Institution: University of Portsmouth

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

Title of case study:
Improved Service Life Management of Safety Critical Aero-Engine Components Subject To Foreign Object Damage

1. Summary of the impact

Research at Portsmouth has had a major impact on risk reduction, improved service life and reduced inspection/maintenance costs of safety critical and expensive fan and compressor components in military and civil aero-engines, as demonstrated particularly by the Liftfan Blisk manufactured by Rolls-Royce.

The research outcomes have also impacted on the specification of design stress levels by Rolls-Royce and MOD for aerofoils susceptible to FOD, enabling damage size inspection limits to be established at higher and more economic levels. The research has also provided increased confidence in the application of weld-repair of FOD and of surface treatment using Laser Shock Peening against FOD.

2. Underpinning research

The Portsmouth group is internationally recognised for the study of fatigue of aero-engine materials and components under complex loading conditions, in collaboration with Rolls-Royce (RR), MOD, QinetiQ and the US Air Force (USAF) over several decades. Rotating aerofoils experience both high cycle fatigue (HCF, from vibrations) and low cycle fatigue (LCF, from large variations of centrifugal and thermal stresses). The Portsmouth team is known as one of the few in the world with expertise in fatigue studies under combined HCF+LCF loading conditions.

It has been recognised in recent years that Foreign Object Damage (FOD) from ingestion of small particles is of major concern for the integrity of aero-engines. The combination of FOD and complex loading conditions experienced during flight could be significant limiting factors for component life [1]. The impact of FOD on fatigue under combined HCF+LCF loading had not been studied until recently. Portsmouth was the *first* group to study the impact of FOD on *early fatigue crack growth under combined HCF+LCF conditions*, as opposed to studies elsewhere on crack initiation due to FOD (Universities of Oxford, Swansea, Manchester, Berkley/Harvard and USAF).The Portsmouth work also included the effects of FOD repair and the benefits of laser shock peening, again focusing on their effects on *fatigue crack growth*. The research was led by Professor Byrne (2002-2005; Emeritus Professor from 2006) and by Professor Tong (from 2006).

The effects of combined HCF+LCF loading on fatigue crack growth from FOD were studied in FOD-indented specimens of Ti-6Al-4V alloy, for both as-FODed and after stress relief, using simulated flight cycles together with finite element modelling [1-3]. The compressive stresses below the bottom of the FOD indent were found to have a significant retarding effect on the fatigue crack growth (FCG). This led to markedly reduced FCG rates in FODed samples during early fatigue crack growth compared with those annealed after FOD.

A study of fatigue behaviour of weld-repaired FOD-damaged aerofoil specimens was also carried out for RR [4]. The data obtained for the repaired aerofoil specimens were compared with those from the base material and data previously obtained under the EPSRC/MOD project [1-3] for LCF and combined HCF+LCF loading. The results showed that the repaired FOD specimens had superior fatigue resistance to crack onset and crack growth behaviour to those without repair, hence offering improved fatigue lives.

Laser shock peening (LSP) enhances fatigue resistance by generating compressive residual stresses along the leading edge of fan blades, such that the critical region becomes more damage tolerant to FOD. In our second EPSRC/MOD project, in collaboration with QinetiQ, RR and the University of Manchester, we examined the effects of LSP on aerofoil specimens with FOD under discrete and combined HCF+LCF loading conditions. This comprehensive study [5, 6] has produced conclusive evidence on the beneficial effects of LSP on early FCG. Furthermore, a rational treatment of fatigue crack growth in a complex residual stress field has been proposed [6, *Lupton*[4]], where both compressive residual stresses due to LSP and FOD and their influence on crack flank closure were considered for the *first* time.

3. References to the research

1. J Ding, R F Hall, J Byrne, J Tong (2007). Fatigue crack growth from foreign object damage under combined low and high cycle loading. Part I: Experimental studies. *International Journal of Fatigue*, Vol. 29(7), pp.1339-1349. DOI: 10.1016/j.ijfatigue.2006.10.020
2. *J Ding, R F Hall, J Byrne, J Tong (2007). Fatigue crack growth from foreign object damage under combined low and high cycle loading conditions. Part II: A two-parameter predictive approach. *International Journal of Fatigue*, Vol. 29(7), pp.1350-1358. DOI: http://dx.doi.org/10.1016/j.ijfatigue.2006.10.014
3. R Hall, J Byrne, J Tong (2008). Influence of foreign object damage on fatigue crack growth of gas turbine aerofoils under complex loading conditions. *Fracture Fatigue Engng Mater Struct*, 31(5), 386-397. DOI: 10.1111/j.1460-2695.2008.01238.x
4. J Byrne, R F Hall and C Lupton (2007). Fatigue behaviour of repaired Ti-6Al-4V specimens, Final Report, Rolls-Royce O/No 5000324728, Mechanical Behaviour of Materials Laboratory, Department of Mechanical and Design Engineering, University of Portsmouth. *Available on request*.
5. *S Spanrad, J Tong (2011). Characterization of foreign object damage (FOD) and early fatigue crack growth in laser shock peened Ti-6AL-4V aerofoil specimens. *Mater Sci Eng A.,* Vol. 528(4-5), pp.2128-2136. DOI: 10.1016/j.proeng.2010.03.188
6. *B. Lin, C. Lupton, S. Spanrad, J Schofield, J. Tong (2013). Fatigue crack growth in laser-shock-peened Ti-6AL-4V aerofoil specimens due to foreign object damage. *Int J Fatigue*, in press. DOI: 10.1016/j.ijfatigue.2013.10.001

* Papers that best indicate the quality of the underpinning research

Related External Grants:

The case study is based on the outcomes of two major research projects jointly funded by the EPSRC and the MOD:

- J Byrne and J Tong, Influence of foreign object damage on the high cycle fatigue tolerance of gas turbine aerofoils under complex loading, EPSRC, GR/R79258, £257K, 2002-2006;
- J Tong and J Byrne, Fatigue crack growth in complex residual stress fields due to surface treatment and foreign object damage under simulated flight cycles, EPSRC, EP/EO5658X/1, £278K, 2007-2010;

and a research contract with Rolls-Royce plc:

- J Byrne, O/No 5000324728, £30K, 2007.

4. Details of the impact

Our research has had a major impact on risk reduction in safety-critical components in aero-engines and led to increased confidence in predicting and avoiding potentially catastrophic situations in service. The work has been carried out under combined HCF and LCF loading conditions, a simplified but realistic representation of those experienced in service by an engine during typical flight cycles.

One of the examples of our research impact is the RR LiftFan Blisk, an integral blade on disc developed for use in the F35B STOVL joint strike fighter (JSF) aircraft for the new UK aircraft carriers. The fan Blisks cost in excess of £250k each. Failure of the Blisk cannot be tolerated under any circumstances, since it would jeopardise the safety of the pilot and risk the destruction of a £35m aircraft. Also unnecessarily frequent inspections will lead to considerable costs. The LiftFan is very highly loaded and susceptible to high cycle fatigue (HCF) so inspection limits of critical parts of the fan need to be set at appropriate levels. The blades of the fan are susceptible to minor impact of FOD from small particle ingress, as all aero gas turbine fans are. The Portsmouth research was targeted at the fatigue integrity of the JSF LifFan. The outcomes of our research have helped to *establish the safe stress level in the presence of a known FOD threat and the inspection limits at a larger damage size and with greater confidence*. As a result, the Blisk provided technical improvement and weight reduction over previous designs, as well as improved airworthiness with *significant economic benefits due to reduced inspections* (the precise values are confidential to MOD and RR). The new knowledge developed is generic and can also be applied to civil aero engines (e.g. RR Trent and BR700 engines) and to legacy RAF engines (e.g. in Typhoon and Tornado aircraft).

All blades are susceptible to some degree of FOD; hence an effective damage management scheme is essential for safety and economy. A high integrity repair process has been under development at RR using a proprietary laser additive technique in order to contain the damage and maintain the structural integrity of the blades. The process is applicable to critical rotating parts, which are key components in the current generation of defence and future civil aero engines, with significant economic benefits. The results of our research have contributed to the validation of the method and increased the confidence in its use towards a lower life cycle cost for critical components such as the Blisk, supporting its economic application.

FOD is estimated by the USAF to cost the international aero-engine industry 4 billion US dollars annually, therefore the development of improved fatigue resistance in the presence of FOD during design and manufacture of components is economically very important. Advanced surface treatments, such as laser shock peening (LSP), have been introduced to provide improved fatigue strength and crack growth resistance. The treatment produces significant compressive residual stresses along the leading edge of aerofoils such as fan blades, so that the critical region becomes considerably more damage tolerant. Typically, LSP can achieve full through section compressive residual stress at the leading edge, therefore improving FOD tolerance where FOD is most expected. A fundamental understanding of the fatigue behaviour of FOD in the presence of LSP is vital, if this treatment is to be utilised to its full potential in enhancing the fatigue resistance of fracture critical components in the event of FOD.

The research carried out at Portsmouth from 2008 has provided some unique insights on the influence of residual stresses due to LSP and FOD on the near-tip stress -strain fields and early crack growth behaviour developed under combined LCF+HCF loading. This is the *first* time such information has become available, also the very *first* time a rational analysis has been developed for early crack growth from FOD in an LSP treated surface under service loading conditions [*Lupton*[4]]. The Portsmouth results have given further confidence in the use of LSP treatment in FOD-susceptible components. *The data and crack models developed at Portsmouth have been used by RR in determining both design stress levels and tolerable FOD damage size* for critical aero engine aerofoil components such as fan and compressor blades. Due to the beneficial effects of the residual stresses from LSP treatment, these limits are now set at higher levels with greater confidence, thus contributing to *safer design and economic life management*.

5. Sources to corroborate the impact

Industrial experts who provided inputs and corroboration of the impact of the research are as follows:

1. Letter from former Capability Leader, Metallic Materials, Platform Sciences Group, Physical Sciences Department, DSTL (MOD).

2. Letter from former Chief of R&T, Transmissions, Structures and Drives, Rolls-Royce plc.

3. Principal Engineer, QinetiQ.

4. Stress & Lifting Engineer, Rotatives Engineering, Rolls-Royce Deutschland Ltd & Co KG, Germany.