Institution: University of Plymouth		
Unit of Assessment: UoA12		
Title of case study: A Transformation in Creep Condition Monitoring for High Temperature, High Pressure Components		
Period when the underpinning research was undertaken: 1/1/2000 - present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Neil James	Professor of Mechanical Engineering (Research)	1996 - present
Period when the claimed impact occurred: August 2013 - present		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Fundamental research, led by Plymouth's Professor Neil James, into process-property-performance relationships in friction welding and associated residual stress underpinned development of a highly portable solid-state coring and repair process platform (WeldCore). The technique has been coupled with through-thickness fracture toughness determination by small punch creep testing to provide a transformation in creep condition monitoring and repair/life extension decisions in power generation and chemical process plant in South Africa.

This step-change derived from certification as a qualified welding process in Supplement 3 of the ASME Boiler and Pressure Vessel Code in 2015. Routine deployment in South Africa was then possible, initially by ESKOM and subsequently by SASOL, in creep condition monitoring and assessment. Impacts include savings of millions of pounds in delayed procurement costs of power generation components by ESKOM, as well as increased power generation availability from lower unplanned outage figures. WeldCore is in use on high temperature process plant operated by Sasol, a South African synthetic fuel and chemical manufacturing company that in 2018 employed 20,945 people, made capital investments in South Africa with a value of circa £1 Billion and provided circa 24% of the liquid fuel needs of South Africa from coal (data from Sasol Integrated Report 2018, 5.10). Their business is therefore centred on chemical process plant and the WeldCore technology has enabled more accurate creep condition monitoring and remnant life assessment of important plant.

2. Underpinning research (indicative maximum 500 words)

Friction stir welding (FSW) is a solid-state process with major advantages in cost and performance, compared with fusion welding. Optimum welding parameters give low residual stresses and defects, with high fatigue strength, although process parameters are generally chosen empirically, which is sub-optimum. Detailed research understanding of process-property-performance relationships is required for development, deployment and certification of any new welding technique in industrial practice.

At Plymouth, process-property-performance relationships for welding, and for FSW techniques in particular, have been a primary research area for James since 1997. In 1998 a long-term and highly productive FSW collaboration was initiated with Hattingh at Nelson Mandela University (NMU) in South Africa [3.1 – 3.6 & 5.8, 5.9 & 5.11], and with industrial partners from the Dutch steel and aluminium firm Hoogovens, subsequently Corus R&D, Rotherham. In 2005, ESKOM, the South African power utility, became actively involved in the work on welding and associated neutron and synchrotron diffraction residual stress experiments led by James.

In collaboration with Hattingh, James' research on interaction between performance and defects, residual stress and process optimisation (Plymouth PhD projects with Lombard and Bradley) [3.1-3.3] enabled a transition from purely empirical selection of FS welding parameters. The FSW and friction taper hydro-pillar processing (FTHPP) research led to a thorough understanding of the influences of tool speed, feed rate and geometry on residual stresses, microstructure and defects, and hence on mechanical and fatigue properties. A significant outcome (jointly supervised PhD at NMU - Blignault) was a unique technique for assessing optimum process parameters via a graphical FSW interface, termed the force footprint diagram [3.4].

In response to an existing industrial need, these research insights led Hattingh to develop an instrumented FSW platform measuring forces, torque and temperature. Further extensive research into the primary parameters influencing weld output properties as a function of tool geometry (2005-2008 – Blignault, Lombard) demonstrated that maximum force on a tool during its rotation (the force footprint apogee) and its angular rotation during welding captured aspects of the plastic deformation in the stir zone which were fundamental to achieving high-performance, defect-free welds. This research showed that fatigue performance and defect population in FS welds could be correlated with frictional power and heat input into the welds (Lombard). For the first time, this allowed prediction of optimised regimes of tool feed and rotational speed in FS welding (Bradley, Lombard) [3.2 & 3.3].

The complementary range of expertise in this 20-year series of projects was fundamental to translation of research from university into industrially-useful computer-controlled platform development [5.1, 5.2, 5.8, 5.9 & 5.11] and the ASME code qualification case [5.3a] that is necessary for routine deployment in condition monitoring [3.6].

3. References to the research (indicative maximum of six references)

3.1 M N James[P], D G Hattingh and G R Bradley[P] (2003), Weld tool travel speed effects on fatigue life of friction stir welds in 5083 aluminium, *International Journal of Fatigue*, 25 pp.1389-1398

3.2 M N James[P], G R Bradley[P], H Lombard[P] and D G Hattingh (2005), The relationship between process mechanisms and crack paths in friction stir welded 5083-H321 and 5383-H321 aluminium alloys, *Fatigue and Fracture of Engineering Materials and Structures*, 28 pp.245-256

3.3 H Lombard[P], D G Hattingh, A Steuwer[P] and M N James[P] (2008), Optimising FSW process parameters to minimise defects and maximise fatigue life in 5083-H321 aluminium alloy, *Engineering Fracture Mechanics* 75 pp.341-354

3.4 D G Hattingh, C Blignault, T I van Niekerk, and M N James[P] (2008), Characterization of the influences of FSW tool geometry on welding forces and weld tensile strength using an instrumented tool, *Journal of Materials Processing Technology* 203 No. 1-3 pp.46-57

3.5 D G Hattingh, D L H Bulbring, A Els-Botes, M N James[P] (2011), Process Parameter Influence on Performance of Friction Taper Stud Welds in AISI 4140 Steel, *Materials and Design* 32 pp.3421-3430

3.6 M N James[P], D G Hattingh, D Asquith, M Newby, P Doubell (2017), Residual stresses in condition monitoring and repair of thermal power plant, *Theoretical and Applied Fracture Mechanics* 92 pp.289-297

3.7

4. Details of the impact (indicative maximum 750 words)

Fundamental research

Plymouth (James) has led work into process-property-performance relationships in friction welding and its associated residual stress states. This work provided the necessary research foundation [5.9] to support development of a condition monitoring process (Weldcore) suitable for integration into a highly portable, automated, friction taper hydro-pillar processing platform and for the submission of an ASME code approval case in 2015. This platform is currently used in thermal power generation (ESKOM) and chemical process (SASOL) plant for creep condition monitoring of thick-walled high-temperature pressure vessel components. Accurate creep condition monitoring is given additional urgency by the fact that much of the electrical generating capacity and other high-temperature plant is now operating well beyond its original design life. Historically, it has been challenging to accurately assess in-depth creep damage, the associated fracture toughness and remnant life in such components, which are critical to meeting the energy, and chemical (e.g. fertiliser) requirements of the modern world.

WeldCore development

The fundamental research directed by James underpinned and supported the design, development and manufacture at NMU of automated friction processing platforms for industry [5.9]. The automated platform cores out an 8 mm diameter sample of the alloy steel, for example on thick-walled steam pipe with diameters of 600 mm to 1050 mm, to a depth of 23 mm and immediately repairs the cored hole by solid-state friction taper hydro-pillar processing (FTHPP). The process is trademarked in South Africa as WeldCore and the eNtsa group at Nelson Mandela University in Port Elizabeth (led by Hattingh) designs and builds the WeldCore platforms used in the creep sampling [5.1, 5.2 & 5.8]. The impact case study submitted in REF 2014 described this development to the prototype stage. The present case study outlines the additional impact since 2014 that has primarily derived from the successful submission of code case approval documentation to ASME for use of the WeldCore technology on high temperature, high pressure plant. The research input provided by Plymouth encompassed the linkages that exist between welding process, microstructure, and residual stress state that control the service performance.

This technology does not require taking the plant out of service nor excising a section of pipe for through-thickness creep damage assessment, which had been the established technique in high-temperature components. The WeldCore process also avoids the necessity for repair by fusion welding, where residual stresses and defects are less controlled than in FTHPP.

ndustrial use and impact

In the South African situation, where the ESKOM power utility (the largest in Africa) generates 44.17 GW with 36.5 GW provided by steam and 1.86 GW being nuclear, aging plant contributes to high levels of unplanned generation losses and consequent electrical load shedding on a rotating basis around the country. Accurate creep condition monitoring is an essential input into both unplanned and planned maintenance, and the WeldCore process supports improvements in planned creep condition monitoring and assists in reducing the number of unplanned power outages for ageing plant. However, to move from a prototype platform (which was the situation in 2014 to routine industrial deployment as an improved condition monitoring tool, requires qualification of the technique as safe to use in the boiler and pressure vessel industry. This needs certification by an international standards authority.

A code case was therefore submitted in 2015 to the American Society for Mechanical Engineers for approval in their International Boiler and Pressure Vessel Code. As was the case for development of the friction hydropillar welding process used in the WeldCore platform, ESKOM was the industrial pull for this, and Plymouth/NMU collaborated on the fundamental process-property-residual stress state research (e.g. synchrotron and neutron diffraction residual stress experiments at the ESRF and ILL with James as the PI). This code case was approved in Supplement 3 Section IX, published in September 2015 (p. xix) [5.3a & b].

Subsequent to the ASME approval, impact has been greatly enhanced through routine application of the technologies in condition monitoring of chemical process plant at SASOL [5.10] as well as expanded use in power generation plant. The transformation in creep condition monitoring described in this case study encompasses automated creep sample extraction by coring, combined with immediate in-situ hole repair, and the subsequent generation of explicit fracture toughness values for creep damaged material at all depths into the alloy, via small punch creep tests on the cored steel. The long-term outcome is more accurate estimation of remnant life for thick-walled, high-temperature industrial components and plant.

South African recognition of innovation and impact

The success and impact of the achievements described in this case study has been widely recognised in South Africa and derives from a combination of research excellence, innovative platform development and a strong industrial pull. For instance, the collaboration between

Plymouth and NMU was chosen as an exemplar of good practices in innovation collaboration between South Africa and Europe [5.8] in the 2015 case studies report produced by the European South African Science and Technology Advancement Programme (ESASTAP). ESASTAP is a collaborative initiative between South Africa and the European Union whose main objective is to strengthen ties within the field of science, technology and innovation and which aims to foster innovation partnerships.

In this context, Hattingh has also received the Gold Medal of the South African Institute of Welding in 2012 for the WeldCore process development [5.6], was a finalist in the 2019/2020 National Science and Technology Forum (NSTF) innovation awards in recognition of an outstanding contribution to science, engineering, technology and innovation, and was recipient of the 2020 Honorary Medal of the Faculty of Natural Science and Technology of the South African Academy for Science and Art.

<u>Commercialisation and extension</u>

The WeldCore process has been commercialised via eNtsa, a South African government research, innovation and engagement hub initiative, whose expertise in FSW technologies is internationally recognised. eNtsa is based at NMU and directed by Hattingh The eNtsa team responsible for WeldCore has grown since 2014 by 12 employees and delivered a total of 15 projects with the technology providing an income of over £1m to eNtsa [5.1 & 5.4 & 5.5], which up to end-2019 had an annual turnover of around the equivalent of £2.5 million, from its complete range of industrial support activities. This growth would not have been possible without the expertise gained from FTHPP research and the associated WeldCore development.

ESKOM has a high current level of unplanned losses of generation capacity and a history of under-investment in maintenance that in 2019-2020 had a very significant impact on South Africa, with rolling domestic power outages commonplace to preserve generating capacity for industrial use [5.2]. The October 2020 ESKOM System Status and Outlook Briefing by the Chief Operations Officer [5.2] stated that “the majority of the coal power stations are operating past the midway of their operational life, resulting in high amounts of breakdowns” and that “the drive to implement the reliability maintenance and refurbishment projects in order to address the unreliability is under way. Part of this drive represents the work done under contract by the eNtsa group which continued on power generation plant during the Covid lockdown in South Africa.

Since 2014, experience gained with ESKOM has enabled the group to extend its work into planned annual condition monitoring of chemical process plant at SASOL [5.11] and to develop a substantial small punch creep testing facility along with associated automated scoop specimen sampling for near-surface creep assessment [5.11]. Small punch data from both the surface and through-thickness cored specimen can be combined with microstructural assessment of creep-induced damage (voids) and linked with finite element analysis to allow the derivation of direct fracture toughness values from the small punch test data. The improved condition monitoring support process therefore encompasses creep sample extraction by coring, combined with automated in-situ hole repair, and obtaining explicit fracture toughness values from small punch creep testing. The outcome is better estimation of remnant life for thick-walled, high temperature industrial components and plant.

Improved plant condition monitoring assists SASOL in keeping its South African synthetic fuel and chemical process plant fully operational and reduces unplanned expenditure on repair and replacement. Much of the plant is aging, and was installed in the absence of detailed fracture mechanics design, which means that accurate assessment of current condition is critical to continued operation, remnant life assessment and replacement planning. Effective control of repair and replacement expenditure benefits South African society, because SASOL impacts on the lives of many South Africans in a variety of ways [e.g 5.8], including direct employment (20,985 people in South Africa), an investment of the equivalent £56M in skills development in South Africa in 2018, a powerful social investment approach, and its embracing of transformation through broad-based black empowerment and the SASOL Foundation. In addition, as its industrial plants supply South Africa with fuels and oils, chemicals and gas, any unplanned plant downtime affects its income and the South African economy.

The importance of this technological development to the power generation and chemicals industries operated by SASOL [5.10] in South Africa arises from the approval by the American Society of Mechanical Engineers (ASME) in September 2015 of a Code Case for the use of the FTHPP for the coring and integrated repair of holes on high temperature and high-pressure plant [5.3]. Certification approval was granted for the technique in Supplement 3 of the 2015 International ASME Boiler and Pressure Vessel Code Section IX p.xix Case 2832 [5.3]. ASME code approval means that the process can be routinely used in condition monitoring, in South Africa and further afield, potentially enabling savings in the billions of Rand [5.4]. Interest in the technology and WeldCore platform has also come from further afield, in the form of visits by personnel from the Electric Power Research Institute in the United States of America and VTT in Finland, along with invitations to give keynote and plenary lectures at international conferences.

Summary

The impact described in this case study is being felt across South Africa through ESKOM, in terms of increased availability of ageing generating capacity and a reduction in unplanned outages, and from the cost benefit contribution to SASOL achieved from more accurate condition monitoring and creep assessment. The skills and training provided through collaboration with Plymouth, and the joint research performed with Hattingh since 1999, and with Newby (ESKOM) since 2005, have enabled a very significant expansion in condition monitoring capability and its impact since 2014 [5.2- 5.7].

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Description of the WeldCore process in application to turbine blade attachment holes, superheater header units and steam pipe creep assessment

5.2 WeldCore Development and Applications in SASOL and ESKOM: Statement from Prof Hattingh on WeldCore Impact History on SASOL and ESKOM

5.3a ASME Code Case for the use of Friction Taper Hydro Pillar (FTHP) Welding

5.3b ASME Certification in BPV Code Supplement 3 of FTHP welding (p.xix)

5.4 New welding technique to save industry billions: Engineering News item on the WeldCore approval for industrial application by ASME 2015

5.5 Welding Coup for NMMU Engineers: Newspaper clipping from the Port Elizabeth Herald 23/9/2015

5.6 Southern African Institute of Welding Gold Medal - Prof Hattingh, 2012

5.7 ESKOM Intelligence Briefing on the use of the WeldCore process on the Hendrina power station rotors

5.8 Good practices in innovation collaboration between South Africa and Europe, Southern African Research and Innovation Management Association ESASTAP Case Studies 2015, Friction Stir Processing/Residual Stresses p.9 – 14

5.9 Letter from NMU Vice-Chancellor outlining the contribution leading to the award of an Honorary Doctorate to James

5.10 SASOL Integrated Report 2018

5.11 Testimonial from Professor Hattingh and the Faculty Dean at NMU on the research role played by James in the development of the WeldCore technology and its ASME accreditation