Institution: University of Portsmouth

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study:
Improved Creep-Fatigue-Oxidation Resistance in Gas Turbine Disc Materials

1. Summary of the impact

Research at Portsmouth has significantly improved the understanding of damage tolerance under creep-fatigue-oxidation conditions experienced in aero-engine components. The understanding has been developed through research on a new-generation disc materials including U720Li and RR1000, which have since been used in Rolls-Royce engines including Trent 900 in Airbus A380, Trent 1000 in Boeing 787 and the latest Trent for Airbus A350 XWB. These new materials have enabled aircraft to operate more efficiently at higher temperatures, with *a major impact on CO_2 emission* and *a significant impact on economy* due to the new market opportunities and the reduction of operating costs.

2. Underpinning research

High-pressure turbine discs in gas turbines are made of nickel-based superalloys. A turbine disc is a fracture critical component where the failure of the disc can lead to the loss of the aircraft. It is also one of the key components that dictates the overall efficiency of an engine cycle. The structural integrity of discs under operational loading conditions, including fatigue, creep and oxidation, is of paramount importance to safety as well as to engine efficiency. The Mechanical Behaviour of Materials (MBM) group at UoP has been working on fatigue crack growth behaviour in nickel-based superalloys for many years, in collaboration with Rolls-Royce (RR) and the Ministry of Defence (now QinetiQ and Dstl). Since 1996, the group (*Tong, Lupton***,** Byrne) has been engaged in collaborative research with RR and other university partners on the development and validation of a new generation of nickel-based superalloys via a powder metallurgy route, including U720Li and RR1000 [1-4]. The role of the Portsmouth group has been distinctive from those of the other university partners in that we have specifically focused on: (i) Novel specialist testing using fracture mechanics concepts that allows well-controlled testing conditions with significantly reduced test durations, which otherwise would not be possible using conventional testing methods; and (ii) constitutive modelling of creep-fatigue and creep-fatigue-oxidation that enables more accurate predictions of crack growth rates at elevated temperature. In particular, we systematically examined the effects of loading waveform and R ratio on crack growth of alloy U720Li [1]; fatigue-creep interaction [2-4]; constitutive modelling under creep-fatigue [3] and proposed a new crack growth criterion [5, *Tong*[1]]. Through these we have developed an essential framework on which crack growth in nickel-based superalloys may be characterised.

This long-standing successful collaborative work led to the invitation of Portsmouth group to a joint bid to TSB, which was subsequently awarded and launched in 2008 as DISPLACE. The Portsmouth work was mainly on the understanding of the effects of in-service loading variables on crack growth rate and predicting crack growth lives for complex engine cycles, utilising both novel experimental testing and advanced numerical modelling. Specifically, we further developed our capacities in constitutive modelling to cover the extended operational temperature range, and utilised the vacuum data from partners to validate our new crack growth criterion [5; *Tong*[1]] for the very first time. We were also able to develop our work into creep-fatigue-oxidation using a crystal-plasticity theory [6; *Lin*[1]; *Karabela*[1]], a new area of research funded by the EPSRC and the TSB. New collaborations have been developed as a result of our crack tip work [5, *Tong*[1, 3]], both in the UK (Universities of Manchester and Sheffield; Rolls-Royce) and abroad (Ecole Polytechnique, France; Huazhong University of Science and Technology, China). These collaborations have also provided a fundamental framework for a recent collaborative research project on oxidation damage and its significance in crack growth, funded by the EPSRC (Zhao & *Tong*, EP/K026844/1, 2013).

Key researchers:

Tong (Senior Research Fellow: 1995-2000; Senior Lecturer: 2000-2003; Reader: 2003-2005; Professor: 2006-present)
Byrne (Professor: 1992-2005; Emeritus Professor 2006-present)
Zhao (Research Associate: 1999-2002; Senior Lecturer: 2005-2012)
Lupton (Research Officer/Fellow: 2001-present)
Karabela (PhD: 2008-2011; University Tutor: 2011-2012; Lecturer: 2013-present)
Lin (Research Associate: 2008-2011; Research Fellow: 2012-present)

3. References to the research

1. J Tong and J Byrne (1999). Effects of frequency on fatigue crack growth at elevated temperature, *Fatigue Fracture Engineering Materials and Structures.* 22, 185-193. DOI: 10.1046/j.1460-2695.1999.00160.x
2. *J Tong, S Dalby, J Byrne, M B Henderson and M C Hardy (2001). Creep, fatigue and oxidation in crack growth in advanced nickel base superalloys, *Int J Fatigue*, 23, 897-902. DOI: 10.1016/S0142-1123 (01) 00049-4
3. *J Tong, Z-L Zhan and B Vermeulen (2004) Modelling of cyclic plasticity and viscoplasticity of a nickel-based alloy using Chaboche constitutive equations. *Int J Fatigue*, 26, 829-837. doi: 10.1016/j.ijfatigue.2004.01.002
4. S Dalby and J Tong, (2005). Crack growth in a new nickel-based superalloy at elevated temperature. Part I: Effects of loading waveform and frequency on crack growth, *J Mater. Sci.,* 40(5), 1217-1228; DOI: 10.1007/s10853-005-6940-2
5. *L. G. Zhao, J. Tong and J. Byrne (2004). The evolution of the stress-strain fields near a fatigue crack tip and plasticity-induced crack closure revisited, Fatigue Fracture Engng. Mater. Struc., 27(1), 19-29. DOI: 10.1111/j.1460-2695.2004.00716.x
6. A Karabela, L-G Zhao, J Tong, N J Simms, J R Nicholls and M C Hardy (2011). Effects of cyclic stress and temperature on oxidation damage for a nickel-based superalloy. *Mater Sci Eng A*, 528(19-10), 6194-6202. DOI: 10.1016/j.msea.2011.04.029.

*Papers that best indicate the quality of the underpinning research

Related external grants:

- Tong: Developing Improved Service Propagation Lives in Arduous Cyclic Environments (DISPLACE), TSB, £300,615. (2008-2011)
- Tong & Byrne: Fatigue Crack Growth in Complex Residual Stress Field due to Surface Treatment and Foreign Object Damage under Simulated Flight Cycles. EPSRC/MOD, £277,947. (2007-2010)
- Zhao: A Micro-Mechanistic Study of Oxygen-Diffusion-Assisted Crack Growth in a Polycrystalline Nickel-based Superalloy. EPSRC 1st grant, £196k. (2007-2011)
- Zhao: Oxidation-Accelerated Fatigue Crack Growth in a Nickel-Based Superalloy. Royal

Society-Leverhulme Trust Senior Research Fellowship, £40k. (2008-2009)

- Tong & Byrne: Effects of Loading Waveform and R Ratio on Crack Growth of RR1000 Alloy. Rolls-Royce plc, £40,000. (2007-2008)
- Tong: Investigation of Creep-Fatigue Interaction in a New Nickel-Based Superalloy. Collaboration with University of Siegen. The Royal Society, £10,400. (2006-2008)
- Tong: Two Stage Fracture Models and Service Life Prediction methods. INTAS (EU), Euro 19,218. (2004-2007)
- Tong & Byrne: A Study of Creep-fatigue Interaction in Superalloys. QinetiQ, £60,000. (2001-2004)
- Tong: Viscoplasticity Modelling of RR1000 Alloy. Royal Society Research Grant, £9,972. (1999-2000)
- Tong & Byrne: Fatigue Integrity of Advanced Nickel Base Superalloys for Gas Turbine Discs. EPSRC, £119,977. (1999-2002)
- Tong & Byrne: Unified Constitutive Models for Creep-Fatigue Interaction in Superalloys. DERA, £59,395. (1999-2001)
- Byrne & Tong: Influence of Load Ratio on FCGR in RR1000 Alloy at Elevated Temperature. Rolls Royce plc, £30,000. (1998-2001)

4. Details of the impact

The research carried out at Portsmouth has impacted on the development and validation of a new generation of nickel-based superalloys via a power metallurgy route, including U720Li and RR1000, which have since been used in Rolls-Royce engines including Trent 500, 900, 1000; BR 700, 710 and 725. The new materials have allowed engines to operate at higher temperatures compared with those using traditional wrought alloys, with significant reduction of CO_2 emission as well as much improved structural integrity of fracture-critical turbine discs.

High-pressure turbine discs in gas turbines are one of the key components that dictate the overall efficiency of an engine. To achieve reduced CO_2 emmission, a higher overall engine efficiency is required by operating the engine with a hotter, more thermodynamically efficient cycle. This requires the use of new materials with better capabilities to resist creep, fatigue and oxidation at higher operational temperatures. New material development requires fundamental research so that their mechanical performance is fully evaluated under simulated service conditions. The MBM lab at Portsmouth is one of the RR-approved centres for new material research and validation work, due to our unique specialist testing facilities developed in-house, which allow well-controlled testing conditions and much-reduced test durations and increased data generation per test piece, which otherwise not possible with conventional methods. For research on fine grain RR1000 and U720Li, work at Portsmouth has provided the *first* set of systematic results on the effects of load ratio and loading waveform on crack growth rates [1] and, identified, *for the first time*, the failure mechanisms in time-independent/dependent regimes [1, 2]. These, together with the concerted efforts of alloy development (Cambridge University) and microstructure characterisation (University of Southampton), have given confidence to RR in *adopting the new materials in their disc production*. For coarse grain RR1000 investigated in the DISPLACE programme, we extended our detailed constitutive model [3] to cover the *entire range of operational and limit temperatures* and developed a *fatigue-creep-oxidation model* [6; *Karabela*[1]] which enabled the prediction of crack growth rate considering the coupling effects of all three factors for the *first* time. Together with the University of Birmingham on the optimisation of material variables to minimise crack growth; Serco on testing under combined thermo-mechanical testing and ZenCrack on developing commercial finite element software for life prediction of crack growth under simulated flight cycles, we successfully delivered the project, with *a direct impact on the RR in-house lifing and materials development programme towards the certification of the material*, which paved the way for its use in the latest RR engines.

RR has confirmed that the new material and lifing technology developed will be used for Trent XWB-1000 engines; and also in new engine projects and up-rated versions of the Trent 900 and 1000 for Airbus A380 and Boeing 787. It has also a retrofit capability into the current high by-pass turbofan engine fleet, thus increasing the potential impact further. These represent a *£1.2 billion per year market opportunity* to the UK aerospace industry. A 1% specific fuel consumption (sfc) saving in these products equates to 350kg less fuel used per engine per trans-Atlantic flight. This reduces the cost of ownership by approximately *£100,000 per engine per year*. The indirect benefits of this include *reduced travel costs* due to reduced fuel consumption; *increased economic competitiveness* of UK airlines in the world market and expansion of *employment opportunities* in associated UK industries. There are *direct economic benefits to end-users* in reduced operating costs, which for the above example are estimated to be *£200,000 per year*. The use of the technology will also provide a *sustainability* benefit through the extended use of components.

It is anticipated that the temperature capability of the engines will be improved by approximately 30ºC as a result of the new material solution from DISPLACE. This equates to a reduction in sfc, which for the designs considered is estimated at 0.3% improvement. For a large twin-engined aircraft flying from London to New York, a 0.3% sfc saving equates to a 700 kg reduction in fuel consumption, which translates into a *reduction of ~ 2.25 tonnes of CO_2 emissions per flight*. RR engines introduced in 2012 onwards offer improved emissions and engine efficiency over current designs as a result of this new material solution, thus a significant step towards the ACARE industry goals for 2050 of a 50% reduction in CO_2 emissions per passenger-kilometre.

5. Sources to corroborate the impact

1. Rolls-Royce: Gas Turbine Technology: http://www.rolls-royce.com/Images/gasturbines_tcm92-4977.pdf
2. Developing Improved Service Propagation Lives in Arduous Cyclic Environments (DISPLACE). TSB Q1525K, TP/8/MAT/6/I/Q1525K: https://connect.innovateuk.org/publicdata/?view=project
3. Letter from Leader of DISPLACE programme, Corporate Specialist (Nickel Alloys), Rolls-Royce plc.
4. MoD monitor for DISPLACE programme, Dstl.
5. Lifting Technologist, Rolls-Royce plc.