Institution: University of Manchester

Unit of Assessment: UoA13a Metallurgy and Materials

Title of case study: Friction Welding for Aeroengine Applications

1. Summary of the impact

Research at the University of Manchester has supported the development of inertia and linear friction welding of high temperature materials for aeroengine application. The research has guided process parameter development and led to deployment of these new welding techniques at Rolls-Royce plc. In particular, inertia friction welding is now used in modern gas turbine engines, such as the Trent 900, which powers the A380, Trent 1000 for the Boeing 787 and Trent XWB for the Airbus A350. In addition, research has enabled blisk technology (welding of blades on disks), which has delivered up to 30% weight saving on critical rotating components.

2. Underpinning research

This research was started by Professor Withers in 1999 with Dr M Preuss working on the project as a PDRA. In 2003, Dr Preuss became a Lecturer at the UoM and continued to lead this research area with support from Prof. Withers.

Drs M Karadge (2005-2009) and M Attallah (2008-2010) also worked as PDRAs on the project.

Dr R Moat became involved in the research activity as an MSc student (2005) and continued to undertake research in the area during his PhD studies (2006-10).

Detailed residual stress and microstructure analysis was carried out between 1999 and 2010 using large-scale research facilities and advanced microscopy to identify the role of welding process parameters and subsequent post-weld heat treatments on the integrity and performance of inertia and linear friction welded aeroengine materials. One of the main challenges was to minimise residual stresses by either identifying optimum welding parameters or applying an appropriate post weld heat treatment that relaxes the stresses sufficiently without compromising the microstructures and properties of the component. The research has progressed through a number of significant advances:

- We showed that residual stresses could be measured reliably, using neutron diffraction [1]. These measurements also highlighted that hole drilling measurements, usually used by Rolls-Royce, do not probe the regions where the most detrimental tensile stresses are observed [1]. Residual stress analysis demonstrated that the proposed post weld heat treatment does not relief the stresses sufficiently and an alternative heat treatment temperature was proposed [1].
- The microstructure analysis demonstrated that the welding process generates a microstructure in the weld region with superior strength than the base material and that the increased post weld heat treatment temperature to relieve residual stresses has minimal impact on the performance of the material [2].
- We also demonstrated the pronounced effect of alloy chemistry on residual stress generation during inertia friction welding of nickel base superalloys [3].
- The work then also expanded in inertia friction welding dissimilar steels for engine shaft applications, highlighting issues related to the ineffectiveness of the proposed post-weld heat treatment procedures [4] and complex microstructure and hardness variations in those

welds [5].

- We expanded into the field of linear friction welding [6], which is a key application for the development of blisks as it enables one to weld blades on disks.

3. References to the research

The research has been published in leading international journals such as Metallurgical and Materials Transactions A and contributed to the award of a number of prizes to the academic staff involved. Professor Philip Withers was awarded the Armourers & Brasiers' Company Prize by the Royal Society in 2010 for his work upon residual stresses and outreach. Professor Michael Preuss was awarded the Grunfield Award and Medal by the Institute of Materials Minerals and Mining, London in 2013, awarded for the engineering application of components made from alloys.

Key publications

1. M. Preuss, J.W.L. Pang, P.J. Withers, G.J. Baxter: Inertia Welding Nickel-based Superalloy. Part II: Residual Stress Characterization, *Metallurgical and Materials Transactions A*, 33A, (2002) 3227-3234. (21 citations, WoS) DOI 10.1007/s11661-002-0308-x
2. M. Preuss, J.W.L. Pang, P.J. Withers, G.J. Baxter: Inertia Welding Nickel-based Superalloy. Part I: Metallurgical Characterization, *Metallurgical and Materials Transactions A*, 33A, (2002) 3215-3225. (31 citations, WoS) DOI 10.1007/s11661-002-0307-y
3. M. Preuss, P.J. Withers, G. Baxter: A comparison of inertia friction welds in three nickel base superalloys, *Materials Science and Engineering*: A, 437, (2006) 38-45. (17 citations, WoS) DOI:10.1016/j.msea.2006.04.058

Additional publications

1. R.J. Moat, D.J. Hughes, A. Steuwer, N. Iqbal, M. Preuss, S.E. Bray and M. Rawson, Residual Stresses in Inertia Friction Welded Dissimilar High Strength Steels, *Metallurgical and Materials Transactions A*, 40A, (2009) 2098-2108. (3 citations, WoS) DOI:10.1007/s11661-009-9915-0
2. R.J. Moat, M. Karadge, M.Preuss, S.E. Bray and M. Rawson: Phase transformations across high strength dissimilar steel inertia friction weld, *Journal of Materials Processing Technology*, 204 (1-3), 2008, 48-58. (9 citations, WoS) DOI:10.1016/j.jmatprotec.2007.10.074
3. M. Karadge, M. Preuss, P.J. Withers, S. Bray: Importance of crystal orientation in linear friction joining of single crystal to polycrystalline nickel-based superalloys, *Materials Science and Engineering*: A, 491, 2008, 446-453.(20 citations, WoS) DOI:10.1016/j.msea.2008.04.064

4. Details of the impact

Context

In order to stay competitive in a world market, aeroengine manufacturers are under constant pressure to develop new engines, which demonstrate dramatically improved fuel efficiency combined with reduced emission. These improvements can only be achieved by optimising high temperature materials or develop new materials with improved temperature capability. With increasing temperature capability, however, the weldability of aero engine materials decreases dramatically making fusion welding completely unsuitable. Consequently, new materials can only be applied once an appropriate joining technique has been developed. A step forward for new disk materials such as powder-processed nickel base superalloys is to transfer from fusion to solid state welding techniques, such as inertia and linear friction welding.

Pathways to Impact

The research carried out in Manchester contributed to developing inertia and linear friction welding parameters in order to join powder processed nickel-base superalloys, high strength dissimilar steels and an advanced Titanium alloy. Detailed microstructure and residual stress analysis provided a new understanding of the welding processes, which in return provided guidance in developing parameters with researchers directly involved in the parameter development by participating in welding trials carried out in the USA. The fundamental research upon inertia welding was funded originally by the EPSRC (1999-2002, £145k). Translation of this research for application by Rolls-Royce in aeroengines has been provided though a number of projects of over the period 2002-2011 with a value £750k, funded from a number of different sources that include the DTI, TSB and Rolls-Royce.

Reach and Significance

Many friction welding combinations that were studied are now employed in modern aeroengines developed by Rolls-Royce. For instance, inertia friction welding of nickel base superalloys has been used in the Trent 900, which powers the A380. The number of friction welds has further increased in the Trent 1000 (entry into service in 2010) for the Boeing 787. The Trent XWB engine (maiden flight in 2013) that powers the A350 Airbus will again see the introduction of additional friction welds where University of Manchester contributed by undertaking detailed microstructural and residual stress analysis. The Trent XWB was custom-designed for the A350, and the A350 with the XWB engines provide a 25% step-change in fuel efficiency compared to its current long-range competitor [A]. More than 1,200 of these engines have so far been ordered [B]. It was announced in April 2013 that the parent company of British Airways, International Airlines Group had placed an order with Rolls-Royce for more than £1 bn for Trent XWB engines to power a fleet of 18 Airbus A350-1000 aircraft, along with an option to buy engines for a further 18 [C].

The implementation of these friction welds allows Rolls-Royce to use new high temperature materials (RR1000), as well as novel material combinations. As a consequence, the engines can operate at a higher temperature than previous engines with material that has about a 50 °C higher temperature capability than previous alloys. The result of this is that Rolls-Royce has been able to develop new engines with improved fuel efficiency. By enabling the operating temperature to be increased, there are also subsequent benefits in terms of NO_x and CO_2 fuel emissions.

In addition, research has enabled blisk technology, which has delivered up to 30% weight saving on critical rotating components. The capability to join materials without the requirement for mechanical joints (such as bolts) has also enabled the development of novel engine architectures. This gives benefits in terms of SFC and has also enabled Rolls-Royce plc to maintain market share as they are able to offer this technology to their customers. All of these aspects are crucial for Rolls-Royce in order to maintain competitive advantage and compete in the global market [D].

5. Sources to corroborate the impact

[A] A350 XWB, downloaded from www.airbus.com, 16/09/2103. Details of the A350 XWB jetliner range showing the reduced operating costs

[B] David Shukman, BBC News Online, Science & Environment, Dated 14 June 2013 News report confirming the number of Trent XWB engines ordered.

[C] Rolls-Royce press release dated 22 April 2013 “Rolls-Royce wins $1.6bnTrent order from IAG”

[D] Letter from Project Manager, Universities at Rolls-Royce, Dated 14 May 2013 confirming the competitive advantage gained by Rolls-Royce from the research.