Institution:
Plymouth University

Unit of Assessment:
UoA15 General Engineering

Title of case study:
An Innovative Friction Welding Platform for Creep Damage Assessment and Repair of Thermal Power Plant Components

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

This case study deals with research undertaken at Plymouth University leading to the development of an innovative friction stir welding process (friction hydro-taper pillar processing, FHPP) and a bespoke welding platform that improves the assessment and repair methodology for creep damaged thermal power station components. This technology, developed in collaboration with Nelson Mandela Metropolitan University and with industry investment, enables power station engineers to extend the life of power generating plant leading to multi-million pound cost savings (over £66M in direct financial savings are demonstrated in this case) plus significant safety and societal impacts. It has been patented in South Africa and a spin-off company has been formed.

Please note that economic impact values were achieved in Rand (R) but are expressed in £ and therefore worth less in £ today than during the period when the stated impact was achieved.

2. Underpinning research (indicative maximum 500 words)

Friction stir welding (FSW) is a solid-state welding process with major advantages in cost and performance, compared with fusion welding. However, process parameters are chosen empirically and no direct measurement of weld process parameters such as force and torque was available on commercial welding platforms until recently. It has therefore been difficult to assess optimum welding parameters in terms of residual stresses, defects and fatigue performance or to make a priori process-property-performance predictions. In order to introduce a new repair technique into the power station industry a detailed research understanding of the process-property-performance relationships is required, and individual weld repair techniques require full certification.

Process-property-performance relationships in FSW have been one of the core research programmes of James (1996-to date Professor of Mechanical Engineering) at Plymouth University over the last 14 years, involving a substantial collaboration with Hattingh at Nelson Mandela Metropolitan University, who led the FSW platform development, and with industrial collaboration and funding from the Dutch steel and aluminium-making firm Hoogovens, subsequently continued through Corus R&D, Rotherham when Hoogovens was acquired by Corus. Latterly, partners from ESKOM, the South African power utility, have been actively involved in the FSW work and in associated neutron diffraction residual stress experiments led by James.

This research, in which Plymouth has made a major contribution to the understanding of defects, process optimisation and residual stress (PhD projects with Lombard and Bradley), has enabled moving away from an empirical approach to choice of FS welding parameters, (James et al. 2003) The research has resulted in 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, which was developed in collaboration with Hattingh over the period 2003-2012 [2-5]. One significant outcome from this work, from a jointly supervised PhD (Blignault), was a unique technique for assessing optimum process parameters via a graphical FSW interface, the force footprint diagram [2] and the development of an instrumented FSW platform measuring forces, torque and temperature. Extensive research into the primary influential parameters on weld output properties as a function of tool geometry (2005-2008 – Blignault, Lombard) further 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 a high performance, defect-free weld (Blignault). 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). This allowed a priori prediction of optimised regimes of tool feed and rotational speed in FS welding (Bradley, Lombard).

The complementary range of expertise contributed by the three partners in this project was fundamental to taking research into platform development for industry. James has driven the fundamental research insights, Hattingh the platform design and development, and Newby/Doubell have provided a direct link into the South African power utility, ESKOM, in the highly important areas of stress analysis and welding (Doubell – Chief Welding Engineer, ESKOM, Newby – Stress Consultant). Support was provided by ESKOM to manufacture the prototype FTPP platform and to make the internal business case for qualifying the machines for power station use.

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

The following publications have all appeared in high quality journals and have been through a peer review process. Plymouth staff are indicated in bold.

1. **James M N**, Hattingh D G and **Bradley G R** (2003), Weld tool travel speed effects on fatigue life of friction stir welds in 5083 aluminium, *International Journal of Fatigue*, **25** pp.1389-1398. *51 citations in Scopus at 31/7/13; journal impact factor in 2012 1.976.*
2. Hattingh D G, van Niekerk T I, Blignault C, Kruger G and **James M N** (2004), Analysis of the FSW force footprint and its relationship with process parameters to optimise weld performance and tool design, Invited Paper (INVITED-2004-01), *IIW Journal Welding in the World*, **48** No. 1-2 pp.50-58. Journal of the International Institute of Welding; non-members papers by invitation only.
3. **Lombard H**, Hattingh D G, **Steuwer A** and **James M N** (2008), Optimising FSW process parameters to minimise defects and maximise fatigue life in 5083-H321 aluminium alloy, *Engineering Fracture Mechanics* **75** pp.341-354. 38 citations in Scopus at 31/7/13; journal impact factor in 2012 1.413.
4. Hattingh D G, Bulbring D L H, Els-Botes A and **James M N** (2011), Process Parameter Influence on Performance of Friction Taper Stud Welds in AISI 4140 Steel, *Materials and Design,* **32,** pp.3421-3430. 4 citations in Scopus at 31/7/13; journal impact factor in 2012 2.913.
5. Blignault C, Hattingh D G and **James M N** (2011), Optimising friction stir welding via statistical design of tool geometry and process parameters, *Journal of Materials Engineering and Performance,* **21**, No. 6, pp.927-935. 5 citations at 31/7/13; journal impact factor in 2012 0.915.
6. Lombard H, Hattingh D G, Steuwer A and **James M N** (2009), Effect of process parameters on the residual stresses in AA5083-H321 friction stir welds, Materials Science and Engineering A, **501** pp.119-124. 23 citations in Scopus at 31/7/13; journal impact factor in 2012 2.108.

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

This case study describes the impact of James' fundamental research into welding and residual stresses which enabled development of fundamental insights into FSW, resultantly to development of the automated Friction Hydro Pillar Processing (FHPP) by James' long-standing collaborator, Hattingh (in conjunction with James), the technology's development and patenting as WeldCore and early industrial application in collaboration with the South African Power Untility, ESKOM. A spin-off company has been formed to further develop the technology and apply across the globe. Savings of more than £66M, in addition to significant process and societal impacts have already been achieved.

This technology has been piloted in providing power station engineers with evidence that secures confidence in life extension of the current power generating plant. It has impacted on business performance by allowing the postponement of major capital expenditure and a multi-million pound cost saving. The underlying research provides the necessary direct link between FHPP welding conditions, the service performance and residual stresses; this enables welding to be performed on safety-critical power plant components using an automated platform. Automated FHPP has been termed Weldcore and provides structural information that was previously unobtainable, which resultantly leads to longer service life of critical structures due to improved monitoring; deferment of capital expenditure; lower risk of catastrophic failure; and increased plant uptime, hence an increased widespread operational profits [Source 5.1].

Weldcore allows cost-effective assessment and repair of creep exhaustion in steam power plant components that would otherwise be difficult or impossible to repair and to certify for continued safe operation. The technology and the impact thereof has only been possible because of a long-standing collaboration between Hattingh and James, instantiated by sabbaticals, shorter professional visits, collaborative research projects and joint publishing, allowing James' fundamental insights to be applied. WeldCore was developed at NMMU and was awarded first prize in the South African National Innovation Competition in August 2010. The process was also awarded the prize for "research leading to innovation by a group" at the South African National Science and Technology Forum awards in May 2011.

The underpinning research carried out by James on welding and residual stresses facilitated focussed development of fundamental insights into FSW and led to a number of collaborative strain scanning experiments with James as PI. Accurate knowledge of weld-induced residual stress distributions and their modification by heat treatment is fundamental to the all-important **certification of new welding processes in the power generation industry**. James has taken a leading role applying neutron and synchrotron diffraction techniques to steam power plant via peer reviewed experiments [5.2]. Making the weld certification case for incorporation of the FHPP into power plant repair would not have been possible without the detailed knowledge of residual stress fields afforded by neutron and synchrotron diffraction experiments [5.3, 5.4]. Equally, the process has to be controlled to deliver specific and reliable outcomes in terms of microstructure, defects and residual stresses, which would not have been possible without the type of in-depth knowledge and understanding of process-property-performance linkages provided by the research.

One example concerns blade attachment holes in the steam turbine rotor discs of Hendrina Power Station in South Africa where original equipment manufacturers (OEM) life calculations led to a replacement recommendation. Turbine component design is complex and historically the industry follows OEM replacement recommendations without testing true life exhaustion of components with complicated geometries.

Testing the WeldCore FHPP platform for creep assessment and repair on Unit 6 at Hendrina Power Station in 2011, showed that the creep life of the high pressure turbine was less than 50% exhausted. This was in contrast to the OEM recommendations to urgently replace the turbines on all ten units after their calculations indicated creep exhaustion levels of >>100% at the unit life (270–300,000h of operation). Unit 6 was returned to service without further outage delay or operation with a reduced output. To meet the OEM's recommendations the alternative would be to remove two stages of blades and run with reduced output until a replacement turbine could be manufactured (2 years) and then enter into a long replacement outage again (an additional 80 days [5.3]). The work on unit 6 demonstrated that the scheduled replacement of the turbines for all ten Units at Hendrina Power Station (with a cost of over £6.5M per unit) could therefore be delayed until the decommissioning date of the Power Station. This condition monitoring and life extension of the discs **saved the power utility some £65M in direct replacement costs and an extended outage period** [5.5]. Aside from the significant cost savings made, the avoidance of any outage is particularly pertinent for ESKOM as whilst *"the international norm for spinning reserve is 15% … Eskom currently has on average 3% ... Any loss of generating capacity increases the risk of load shedding (blackouts)"* [5.3]. The extended outage period avoided has been estimated as at least 8 weeks [5.3]. The work by Plymouth on the performance-processing-weld parameters in FHPP was fundamental to the certification and to the parametric design of the welding platform.

To maximise the impact of the research, James has also provided ESKOM with CPD short courses on failure analysis. During the most recent course in 2011, 33 mechanical and materials engineers from ESKOM's Research, Testing and Development department attended. James delivered this training at below market rates (R40000 paid rather than estimated market value of R132000 [5.3, 5.4]) as part of the technology transfer process. ESKOM clearly regard the training as important stating: *"failure analysis knowledge is critical for engineers operating in our environment"* [5.3]

Since initial use on the turbine blades WeldCore has also been applied to two main steam pipework applications at Lethoabo Power Station and a main steam valve inlet pipe at Kendal Power Station. At Lethoabo, application of the technique (in 2012) proved that the components had to be replaced (total cost = R318m (~£19.8m)) in order to prevent a major safety incident of these safety critical systems. ESKOM views safe operation as extremely important [5.3] and in early 2013 at Kendal, WeldCore proved that the serviceable life of the steam valve inlet pipe could be extended, thus saving ESKOM a further R16m (~£1m) in parts/down time/etc. costs. [5.3]

Now that initial technology transfer and development work has been completed a spin-off company (MantaCor (Pty) Ltd) was registered on 28 March 2011 and has been assigned the rights to conduct commercial activities to develop and market the machines on a commercial scale. As a result of the early commercial work two further commercial projects with a combined value of £100k have been completed outside the scope of that taken on for ESKOM and resultantly, a systems engineer, a process engineer and two technicians are employed in South Africa [5.4. 5.6, 5.7].

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

[5.1] Eskom internal intelligence brief "INTELLIGENCE BRIEF – QUANTIFICATION OF CREEP EXHAUSTION IN TURBINE ROTORS" RTD/MAT/13/172.

[5.2] Experiments: 1-01-8, 1-01-58, 1-01-73, 1-02-83, RB720574, RB910338 (2008-2011) https://club.ill.fr/cv/servlet/ReportFind.

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[5.4] Director of MantaCor/Professor of Mechanical Engineering/Director of eNtsa, Nelson Mandela Metropolitan University, Summerstrand Campus (North), P.O. Box 77000, Port Elizabeth, 6031, Tel: 041 504 3608, Fax: 041 504 9123

[5.5] Technology Strategy and Research Manager (acting), ESKOM, Sustanability Division, Research Testing and Development, Lower Germiston Road Private Bag 40175, Cleveland, 2022 SA.

[5.6] Director: Innovation and Technology Transfer, Summerstrand Campus South, NMMU.

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