Institution: 10007822

Unit of Assessment: 12

Title of case study: Extended life of industrial gas turbine blades using novel coatings

1. Summary of the impact (indicative maximum 100 words)

This research enables longer component lives for industrial gas turbines and jet engines, and development of new protective coating systems. Siemens and Rolls Royce have improved their selection of materials systems used in components in the hot gas paths e.g. blades, vanes, discs, and seals. Degradation mechanisms in operating turbines, or anticipated in future materials systems, limit the lives of these components and the efficiencies of systems. New functionally graded coatings were created that are highly resistant to hot corrosion and oxidation. Methodology has been adopted in ISO standards BS ISO 26146:2012, BS ISO 14802:2012 and ISO/CD 17224.

2. Underpinning research (indicative maximum 500 words)

Cranfield has investigated environmentally induced degradation (forms of hot corrosion and oxidation) for various materials systems (base alloys and metallic coatings) used in components (e.g., blades, vanes, discs and seals) of industrial gas turbines and jet engines. The drivers have been the need to improve efficiencies, reducing CO_2 emissions and fuel use; to allow the use of new fuel sources; and to improve reliability by maintaining, or improving, component lives whilst using higher operating temperatures and fuels with higher levels of contaminants.

This work has been aimed at improving the understanding of hot corrosion (high and low temperature) and oxidation in these systems [G2, 3, 5; P1-3, 5, 6]. Cranfield has investigated the relationships between the damage observed in different materials systems and the contaminants in the hot gas stream (from different sources and qualities of fuel and air), gas temperatures and pressures, component surface temperatures and deposits formed on surfaces.

We optimised a methodology for assessing hot corrosion damage of materials [G2, 3, 5; P2, 6]. This involves the use of deposit re-coat testing combined with exposure in controlled-atmosphere furnaces. Samples are measured before and after exposure to quantify the distribution of damage in a statistically reliable method. One benefit of this method is it allows the effects of specific aspects of the exposure to be quantitatively linked to the materials damage found [P2, 6]. This enables the sensitivity of materials to changes in exposure conditions to be determined, and compared to the conditions/damage seen in operating systems.

A further investigation explored the ability of alternative metallic coating compositions to resist particular degradation modes [G1, 4; P4]. This covered new developments for Al-Si diffusion coatings and MCrAlY sprayed coatings. In addition, research on protective coatings examined a new class of functionally graded metallic coatings that can resist multiple degradation modes [G4].

A third strand investigated the performance of existing and developmental metallic coatings/alloys in industrial gas turbines, in future power generation systems [G2, 5], [P1, 3, 5]. The need for new materials and changes to more realistic system configurations has been identified. For example, integrated gasification combined cycle (IGCC) systems that use biomass/coal derived syngases (i.e., synthetic fuel gases), or hydrogen enriched syngases (e.g., for EU H2-IGCC project), to fire gas turbines, and gas turbines using oxy-fired natural gas (e.g., natural gas fired zero emission power plant, GAS-ZEP). Assessment of the exposure environments and operating conditions for components in these new power systems have been used as a basis for the experimental work. These activities have guided the development of power system concepts to optimise the balance between gas turbine operating conditions, gas cleaning system requirements, fuel specifications and component lives.

Key researchers	Post details*	Dates involved	Research
Dr A Encinas-Oropesa	Academic fellow	1999 – present	Improved understanding and measurement of hot corrosion of metallic coatings and base alloys
Prof J R Nicholls	Professor	1974 – present	Above topic and new metallic coating systems
Dr S J Mabbutt	Research fellow	2002 – 2008	Performance of current standard metallic coatings and base alloys in new power generation systems
Dr P Kilgallon	Research fellow	2000 – 2009	
Prof J Oakey	Professor	1999 – present	
Dr J Sumner	Academic fellow	2010 – present	All topics above
Dr N J Simms	Reader	1998 – present	

* highest grade in period given

3. References to the research (indicative maximum of six references)

Evidence of quality – peer-reviewed journal papers

P1 A Bradshaw, N J Simms & J R Nicholls, Passage of trace metal contaminants through hot gas paths of gas turbines burning biomass and waste-fuels, *Fuel*, **87** (17-18), pp. 3529-3536 , 2008. doi: 10.1016/j.fuel.2008.06.012

P2 * N J Simms, A Encinas-Oropesa & J R Nicholls, Hot corrosion of coated and uncoated single crystal gas turbine materials, *Materials and Corrosion-Werkstoffe und Korrosion*, **59** (6), pp. 476-483, 2008. doi: 10.1002/maco.200804130

P3 A Encinas-Oropesa, N J Simms, J R Nicholls, G L Drew [a], J Leggett [a] & M C Hardy [a], Evaluation of oxidation related damage caused to a gas turbine disc alloy between 700 and 800 ºC, *Materials at High Temperatures*, **26** (3), pp. 241-249, 2009. doi: 10.3184/096034009X465202

P4 * M Seraffon, N J Simms, J Sumner & J R Nicholls, The development of new bond coat compositions for thermal barrier coating systems operating under industrial gas turbine conditions, *Surface & Coatings Technology*, **206** (7), pp. 1529-1537, 2011. doi: 10.1016/j.surfcoat.2011.06.023.

P5 S J Mabbutt & N J Simms, Investigation of gas turbine material performance in high CO_2 and steam atmospheres, *Anti-Corrosion Methods and Materials*, **57** (4), 192-203 (2010). doi: 10.1108/00035591011058200

P6 * J Sumner, A Encinas-Oropesa, N J Simms & J R Nicholls, Type II Hot Corrosion: Kinetics Studies of CMSX-4, *Oxidation of Metals*, **80** (5-6), pp. 553-563, 2013. doi: 10.1007/s11085-013-9395-x

<u>Key</u>
a Roll Royce plc, Elton Road, Derby, UK

* 3 identified references that best indicate the quality of the research

Further evidence of quality – underpinning research grants

G1 EPSRC/TSB - SAMULET Project 1 - High Efficiency Turbomachinery (EP/G035369/1) – 2009-2013 – £957k – one of a series of university collaborative projects with Rolls Royce – Nicholls, Simms

G2 EPSRC - SUPERGEN 2 - Conventional Power Plant Lifetime Extension Consortium – Phase 2 (EP/F029748/1) – 2008-2012 – total consortium grant £4.19m (four universities and 10 industrial companies, led by Loughborough University) – Cranfield grant £1.02m – Simms, Nicholls, Oakey

G3 EPSRC - SUPERGEN 2 - Conventional Power Plant Lifetime Extension Consortium – Phase 1 (GR/S86334/01) – 2004-2008 – total consortium grant £2.11m (four universities and 11 industry partners) – Cranfield grant £559k – Simms, Nicholls, Oakey

G4 TSB – Carbon Abatement Using Surface Engineering Technologies (CASET) (TP11/CAT6/I/BP103K) – 2010-2012 – total project value £1.6m (2 universities and 3 industrial partners) – Cranfield grant £349k – Simms, Nicholls

G5 DTI / DECC - UK – US Collaborative Project on ‘Advanced Materials for Low Emission Power Plant’ (Project C/07/00361/00/00) – Phase 1 – 2004-2009 – total UK project value £6.91m (2 universities and 5 industrial companies) – Cranfield grant £482k – Oakey, Simms

4. Details of the impact (indicative maximum 750 words)

Cranfield’s research into materials degradation in industrial gas turbines has influenced materials selection, the standardisation of test methods, new coating systems and systems and fuel specification in power generation.

- **Materials selection and component life assessment**

Siemens, Rolls Royce and others have used our methods for selection of improved materials systems for particular applications [C2, C4, C5, C8, C10]. The selection of the best materials systems (coatings and base alloys) for components in jet engines and gas turbines improves their potential lives [C1, C6, C7]. High temperature oxidation and the various types of hot corrosion are critical issues for many components in turbine power systems e.g. blades, vanes, discs, and seals. In well-designed components, or with particular fuels/operating conditions, such degradation modes can limit component life. The damage can affect times between overhauls and risk of component failure.

- **Test method standardisation**

The deposit recoat test methodology for assessing corrosion in gas turbines developed at Cranfield was incorporated into an EU code of practice, and has become one of the recognised routes for assessing high temperature corrosion (draft ISO/CD 17224). This is one of the first ISO standards for high temperature corrosion and oxidation. Our dimensional metrology processes and methods for data analysis form parts of two other ISO standards issued in 2012 (BS ISO 26146:2012 and BS ISO 14802:2012, respectively. Rolls Royce and Siemens have adopted the methods as their standard approaches to assessing the performance of metallic gas turbine materials for these forms of damage. The consequence has been increased confidence in materials selection to resist degradation by hot corrosion [C8, 10].

- **New coating systems**

Novel coating systems were developed for different specific environments, focused on meeting the needs of Rolls Royce [C6-8] and Siemens Industrial Turbo-machinery [C9, 10]. The work is of particular interest to jet engine and industrial gas turbine manufacturers, who need coatings that can be operated for longer and in more arduous conditions. Such developments involve increasingly complex coating systems applied in multiple stages, but are commercially sensitive [C6, 7]. Functionally graded coatings that are highly resistant to hot corrosion and oxidation were produced with Siemens and Praxair (Siemens was granted a patent with Cranfield co-authors) [C9, 10].

- **Advanced power generation systems and fuel specification**

Guidance is being provided for the development of overall power system concepts to optimise the balance between gas turbine operating conditions, gas cleaning system requirements, fuel specifications and component lives. The advanced fossil fuel/biomass fired power systems that are under development (e.g., using gasification technologies) need to push the boundaries of materials performance in many respects with degradation due to creep, fatigue and corrosion/oxidation limiting both component lives and plant operating efficiencies. An example is a UK-US programme on quantifying the relationships between contaminant levels and materials damage from hot corrosion, with Siemens [C1 – C5]. These activities have identified materials systems to be used for gas turbine blades/vanes (and materials systems to be avoided) for viable component lives.

5. Sources to corroborate the impact (indicative maximum of 10 references)

C1 Paper presented by Dr A Kulkarni (Siemens, USA) at US DoE Conference on Materials for Fossil Energy Systems 2009. *Gas Turbines Fired on Syngas and Other Fuel Gases* (http://www.netl.doe.gov/PUBLICATIONS/proceedings/09/fem/presentations/Kulkarni.FE%20Materials%20Final%20UK-US%20presentation_14May09.pdf).

C2 Contact: Principal Engineer at Siemens Energy Inc., Orlando, Florida, USA.

C3 UK-US collaboration on Advanced Materials for Fossil Energy R&D: http://us-uk.fossil.energy.gov/Materials_Phase_I_Ke.html - overview and output summaries.

C4 Contact: Deputy Director, Office of Coal and Power Research and Development, US Department of Energy, USA.

C5 Contact: Deputy Director, Materials Science & Technology Division, Oak Ridge National Laboratory, USA.

C6 Paper presented by Dr M Hardy (Rolls Royce) at Superalloys Conference 2008: Effects of Oxidation and Hot Corrosion in a Nickel Disc Alloy. Co-authors: G.L. Drew and A.J. Leggett (Rolls Royce); A Encinas-Oropesa, J.R. Nicholls and N.J. Simms (Cranfield University). Superalloys 2008, Ed R Reed et al (TMS, 2008).

C7 Paper presented by Dr A J Leggett (Rolls Royce) at Parsons 2007 Conference: *Turbine Blade Coating Selection for Sulphidation Resistance*. Co-authors: D S Rickerby (Rolls Royce); N J Simms (Cranfield University). Parsons 2007 – Power Generation in an Era of Climate Change, Ed A Strang et al (2007).

C8 Contact: Corporate Specialist Surface Engineering, Rolls Royce plc, UK.

C9 Patent (granted): Layered coating system with a MCrAlX layer and a chromium rich layer and a method to produce it, EP 2435595 A1 (publication 2012). (http://www.google.com/patents/EP2435595A1?cl=en)

C10 Contact: Metallurgical Laboratory Manager, Siemens Industrial Gas Turbines, Lincoln, UK.