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| **Institution:** Swansea University | |
| **Unit of Assessment:** 15 - General Engineering | |
| **Title of case study:** Rolls-Royce Gas Turbine Engines - Materials Characterisation to Underpin Design, Efficiency and Safe Service | |

## 1. Summary of the impact

Research in materials characterisation at Swansea University has produced a deeper understanding of the mechanical behaviour of proprietary engine components, and the potential improvements that can be made. The research has provided a critical technological contribution to the manufacture of efficient and robust gas turbine engines, fundamentally supporting the declaration of safe working lives for critical rotating components, contributing to a significant reduction in specific fuel consumption, and enabling Rolls-Royce to maintain a 40% share of the global civil aviation market. The research has led to the creation of a profitable spin-out company (Swansea Materials Research & Testing Ltd – SMaRT) with an initial annual turnover of £1m.

## 2. Underpinning research

The research underpinning this impact case is based on two core topics: a fundamental understanding of "cold dwell sensitivity" in near-alpha titanium alloys, and advanced lifing (component life estimation) correlations supporting component design and safe operation.

i) **Cold dwell behaviour** was first acknowledged from the in-service failure of RB211 fan discs in the 1970s. Through expertise transferred to Swansea University from the National Gas Turbine Establishment Farnborough (WJ Evans), plus core research undertaken at Swansea (MR Bache), the combination of anisotropic crystal plasticity and stress redistribution was attributed as the pre-requisite for "quasi-cleavage facet formation" and dwell induced failures. A series of seminal academic papers, keynote presentations at international conferences [R1] and high citations [R2] resulted, describing the "Evans-Bache" model.

The application of electron back scattered diffraction for measuring facet inclination on fracture surfaces was pioneered at Swansea [R3] and more recent numerical codes have allowed automated quantitative tilt fractography. Testing in collaboration with Rolls-Royce has provided new insights into the behaviour of titanium crystalline structures, with the result that new titanium alloys have been developed. Every alloy used by Rolls-Royce now goes through the dwell and fatigue assessment developed at Swansea.

ii) Unrivalled testing facilities for the characterisation of constitutive behaviour have underpinned the development of **advanced lifing algorithms** applied to Class "A" safety critical titanium components. Research conducted under EPSRC grant (GR/R80926/01) along with Rolls-Royce private venture funding (£420K, 2006) married fundamental materials knowledge to non-linear, strain based lifing procedures applied to Ti6/4 fan disc material, which was subsequently selected for the F136 engine variant of the Joint Strike Fighter. Similar studies were completed on Ti6246 compressor disc alloy. Such techniques encompassed intimate knowledge of creep-fatigue-environmental interactions gathered from precise, empirical experimentation in the Swansea laboratories.

Fatigue crack initiation and crack propagation were predicted based only on deformation characteristics in the alloy [R4]. Specific expertise in creep has been extended, superseding the former "Theta" creep models developed pre-2000, with the "Wilshire Equations". MT Whittaker and KM Perkins have applied the latter to a range of conventional and intermetallic alloys with great success, acknowledged by keynote presentations and publication in high impact factor journals [R5, R6].

**Context:** Swansea University's expertise in gas turbine materials has attracted international recognition through research publications and seminal texts in the fields of high temperature creep (B Wilshire and RW Evans) plus fatigue and fracture (WJ Evans and MR Bache). This led to the award of the EPSRC Interdisciplinary Research Centre in High Performance Materials (1989) and the Rolls-Royce University Technology Centre (UTC) in Titanium (1995). The establishment of the Swansea UTC enabled long term, strategic activities in the areas of material processing, microstructure evolution, mechanical behaviour and component life estimation, providing a holistic approach to understanding their inter-relationships. More recently this research culminated in the inclusion of the Swansea UTC in the EPSRC Rolls-Royce Strategic Partnership in Structural Metallic Systems for Gas Turbine Applications (EP/H500383/1 and EP/H022309/1 with a total value for research and training of £50m, 2009-2019).

Research in cold dwell behaviour led to the award of the IoM3 Harvey Flower Titanium Prize for “contribution to an improved understanding of titanium metallurgy or alloy development” to WJ Evans in 2007 and MR Bache in 2012.

The researchers involved at Swansea were:
Prof Brian Wilshire OBE FREng, Lecturer through to Emeritus Professor, 1960 to present
Prof Russell Evans, Lecturer through to Professor, 1960 to 2006 (deceased)
Prof John Evans, FREng, Lecturer through to Emeritus Professor, 1985 to present
Prof Martin Bache, Lecturer through to Professor, 1999 to present
Dr Mark Whittaker, Lecturer through to Associate Professor, 2007 to present
Dr Karen Perkins, Lecturer, 2007 to present

## 3. References to the research

References R1-R3 relate to underpinning research in the area of cold dwell sensitivity. References R4-R6 concern advanced lifing (component life estimation) correlations. Citation evidence was obtained from Scopus. R1, R2 and R5 best indicate the quality of the underpinning research.


[R1] M.R. Bache, “A review of dwell sensitive fatigue in titanium alloys: the role of microstructure, texture and operating conditions”, Int. J. Fatigue, 25, pp.1079-1087, 2003. ***54 citations***

[R2] W.J. Evans and M.R. Bache, “Dwell-sensitive fatigue under biaxial loads in the near - alpha titanium alloy IMI685”, Int. J. Fatigue, 16, pp.443 - 452, 1994. ***64 citations***

[R3] M.R. Bache, M. Cope, H.M. Davies, W.J. Evans and G. Harrison, “Dwell sensitive fatigue in a near alpha titanium alloy at ambient temperature”, Int. J. Fatigue, 19, Supp. 1, pp. S83-S88, 1997. ***45 citations***

[R4] PJ Hurley, MT Whittaker, SJ Williams, WJ Evans, “Prediction of fatigue initiation lives in notched Ti 6246 specimens”, International Journal of Fatigue, Volume 30, Issue 4, April 2008, pp 623-634, 10.1016/j.ijfatigue.2007.05.013. ***9 citations***

[R5] B. Wilshire and M.T. Whittaker, “The role of grain boundaries in creep strain accumulation”, Acta Materialia, Volume 57, Issue 14, August 2009, pp 4115-4124, doi:10.1016/j.actamat.2009.05.009 ***8 citations***

[R6] Z. Abdallah, K. Perkins, S. Williams “Advances in the Wilshire extrapolation technique—Full creep curve representation for the aerospace alloy Titanium 834. Mater. Sci. Eng. A, 2012, 550, pp 176–182. **1 *citation***


**Selection of major relevant research grants**

- B. Wilshire and R.W. Evans, IRC in Materials for High Performance Applications, SERC/EPSRC, 1989-99, *£10M*.
- W.J. Evans, High temperature Fatigue/Creep/Environmental Interactions at Notches in Titanium and Nickel Disc Alloys, EPSRC, 2003-06, *£260K*.
- W.J. Evans and M.R. Bache, Advanced Aero-engine Materials - Defence and Aerospace Research Partnerships (DARP), EPSRC/DTI/Rolls-Royce, 2003-07, *£400K*.
- M.R. Bache, Red Top Investigation on Ti 6246 Disc Manufacture and Properties, Rolls-Royce, 2005-06, *£75K*.
- W.J. Evans and M.R. Bache, Materials for Arduous Cycle and Emissions (MACE), DTI/Rolls-Royce, 2005-08, *£465K*.

- W.J. Evans, Characterisation of Titanium 6-4 alloy, Rolls-Royce, 2006-10, *£420K.*
- M.R. Bache, Processing of an Advanced Nickel Alloy for Critical Engine Applications (PANACEA), DTI/Rolls-Royce, 2007-09, *£230K*.
- M.R. Bache, Effective Structural Unit Size in Polycrystals: Formation, Quantification and Micromechanical Behaviour, EPSRC, 2007-10, *£350K*.
- M.R. Bache, Structural Integrity of Components With Deep Compressive Residual Stresses, EPSRC, 2007-10, *£225K*.
- M.R. Bache, Fatigue crack growth in combustor alloys, Rolls-Royce, 2009-11, *£105K*.
- M.R. Bache, SAMULET Multi-axial Deformation of Single Crystals, TSB/Rolls-Royce, 2009-11, *£290K*.
- M.R. Bache, M.T. Whittaker and K.M. Perkins, EPSRC Rolls-Royce Strategic Partnership in Structural Metallic Systems for Gas Turbine Applications, EPSRC, 2009-19, *£17M*.
- M.R. Bache and M.T. Whittaker, SILOET WP4 High Temperature Materials, TSB/Rolls-Royce, 2010-13, *£260K*.
- M.R. Bache and K.M. Perkins, SILOET WP7 Repair Technologies, TSB/Rolls-Royce, 2010-13, £*410K*.
- M.R. Bache and K.M. Perkins, Corrosion Lifing Methods and Testing (CLIMATE), TSB/Rolls-Royce, 2010-13, *£425K*.
- M.R. Bache, K.M. Perkins and M.T. Whittaker, SILOET II WP6, High Temperature Capability – Compressors and Discs, TSB/Rolls-Royce, 2013-15, *£1.3M*.

## 4. Details of the impact

Swansea's research in cold dwell sensitivity and advanced lifing has delivered significant commercial and economic impact, with improved understanding of mechanical behaviour, deformation and failure mechanisms that has defined safe operational envelopes for various titanium and nickel alloys utilised in fan, compressor and turbine applications in the current generation of Rolls-Royce Trent engines. More than five hundred Trent 800 engines are currently in service [C1].

Rolls-Royce supplies approximately 40% of new aero-engines to the global market, acting as one of three major international manufacturers of civil aero-engines with an order book exceeding £60,000m; Swansea's contribution to the mechanical characterisation of metallic alloys and ceramics therefore provides significant and tangible impact. Knowledge generated through long standing collaboration between industry and academia has been transferred to Rolls-Royce and key supply chain companies (Timet in particular, the largest producer of titanium in Europe). Research has made critical technological contributions to the manufacture of efficient and safe gas turbines, with impact evident in the following ways:

**Titanium alloy selection and fan disc design in Rolls-Royce Trent engines**, informed by models describing crystal plasticity and stress redistribution. The Evans-Bache model describing cold dwell behaviour in titanium alloys has underpinned the exchange of coarse grained alloys (e.g. Ti685, Ti829) as compressor disc materials for alternative alloys (Ti6/4, Ti834, Ti6246) with superior cold dwell resistance.

> "*Component design, full scale rig evaluation and service stressing have been greatly influenced by this research. The impact dates back to the RB211 fleet through to the latest generation Trent XWB series. Swansea investigations into Ti834 for example, used in high pressure compressor discs in the Trent 800 engine with >500 currently in service powering 225 aircraft, remain key to our future implementation of titanium alloys*" Company Fellow - Titanium Alloys / Fan Systems, Rolls-Royce [C1].

Provision of **confidential, non-advocate reviews**. Rolls-Royce's high profile 'Red-Top' investigations are used to assess issues relating to the processing and safe operation of engine components. Within the REF period, Evans and Bache have provided scrutiny for topics including fan blade manufacture, stress concentration features in compressor discs and interpretation of fatigue crack initiation and growth in titanium metal matrix composite under spin rig assessment.

Innovative fractography has been employed to investigate manufacturing and service issues and understand fundamental material response.

> "*Knowledge transferred from the Swansea UTC academics into our industry is a key independent resource, which can actually prevent major fleet disruptions*" Head of Materials, Rolls-Royce [C2].

Swansea provides major contributions towards more efficient, environmentally friendly engines by characterising mechanical behaviour at ever increasing temperatures. The combined portfolio of research has delivered **a reduction of 1% in specific fuel consumption**, representing significant environmental and economic impact. By elevating the operating temperature through all stages of the engine, the volumes of sulphur / nitrogen based emissions have been progressively reduced, meeting objectives set by International government agencies. This places significant demands on existing alloys, expected to operate beyond their original design limits. Specifically, **mechanical data and lifing correlations were incorporated into proprietary computer models at Rolls-Royce** in 2008, allowing the alloy Ti6246 to continue under safe operation some 50$^{o}$C above pre-envisaged limits. This required detailed understanding of high temperature damage mechanisms. This alloy is used across the Trent range (>3000 engines in service). Similarly, advanced lifing correlations were applied to the Ti6-4 lift-fan in the F136 Joint Strike Fighter, allowing development on this engine through to 2011.

> "*Swansea based correlations have been transferred to several engine marks and alloys, allowing extended operation of in service alloys through reducing conservative safety margins*" Associate Fellow, Critical Parts Lifing and Integrity, Rolls-Royce [C3].

Similar research has been directed towards nickel superalloys, with the same proprietary codes used to design future engine variants (Trent 1000, XWB etc). Detailed understanding of the role of microstructure on fatigue has allowed rationalisation amongst modelling procedures, with multiple codes previously deemed necessary to describe different forms of the same alloy.

The Swansea UTC is a core member to the EPSRC Rolls-Royce Strategic Partnership in Structural Metallic Systems for Gas Turbines (2009), incorporating postdoctoral research and doctoral training to develop high calibre materials engineers for the UK metals community over a ten year horizon. Value to the UK public sector and overall success of this scheme is constantly reviewed by EPSRC, with Swansea knowledge transfer activities singled out for a RCUK online impact case study "Excellence With Impact" [C4]. The rolling value of the research in progress under the combined UTC research portfolio currently stands >£7.8m.

Economic impact has also been achieved through the **creation of a profitable spin-out company.** Swansea University has combined extensive consultancy activities with a major transfer of equipment from the former Rolls-Royce laboratories at Derby (replacement value >£5m). A spin-out company – Swansea Materials Research & Testing Ltd (SMaRT) has been incorporated [C5]. Rolls-Royce places significant onus on this operation, "SMaRT acts *as a vital, strategic, approved supplier for mechanical property understanding at technology readiness levels (TRL) zero to four*" (C2). This outsourcing strategy includes close collaboration with the Rolls-Royce Mechanical Test and Operations Centre in Germany (MTOC). SMaRT delivers commercial testing and academic interpretation for an expanding customer base, and is integral to the development of the University's new, £250m Science and Innovation Campus, which in turn addresses Welsh Government strategies for regional development in South-West Wales. SMaRT has recently achieved ISO 17025 accreditation, employs nine full-time staff, turning over approximately £1M per annum, with operating profits of £146k posted in 2011-12 [C5].

## 5. Sources to corroborate the impact

[C1] Materials Division / Fans & Compressors Supply Chain Unit, Rolls-Royce plc

[C2] Materials Division, Rolls-Royce plc

[C3] Rotatives Supply Chain Unit, Rolls-Royce plc

[C4] http://www.rcuk.ac.uk/media/brief/impactcase/business/Pages/Bache.aspx

[C5] SMaRT Incorporation Certificate and Management Accounts, Company's House, 2009.