Institution:
University of Manchester

Unit of Assessment: UOA13a Metallurgy and Materials

Title of case study: Analysis of residual stress in aero engine fan blades

1. Summary of the impact

Wide Chord Fan Blades provide a key competitive advantage for Rolls-Royce's £8.6bn aero-engine business employing 1500 staff. In service, blades experience massive loads and high-frequency vibration, creating the potential for failure. In response to blade-off events on the Trent™ 800 engine, Rolls-Royce (RR) urgently needed a means of inhibiting fatigue crack growth, and selected laser shock peening (LSP). Research in the UoA, elucidating the mechanism and outcomes of LSP, provided critical scientific underpinning for its introduction into the production process for the Trent™ 800 and, subsequently, other engines. Further the UoA now provides manufacturing process QA. Orders for the new Trent™ XWB engine, relying on LSP, exceed £60bn, with partners The Metal Improvement Company establishing dedicated LSP treatment facilities for RR in the UK (with 30 employees) and Singapore.

2. Underpinning research

The underpinning research is based on world-leading knowledge of residual stress and damage in the UoA. Its origin can be traced back to 2000 when the Joint Infrastructure Fund, a scheme to regenerate the research infrastructure of British Universities, was used to establish a £1.8M Unit for Stress and Damage Characterisation. In terms of journal citations it is now the leading centre world-wide for residual stress research. The research has been fundamental to understanding the nature of LSP-induced compressive residual stress, and how LSP may confer benefits over more established shallow peening techniques, especially under the contact fatigue conditions representative of fan blade roots in service. Highlights of the underpinning research include:

- a major (most cited) international review showing the importance of developing reliable methods of measuring residual stress in materials and understanding the importance of controlling residual stresses in materials for engineering applications [1].
- confirmation, using high-energy synchrotron X-ray diffraction, that laser peening introduces stresses deep into fan blades and that these stresses remain even after fretting fatigue representative of in-service loading [2].
- development of the world's first dedicated neutron strain measurement [6] instrument at ISIS (leading to many similar instruments world-wide). It was designed to measure stresses deep beneath the surface of engineering components and has supported engine development with RR including LSP and inertia welding of whole disc assemblies.
- a key review outlining how residual stresses may interact with applied stresses to affect the failure of engineering structures. The most important origins of residual stress are identified, opportunities for removing harmful, or introducing beneficial, residual stresses are recognized, and approaches to their incorporation into lifing laid out [3].
- an investigation into the long-term stability of peening-induced residual stress in aero engine alloys exposed to conditions representative of those in an aeroengine, in terms of mechanical fatigue loads and elevated temperature. The extent of residual stress relaxation in was measured using laboratory X-rays using the $\sin^2\psi$ technique [4].
- a comparative study of four candidate peening surface treatments. Shot peening (SP), laser shock peening (LSP), ultrasonic impact treatment (UIT) and water jet cavitation peening (WJCP), also known as cavitation shotless peening (CSP). Residual stress measurements show that LSP, UIT and WJCP can introduce compressive residual stresses to mm depths compared to hundreds of microns for conventional SP [5].

The key academic leading this activity is Prof Philip Withers, Professor of Materials Science and Director of the BP International Centre for Advanced Materials (BP ICAM); formally Director of the University of Manchester Aerospace Research Institute (UMARI). [Appointed 1998-present].

University of Manchester researchers who made key contributions to this work are listed below:

- Suzanne Clitheroe – PhD student [graduated academic year 2010/2011]
- Alexander Evans – PhD student [graduated academic year 2006/2007] now at Rolls-Royce
- Chris Gill – PhD student [graduated academic year 2008/2009] now at Rolls-Royce
- Andrew King – PhD student [graduated academic year 2004/2005]
- Wei Li – PhD student [graduated academic year 2008/2009] now at Rolls-Royce
- Mark Turski – PDRA [2006 – 2008]
- Philipp Frankel – PDRA [2005-9;Rolls Royce EngD], [2009-12 Rolls-Royce Post-doc], [2013- currently a Research Fellow]
- Michael Preuss – PDRA [1999 – 2003; EPSRC post doc], [2004-20011; lecturer], [2012- Professor of Metallurgy]

3. References to the research

The research has been published in leading international journals and led in part to Prof. Phil Withers being awarded the Royal Society Armourers and Brasiers' Company Prize in 2010 for the use of neutron and hard x-ray beams to map stresses and image defects. Key publications are listed below. Reference 1 (Part 1) has been cited 306 times, is the 4th most cited paper in the history of the Materials Science and Technology journal, and has been in the top 2 of downloaded publications every year since 2003.

Key References Indicating Quality of Research

[1] P. J. Withers, H. K. D. H. Bhadeshia: 'Residual Stress, Part 1 – Measurement techniques; Part 2 – Nature and origins, Mat. Sci & Tech, **2001**, 17, 355-374. (306 citations, WoS). DOI: 10.1179/026708301101509980 & 10.1179/026708301101510087

[2] A. King, A. Steuwer, C. Woodward, and P. J. Withers: 'Effects of fatigue and fretting on residual stresses introduced by laser shock peening', *Mat. Sci. & Eng.*, **2006**, *435-6*, 12-18. (29, WoS) DOI:10.1016/j.msea.2006.07.020

[3] P. J. Withers: 'Residual stress and its role in failure', *Rep. Prog. Phys.,* **2007**, *70*, 2211-2264. (83, WoS) DOI:10.1088/0034-4885/70/12/R04

Other References

[4] A. Evans, S. B. Kim, J. Shackleton, G. Bruno, M. Preuss, and P. J. Withers: 'Relaxation of residual stress in shot peened Udimet 720Li under high temperature isothermal fatigue', *Intl. J. Fatigue*, **2005**, *27*, 1530-1534. (15 citations, WoS) DOI: 10.1016/j.ijfatigue.2005.07.027

[5] M. Turski, S. Clitheroe, A. D. Evans, C. Rodopoulos, D. J. Hughes, and P. J. Withers: 'Engineering the residual stress state and microstructure of stainless steel with mechanical surface treatments', *Appl. Phys. A* **2010**, *99*, 549-556. (11, WoS) DOI: 10.1007/s00339-010-5672-6

[6] P.J. Withers, M.W. Johnson, J.S. Wright. 'Neutron Strain Scanning Using a Radially Collimated Diffracted Beam', *Physica* B, **2000,** 292, 273-285. DOI:10.1016/S0921-4526(00)00481-6

4. Details of the impact

Context

In contemporary high-bypass aero engine designs (such as the Rolls-Royce Trent^{TM} engines) the fan forms the first compression stage and can provide as much as 80% of total thrust. Fan blades are attached to a disc by mechanical 'dovetail' joints; these joints are subject to large centripetal loads and high-frequency vibrations resulting in the root of the blade experiencing a combination of high and low cycle fatigue loading. Failure of a fan blade can be catastrophic to an engine, and can endanger the aircraft if the resulting fragments are uncontained. The initiation and growth of fatigue cracks in aerospace materials can be halted by the introduction of compressive residual stresses. The traditional and most commonly used method is to fire “shot” at the surface. However, the depth of the compressive residual stress is only around 250 µm, and provides poor resistance to fretting fatigue. Following two Trent™ 800 fan blade-off events in the early 2000’s [B], RR decided to explore laser shock peening (LSP) as an alternative treatment, working in partnership with The Metal Improvement Company (MIC). LSP involves the plastic deformation of surface layers through a plasma created by a pulsed high power laser beam. Numerous LSP trials were performed during the early 2000s to optimise the peening process but, prior to our research, the mechanism and outcomes of compressive residual stress generation were determined by RR to be insufficiently well understood for production use.

Pathways to Impact

The research was carried out in close collaboration with Rolls-Royce and MIC, using MIC treated fan blade root samples, thus providing a direct route to implementation. As well as providing the academic basis to underpin engineering practice, the Unit also established a Materials Testing & Analysis (MTA) Lab, able to test manufactured fan blade components on a commercial basis for RR, so as to provide routine documented assurance of the treatment. The MTA Lab is the only XRD Residual Stress Measurement laboratory in the UK to be accredited to ISO 17025:2005, and residual stress measurements are performed to BS EN 15305_2008: Non-destructive testing. Test method for residual stress analysis by X-ray diffraction [A]. Our neutron measurements conform to the TWA20 VAMAS methodology. In addition, Prof Withers has given lectures to MIC staff to explain the LSP process in detail, and at workshops organised by MIC in the UK, Germany and Sweden, to explain the science, potential benefits and possible pitfalls of LSP to over 100 companies in the aerospace, nuclear and automotive sectors.

Reach and Significance

Wide chord fan blade technology is critical to RR’s £8.6bn pa, 1500 employee aero-engine business. Following high-profile adverse incidents with the Trent™ 800 engine, eliminating fan blade-off events, was critical to re-establishing airline and consumer confidence. RR had already identified LSP as a potential means of prolonging the life of fan blades, prior to our collaboration, but the science to support this choice was limited. By quantifying the efficacy of the LSP process in generating deep compressive stresses, and demonstrating their stability in the harsh service environment, the research gave the company the confidence to transition LSP from a laboratory research and development activity, to a reliable and production-qualified technology [C & D]. As a result, RR were able not only to solve the problem with the Trent™ 800 engine, but have since introduced the method more widely across its range of aero-engines – extending LSP treatment to cover Trent™ 500, 800, 1000 and XWB engines in the REF period.

The role of the MTA Lab is critical to the on-going quality assurance of fan blade production, confirming the integrity of the LSP-based manufacturing process on a monthly schedule, assessing the likely performance of newly designed components, and analysing component failures – generating a turnover of around £100,000 pa from RR alone. Its world-class stress measurements performed on blade roots and disk posts ensure the LSP process is applied consistently, and forms an integral part of Rolls-Royce’s QA procedure, contributing to Civil Aviation Authority accreditation of Trent™ aero-engines.

The Trent™ XWB was custom-designed for the A350 Airbus and relies on LSP-treated fan blades. More than 1,200 of these engines, with a total value of over £60 billion, have been ordered so far [E]. For example, it was announced in September 2013 that Lufthansa had selected Rolls-Royce Trent™ XWB engines to power 25 Airbus A350-900 aircraft, an order worth $1.5 billion. The airline also has options for a further 30 of the same aircraft and engines – which would bring the total number to 55 aircraft [F].

MIC are contracted by Rolls-Royce to carry out LSP of fan blades, and have, as a result, established a dedicated facility employing 30 staff at Earby, close to the RR Barnoldswick fan blade production facility. Recently they won a contract to set up a similar facility within RR’s Singapore plant. At full capacity the Singapore site will produce over 6,000 blades per year.

Finally, the impact of this research has been recognised with the award of the 2013 Queen's Anniversary Prize for Higher and Further Education for developing "New Imaging Techniques to Support Advanced Materials and Manufacturing". The work undertaken during the assessment period upon laser peening in support of MIC and Rolls-Royce was featured as a major case study in the application, highlighting the socio-economic impact of the research.

5. Sources to corroborate the impact

[A] United Kingdom Accreditation Service, ISO/IEC 17025:2005. Accreditation re-assessment for the MTA residual stress analysis by X-ray diffraction facility (21/10/2013, UKAS reference number 2709)

[B] Report of the Australian Transport Safety Bureau investigation into failure of a Trent™ 800 engine due to fan blade detachment.

[C] Letter from Regional Sales and Marketing Manger of the Metal Improvement Company LLC, 05/09/2013, confirming the use by the company of the methods developed in the research, and details of the Earby and Singapore facilities

[D] Letter from Project Manager, Universities at Rolls-Royce, 10/10/2013, confirming this Impact Case Study is "an accurate description of the contribution and impact arising from the research undertaken at the University of Manchester."

[E] David Shukman, BBC News Online, Science & Environment, Dated 14 June 2013 report giving details of the numbers of aircraft ordered with Trent™ XWB engines.

[F] Rolls-Royce press release dated 19 September 2013 "Rolls-Royce Trent XWB engines worth $1.5bn to power 25 Lufthansa aircraft".