Institution: Swansea University		
Unit of Assessment: 12 - Engineering		
Title of case study: Gas turbine engines – structural materials solutions supporting a reduced carbon future.		
Period when the underpinning research was undertaken: 2003 - 2017		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Mark Whittaker	Professor	1999-present
Martin Bache	ISM Director/Professor	1986-present
Karen Perkins	Associate Professor	2003-present
Robert Lancaster	Associate Professor	2007-present
Helen Davies	Associate Professor	2011-present
Spencer Jeffs	Senior Lecturer	2013-present
John Evans	Former Head of Research Group	1986-2008
Brian Wilshire	Former Head of Materials	1960-2015
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Ongoing research in structural materials characterisation at Swansea University has enhanced the understanding of the mechanical behaviour of proprietary gas turbine engine components. Internationally recognised expertise has allowed for progression of new materials towards service and extended safe operation of in-service components. Swansea research has attracted GBP4,600,000 of direct investment from Rolls-Royce and has delivered critical technological solutions towards the manufacture of efficient and robust engines. Significant savings exceeding GBP3,500,000,000 has been achieved by Rolls-Royce through reduction of component costs and safe life extension of critical rotating components. Research performed by our team at Swansea University, as part of a larger collaborative effort, contributed to a 1% reduction in specific fuel consumption of Rolls-Royce engines, leading to significant reduction in aerospace CO_2 emissions and enabling Rolls-Royce to maintain a minimum 50% share in the global civil aviation market.

2. Underpinning research

Reduction of carbon emissions from gas turbine engines is mainly achieved through reduction in weight or increases in operating temperature that increase thermal efficiency. Development of materials for these arduous operating conditions can only be validated through mechanical characterisation which allows for the declaration of safe operating lives of components. Swansea University is a University Technology Partner (UTP) within the framework of Rolls-Royce University Technology Centres (UTC) that aims to support the company through a network of leading institutions. Examples of Swansea University's ongoing expertise in this area, which contribute to impact for Rolls-Royce are detailed below.

i) **Titanium alloys**

Swansea University is a leader in the study of "cold dwell sensitivity" in near-α titanium alloys, where extended periods under stress at low temperatures can cause premature fatigue failures. Cold dwell sensitivity was first acknowledged from the in-service failure of Rolls-Royce RB211 fan discs in the 1970s. Research undertaken at Swansea (Prof Bache) determined that 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 **[R1]** and keynote presentations at international conferences resulted.

The application of electron backscattered diffraction for measuring fracture surface crystal orientation and facet inclination was pioneered at Swansea and further developed for industry in 2010. The "Evans-Bache" model which describes quasi-cleavage facet formation, has been applied since 2000 to a range of alloys and has underpinned the exchange of coarse-grained alloys (e.g. Ti685, Ti829) as compressor disc materials for alternatives (Ti6-4, Ti834, Ti6246). As Swansea's University Technology Partnership (UTP) Director, both Prof Bache and Prof Evans have provided independent, confidential scrutiny for titanium technologies including fan blade manufacture, stress concentration features in compressor discs and interpretation of fatigue crack initiation and growth in titanium metal matrix composites.

Research conducted under an EPSRC grant **[G1]** along with private venture (PV) funding **[G2]** married fundamental materials knowledge to non-linear, strain-based life prediction modelling procedures applied to Ti6-4 fan disc material and Ti6246 compressor disc material. Similar PV-funded studies, led by Prof Bache, focused on the Ti6246 compressor disc alloy **[G3]**. Two major collaborative EPSRC projects **[G4, G5]** assessed the processing/texture/property relationship and benefits of laser shock peening, respectively for the titanium alloy Ti6-4. Parallel postgraduate programmes in 2011 characterised the fatigue behaviour of novel titanium alloys (Ti-639, Ti575) for civil engine fan systems **[R2]**.

ii) **Component design and safety**

Unrivalled testing facilities, in terms of scale and capability, to characterise constitutive behaviour and damage tolerance have underpinned advanced algorithms used to declare safe operational lives for Class "A" safety critical components. Such life prediction techniques encompassed intimate knowledge of creep-fatigue-environmental interactions.

Longstanding expertise in creep has been extended, superseding the "Theta" creep models with the "Wilshire Equations" after 2005. Prof Whittaker has applied the latter to various titanium, nickel, steel and intermetallic alloys, improving predictive capability in each case, specifically through extrapolation of limited data sets to extended conditions **[R3]**. As core partners in the EPSRC Strategic Partnership in Structural Metals for Gas Turbine Applications **[G6]**, Prof Whittaker, Dr Lancaster and Prof Bache extended modelling of creep behaviour to include thermo-mechanical fatigue regimes and high-temperature dwell crack growth **[R4]**, also incorporating novel work on thermo-mechanical fatigue crack growth **[R5]**. Additionally, a suite of unique experimental facilities for the characterisation of hot corrosion informed compressor and turbine disc life prediction methodologies after in-service sulphidation pitting (Dr Perkins). Parallel research (between 2005 and 2020) into a range of service critical issues was funded by Department of Trade and Industry (DTI)/Technology Strategy Board (TSB)/Innovate UK (IUK)/Aerospace Technology Institute (ATI) contracts exceeding GBP6,000,000 in value. Much of this research was directed towards nickel superalloys, especially RR1000 **[R5]**, feeding proprietary codes used to design recent engine variants, such as Rolls-Royce's Trent 1000/XWB.

iii) **Novel materials**

Early creep and fatigue research (Prof Bache) into ceramic matrix composites (CMCs), encompassing silicon nitride, silicon carbide and alumina-based systems, has been conducted with the aim to develop commercially viable CMC aero-engine components. Notable projects include a study to establish a UK processing capability for oxide-oxide CMCs **[G7]**, evaluation of fatigue and thermo-mechanical fatigue of silicon carbide fibre/silicon carbide matrix CMCs **[G8]**. Additionally, influential research on the processing and properties of additive structures (titanium, steel and nickel variants) spawned international expertise in the field of miniaturized test techniques and joining of high-performance materials. More specifically research into solid state welding processes for bladed disk (blisk) applications through has been implemented for titanium-based alloys for compressor disc applications (Dr Jeffs) **[R6]**.

3. References to the research

The outputs below represent five peer-reviewed journal papers all published in either Q1 or Q2 journals and one PhD Thesis. Three have industrial collaboration on the paper (TIMET and Rolls Royce). Four papers were supported by external funding sources including Welsh Government, EPSRC, and Rolls Royce. Eight competitively won grants support the body of work totalling GBP4,658,929. This research has made important contributions to the discipline internationally and contributes important knowledge to the field likely to have a lasting influence.

[R1] Bache, **M.R., & Evans, W.J.** (2003). Dwell sensitive fatigue response of titanium alloys for power plant applications. *Journal of Engineering for Gas Turbines and Power*, 125 (1), 241-245. doi.org/10.1115/2001-GT-0424

[R2] Hewitt, J.S., Davies, P.D., Thomas, M.J., Garratt, P., & **Bache, M.R.** (2014). Titanium alloy developments for aeroengine fan systems. *Materials Science and Technology*, 30 (15), 1919-1924. doi.org/10.1179/1743284714Y.0000000669

[R3] Wilshire, B., & Whittaker, M.T. (2009). The role of grain boundaries in creep strain accumulation. *Acta Materialia*, 57 (14), 4115-4124. doi.org/10.1016/j.actamat.2009.05.009

[R4] Bache, M.R., Jones, J.P., Drew, G.L., Hardy, M.C., & Fox, N. (2009). Environment and time dependent effects on the fatigue response of an advanced nickel based superalloy. *International Journal of Fatigue*, 31 (11–12), 1719–1723. doi.org/10.1016/j.ijfatigue.2009.02.039

[R5] Pretty, C.J., **Whittaker, M.T.,** & Williams, S.J. (2017). Thermo-Mechanical Fatigue Crack Growth of RR1000. *Materials*, 10 (1), 34. doi.org/10.3390/ma10010034

[R6] Jeffs, S. (2014). On cooling properties and microstructure studies of Ti-6Al-4V. PhD Thesis, Swansea University.

Grants

[G1] Evans, W.J. [Principal Investigator]. (1/1/03-31/12/05). High Temperature Fatigue/Creep/Environment Interactions at Notches in Titanium and Nickel Disc Alloys [GR/R80926/01]. EPSRC. GBP362,764.

[G2] Evans, W.J., & Whittaker, M.T [Principal Investigator]. (01/08/05-31/07/09). Characterisation of the Titanium Alloy Ti6-4 [RR PV JSF]. Rolls Royce. GBP420,000.

[G3] Bache, M.R. [Principal Investigator]. (01/12/09-30/11/11). Strategic Affordable Manufacturing in the UK through Leading Environmental Technologies [SAMULET]. Rolls Royce. GBP180,000.

[G4] Bache, M.R. [Principal Investigator]. (01/10/07-30/09/10). Effective Structural Unit Size in Polycrystals: Formation, Quantification and Micromechanical Behaviour [EP/E043917/1]. EPSRC. GBP281,517.

[G5] Bache, M.R. [Principal Investigator]. (01/04/09-30/09/11). Structural Integrity of Components with Deep Compressive Residual Stresses [EP/F028830/1]. EPSRC. GBP230,993.

[G6] Bache, M.R. [Principal Investigator]. (01/10/09- 0/09/14). Structural Metallic Systems for Advanced Gas Turbine Applications [EP/H500383/1]. EPSRC. GBP1,791,426.

[G7] Bache, M.R. [Principal Investigator]. (01/10/08-30/09/12). Advanced ceramic matrix composites for energy generating gas turbine applications [TS/G000484/1]. EPSRC. GBP254,217.

[G8] Bache, M.R., Whittaker, M.T., & Perkins, K.M. [Principal Investigator]. (01/01/14-21/12/16). Strategic Investment in Low Carbon Engine Technology [SILOET 2 WP19 CMCs]. Technology Strategy Board. GBP1,138,012.

4. Details of the impact

As one of three major international manufacturers with an underlying revenue exceeding GBP15,000,000,000 (as of 2018), Rolls-Royce supplies approximately 50% of the global large civil aeroengine market. Over 4,000 Trent engines are currently in service (including the 900/1000/7000/XWB engines) and this number is projected to increase to around 7,500 by 2030. Swansea's research into the mechanical characterisation of metallic alloys and ceramics provided significant and tangible impact, enabling the definition of safe operational envelopes for various titanium and nickel alloys utilised in fan, compressor and turbine applications across the Trent fleet.

Swansea academics contribute to confidential, non-advocate company reviews. 'Red-Top' investigations are used to assess issues relating to the processing and safe operation of engine components. Within the REF period (between 2014 and 2020), as an expert non-advocate reviewer Prof Bache supported a major review between 2016 and 2019 into cold dwell related in-service experience, life prediction models and laboratory validations and scrutinised the implementation of academic understanding of hot corrosion into company protocols. In particular, the review of cold dwell led to a revised processing route for the disc alloy Ti834 in 2014, which had commercial impact through the increased competitiveness of disc components. The work by Bache was also referenced in the 2020 Bureau d'Enquetes et d'Analyses (BEA) Accident Report of an AIRBUS A380-861 (https://www.bea.aero/fileadmin/uploads/tx_elydbrapports/BEA2017-0568.en.pdf) **[C1]**.

Swansea's expertise has led to Rolls-Royce's direct investment between 2014 and 2020 exceeding GBP4,600,000 and involvement as a core member in the second phase of the EPSRC Rolls-Royce Strategic Partnership in Structural Metallic Systems for Gas Turbines (between 2014 and 2019). This programme was set up with the clear aim that, through fundamental research, it would provide the foundation for next-generation aero-engines that, running hotter or faster than current designs, deliver significant improvements in engine efficiency and environmental impact Furthermore, Swansea's research has led to a spin out company, Swansea Materials Research & Testing Ltd (SMaRT), incorporated in 2009 **[C2]**, which greatly increased experimental capacity (approximately three fold in terms of test frames) for the research team at Swansea. This expansion proved to be a major factor in facilitating much of the impact described below.

Through the development of this unique partnership between Swansea University and Rolls-Royce, Swansea's research has been transferred to Rolls-Royce and their key supply chain companies. Critical research undertaken at Swansea has led to technological contributions to the manufacture of efficient and safe gas turbines, which include the following examples:

- Swansea's research into thermo-mechanical fatigue crack growth **[R5]**, contributed to the safe life extension of disc materials. As described by the Project Manager for Universities within Rolls-Royce:

  "*Life extension has allowed for revision of disc service intervals from 3,600 cycles to 4,000 cycles. Over the lifetime of the engine this leads to a reduction in overhauls from 10 to 9 (around £1M in spares and labour costs per overhaul). The number of Trent 900/1000/XWB engines delivered in the REF period (since 2013) exceeds 3,500, therefore providing an approximate £3.5b ongoing cost avoidance over the lifetime of these engines.*" **[C3]**.

- Swansea has also worked closely with Rolls-Royce strategic suppliers on the fundamental understanding of new titanium alloys **[R2]**. The research supports the wider application of titanium alloys for life cycle cost reduction and component optimisation. To quote a Rolls-Royce titanium specialist:

  "*A new alloy has been implemented in 2017 as part of an improved fan system, realising a cost reduction of ~£25k per engine.*" **[C4]**.

- Investigations into solid-state welding processes for bladed disks (blisks) **[R6]** led to a cost avoidance of GBP250,000 per blisk component from 2014 due to refined safety tolerances in assessing weld process data concessions **[C5]**.

It is recognised that the combined University Technology Centre (UTC) portfolio has had significant impact on gas turbine emissions.

"The research conducted directly by Swansea on industrially related programmes combined with the UTC UK portfolio has enabled Rolls-Royce to deliver over 1% reduction in specific fuel consumption (SFC). This 1% reduction has translated into reductions in the millions of tonnes of CO_2 being emitted into the atmosphere." Head of Capability Acquisition – Materials, Rolls Royce **[C6]**.

This represents significant environmental and economic impact given that the aviation sector accounts for 9% of UK energy consumption and Rolls-Royce supplies approximately 50% of the global large civil engine market. Since the ongoing goals of the industry are to improve efficiency and reduce emissions through higher operating temperatures, Swansea's input through all stages of the engine manufacturing process has contributed to the volumes of sulphur- and nitrogen-based emissions being progressively reduced, meeting objectives set by international government agencies (such as ACARE 2020/FLIGHTPATH 2050).

The Trent 7000 model features a decrease of 10% in SFC compared to the Trent 700. However, the increased temperatures required to improve thermal efficiency places significant demands on existing alloys, as they are expected to operate beyond their original design limits. A detailed understanding of the role of microstructure on fatigue has allowed rationalisation amongst modelling procedures allowing for safe life extension through reduction of overly conservative safety factors. Swansea has underpinned novel alloy development (i.e., RR1000) **[R4]** by characterising mechanical behaviour at continually increasing temperatures and subsequently evaluating in-service findings, both of which allow the company to manufacture fuel efficient engines and remain competitive in terms of engine sales, by using this alloy, which is currently employed in over 4,000 in-service Trent engines **[C6]**.

5. Sources to corroborate the impact

Where organisations provide testimonials below, in what capacity they are involved with the impact follows in brackets:

[C1] Letter of Support: Engineering Specialist – Materials Engineering, Rolls-Royce plc, UK (Reporter)
[C2] EPSRC Impact Report, p. 20
https://epsrc.ukri.org/newsevents/pubs/impactreport2016-2017/
[C3] Letter of Support: Project Manager – Universities, Rolls-Royce plc, UK (Reporter)
[C4] Letter of Support: Titanium Specialist – Materials, Rolls-Royce plc, UK (Reporter)
[C5] Letter of Support: Engineering Specialist – Solid State Joining, Rolls-Royce plc, UK (Reporter)
[C6] Letter of Support: Chief of Capability Acquisition – Materials, Rolls-Royce plc, UK (Reporter)