Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: At the cutting edge of Rolls-Royce aero-engines		
Period when the underpinning research was undertaken: 2010–2020		
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:**
Matthew Marshall	Professor of Tribology	2005–present
Period when the claimed impact occurred: August 2013–July 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Research at the University of Sheffield, pioneering high-speed *in-situ* measurements, has provided new insights into the wear mechanics involved in compressor blade interactions with abradable engine lining materials for Rolls-Royce. Improved blade tip design and engine liner composition has directly benefited the full range of Rolls-Royce's engine fleet (c.10,000 engines). [Text removed for publication].

2. Underpinning research (indicative maximum 500 words)

Over the last 40 years, aero-engine manufacturers have focussed on minimising compressor blade tip clearances to improve sealing and ultimately engine performance. To achieve this they have used abradable linings on the inner wall of the engine casing to maximise sealing and minimise wear of the fast-moving blade tips.

Historically, abradable lining research has required the construction of full-scale test rigs typically using scrap, albeit costly, aero-engine compressor units. The nature and complexity of the test setup means that the instrumentation is unique and repeatability is difficult to obtain. Test data collected under these conditions gives a static view of the ultimate abrasion outcome, as dynamic measurements are not taken throughout the test, thus it is impossible to explore fully the deterioration of abradable lining material and generate a fundamental understanding of the underlying wear processes.

This led to the University of Sheffield's Leonardo Tribology Centre and specifically Professor Matthew Marshall recognising the need for a suitable *in-situ* test platform. The challenge was to create a test environment that could reliably and repeatedly induce the wear mechanisms occurring in an aero-engine and integrate suitable instrumentation to investigate the fundamental mechanics of the abrasion process.

Initial work focused on developing a stroboscopic imaging system capable of capturing wear of a blade on a pass-by-pass basis, as it interacts with the abradable liner **[R1]**. This led to the determination of characteristic adhesion rates for aluminium based abradable materials, specifically the relationship between the blade strike speed, incursion rate and superficial hardness of the liner. In addition, force and temperature measurements were achieved on a millisecond time window scale, leading to an integrated real-time view of how abradable liners dynamically fracture and release material, thus uncovering the prevailing wear mechanism **[R2]**.

A particular research highlight has been the identification of the material removal mechanisms occurring in the liners at high and low blade incursion rates. For both rates, the penetration depth of the blade into the abradable is smaller than the size of the constituent particles of the liner material. Hence, one would expect a rubbing removal mechanism instead of a cutting material removal mechanism. However, unusually and importantly, cutting is observed at the higher rates. Combining the *in-situ* measurements developed along with statistical techniques, a clear explanation of the material removal mechanism was given, for the first time determining why cutting is observed under these conditions **[R3]**.

Similarly, thermal modelling in conjunction with the set-up described above has demonstrated the poor thermal connectivity between metal and hexagonal boron nitride (hBN) in aluminium based abradables that use hBN as a dislocator which leads to the concentration of heat at the surface of the abradable material. This effect was shown to be dependent on the microstructure produced during the abradable material thermal spraying process, which for harder coatings can result in localised hBN hot spots on the surface of the abradable liner causing the blade to soften and wear unevenly during operation **[R4]**.

Finally, material removal mechanisms occurring in the presence of fin seals have been investigated. This class of seal has been shown to either extrude material from the sides of the contact or be prone to compaction and eventual rupture at the base of the groove developed by the fin, resulting in high temperature sparks of the abradable material **[R5]**. Whether this occurs over the preferable lower temperature extrusion mechanism is linked to material microstructure and incursion conditions **[R6]**.

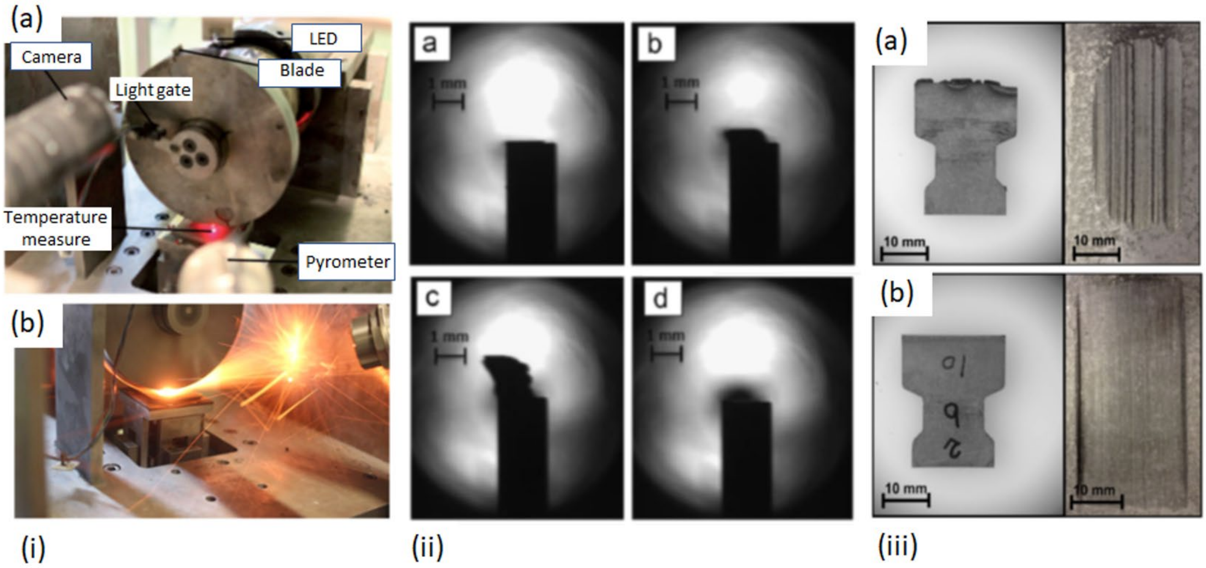

Figure 1. (i) Experimental rig for wear testing **[R3, R4]** (ii) Stroboscopic images of the liner material after blade tip passes showing liner wear and adhesion **[R2]** (iii) Blade tips and abradable samples showing (a) thermal damage and (b) cutting wear **[R2]**.

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

University of Sheffield staff and students in **bold**

R1. **Stringer, J.,** & **Marshall, M. B.** (2012). High speed wear testing of an abradable coating. *Wear, 294–295*, 257–263. https://doi.org/10.1016/j.wear.2012.07.009. Cited by 40.

R2. **Fois, N., Stringer, J.,** & **Marshall, M. B.** (2013). Adhesive transfer in aero-engine abradable linings contact. *Wear, 304(1–2)*, 202–210. https://doi.org/10.1016/j.wear.2013.04.033. Cited by 29.

R3. **Watson, M.,** & **Marshall, M.** (2018). Wear mechanisms at the blade tip seal interface. *Wear, 404–405*, 176–193. https://doi.org/10.1016/j.wear.2018.03.009. Cited by 6.

R4. **Fois, N., Watson, M.,** & **Marshall, M. B***. (2016).* The influence of material properties on the wear of abradable materials*. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 231*(2), 240–253. https://doi.org/10.1177/1350650116649528. Cited by 4.

R5. **Zhang, B.,** & **Marshall, M.** (2018). Investigating the application of a honeycomb abradable lining in the turbine stage of an aero-engine. *Tribology International, 125*, 66–74. https://doi.org/10.1016/j.triboint.2018.04.013. Cited by 5.

R6. **Zhang, B.,** & **Marshall, M.** (2019). Investigating material removal mechanism of Al-Si base abradable coating in labyrinth seal system. *Wear, 426–427*, 239–249. https://doi.org/10.1016/j.wear.2019.01.034. Cited by 0.

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

Sheffield's research has pioneered a new era of understanding regarding the wear mechanics associated with sealing in aero-engines. This understanding has been applied to critical engine issues and also enabled improved fuel efficiency. The Rolls-Royce Chief of Technology and Digital – Fans and Compressors stated, "*Ultimately, Sheffield's research has enabled us to realise huge economic savings, enabling planes to quickly return to service, and surmounting serious aero-engine challenges. It has directly resulted in knowledge enhancement and new capabilities throughout the organisation, and ultimately boosted the service that we provide to airlines, which has consolidated our reputation and market position*" **[S1] [R3, R4, R6]**.

Economic impact

Unplanned maintenance of aero-engines incurs enormous costs and service disruption. In 2019 Rolls-Royce announced a £1.2bn bill to compensate airlines that were unable to fly Boeing 787 aircraft with Trent 1000 engines, due to parts "*wearing out faster than expected"* **[S2]**. The Chief of Technology and Digital at Rolls-Royce stated, "*Professor Marshall's valuable research has provided novel understanding of the interaction of compressor blades and sealing fins with abradable liners. This has huge significance for Rolls Royce due to the volume of events that are attributable to abradable failures and the considerable costs incurred from planes being removed from service and the resulting penalties (in accordance with fuel target agreements).* […] *the research has directly benefited the fleet of c.10,000 Rolls-Royce engines that are currently in service*". Sheffield's research allowed normal maintenance schedules to be re-established avoiding continuing financial penalties **[S1]**. [Text removed for publication].

Key examples of the engine issues, Sheffield's research and impact are [Text removed for publication].

Furthermore, Sheffield's research into understanding the material wear mechanisms at the blade tip seal interface has directly improved overall engine performance **[R3]**. The Chief of Technology and Digital stated, "*the research has directly enabled reduced fuel burn and emissions*" **[S1]**. Effective air pathway sealing within the turbine is critical to the efficiency of aero-engines and improvements to fuel consumption, which is fundamental to the Rolls-Royce business model. The Chief of Technology and Digital confirmed the following cost savings since 2016:

- *"improvement in engine sealing at pass off, meaning that the engine is transferred to the customer with an improved overall performance. […] benefit translates to £17k unit cost per engine at pass off, where functional deeper seals can now be cut leading to improved overall sealing"* **[S1]**.
- *"the sealing performance has been maintained at an optimum level for longer in service, improving the overall performance of the engine between maintenance shop visits as well as lengthening the required maintenance cycle for the components impacted. […] benefit translates to £38k unit cost per engine in service, where an operability improvement associated with the accommodation of increased flight incursion events, meaning that clearances between the blade and trough of the liner can be reduced"* **[S1]**.

Environmental impact

The aforementioned improvements in aero-engine fuel consumption, achieved through superior abradable sealing, inherently leads to reduced CO_2 emissions. Uptake of Sheffield's research by Rolls-Royce and application to the Trent 1000 engines, used within the Boeing 787 Dreamliner, has supported the achievement of an overall 20% improvement in fuel use compared to other similarly sized airplanes **[S3]**. The Dreamliner is flown by 16 airlines across the globe and whilst it is not possible to explicitly state the reduction in emissions attributed to Sheffield's research due to the disconnect between manufacturer power pricing contracts and the huge variety of engine deployments. It is clear that improved engine sealing has contributed to the aviation industry's overall global emissions reduction targets.

Impact on practitioners within the aerospace industry

Rolls-Royce has benefited via the creation of 'Rolls-Royce Design Standards for abradable materials and incursion events (2018)', which is directly based on Sheffield's research **[R3]**. These design standards capture learning with respect to current abradables used by Rolls-Royce, and best practise guidance for the improvement of sealing performance in novel blade designs and seals **[S1]**. The Chief of Technology and Digital – Fans and Compressors at Rolls-Royce stated that "*recently these standards were integral in resolving issues with respect to blade tip notching as a consequence of compaction of the liner during manufacture, where the root cause of the issue was swiftly identified and resolved.*"

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

S1. Confidential testimonial letter from the Chief of Technology and Digital – Fans and Compressors at Rolls-Royce (2020). Corroborates a) mitigated economic and reputational impact on R-R, b) how Sheffield's research identified and solved the technical challenges, c) impact on engine performance, & d) best practice design guides.

S2. Various media articles on the scale, causes, and solutions of Rolls-Royce Trent 1000 engine failures. (Accessed 21st July 2020).

a) The Telegraph article detailing the cost (GBP1.2bn) of compensating RR customers (November 2019). (Subscription required). http://bit.ly/38GNPSZ

b) Simple Flying (world's largest aviation news website) article outlining Rolls-Royce's Trent 1000 Issues (August 2019). https://simpleflying.com/trent-1000-issue-timeline/

c) The Engineer article outlining issues around turbine blade cracking (June 2019). http://bit.ly/2P0huQc

S3. Information from Rolls-Royce on the Trent 1000 engine, and its use in the Boeing 787 Dreamliner, reporting that it is 20% more fuel efficient than the Boeing 767 aircraft it replaces. (Accessed 21st July 2020). https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-1000.aspx#/