power Research Institute (EPRI): '*without this capability [in accuracy of measurement location] that your code provided, the uncertainty in location and hence accuracy in stress would have been at least doubled and hence likely of little value. The neutron residual stress maps were critical to providing confidence limits on the best FEA models that enable EPRI and NRC to then predict the probability of failure at the critical dissimilar metal weld region. These advances will enable the USA nuclear industry to predict the likelihood of surviving any of multiple possible events that potentially could lead to catastrophic failure of an operating nuclear plant*' [5.5].

5. Sources to corroborate the impact

5.1 'Impact of OU research on residual stress measurement techniques and instrumentation', Letter from the Director of the ISIS Neutron Facility, Rutherford Appleton Laboratory, UK, dated 30 July 2013.

5.2 Instrument Beamline Scientist, ENGIN-X, ISIS Facility, Science and Technology Facilities Council.

5.3 'Impact of OU research in support of the new IMAT combined imaging and diffraction instrument at ISIS', Letter from the Director of the ISIS Neutron Facility, Rutherford Appleton Laboratory, UK, dated 30 July 2013.

5.4 'Concerning the use of the SScanSS software at the Australian Nuclear Science and Technology Organisation', Letter from the Head of the Bragg Institute, ANSTO, Australia, dated 16 September 2013.

5.5 'Impact of your program on residual stress measurement', Letter from Group Leader, Diffraction and Thermophysical Properties Group, Oak Ridge National Laboratory, USA, dated 19 August 2013.