Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: Making Rolls-Royce aero-engine parts completely competitive		
Period when the underpinning research was undertaken: 2003–2019		
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:**
Hughes J.	Research Director	2006–present
Sims, N.D.	Professor of Mechanical Engineering	2000–present
Ozturk, E.	Senior Technical Fellow	2010–present
Sharman A.	Head of NAMTEC	2003–present
Turner, S.	Chief Technology Officer AMRC	1997–2017
Ridgway, K.	Professor of Design and Manufacture	1988–2019
McLeay, T.	Research and Development Manager	2008–2016
Yusoff, A.R.	Post-Doctoral Researcher	2007–2010
Period when the claimed impact occurred: 2014–2020		
Is this case study continued from a case study submitted in 2014? N		

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

Sheffield's machining research into vibration control, cutting tool design, and residual stress management has revolutionised the manufacturing of Rolls-Royce aero-engine discs and shaft components. The resulting 50% reduction in cycle times and "right first time" production rates, rising from 85% to >99%, has realised over £135m in cost savings. This has enabled UK-based production to be completely competitive, and safeguarded 400 UK jobs. This research has led to an improvement in the skills of Rolls-Royce engineers and now underpins the manufacturing backbone of Rolls-Royce's global Rotatives business. Sheffield-derived approaches are now deployed in several facilities in the UK, Germany, and the USA.

2. Underpinning research (indicative maximum 500 words)

Modernising the UK's manufacturing base is key to ensuring ongoing global competitiveness but requires significant innovations in productivity and quality.

Machining vibration (chatter) is the main obstacle in achieving high-performance machining operations in industry and often results in noise, degraded surface quality, and cutting tool failure. Sheffield's Advanced Manufacturing Research Centre (AMRC) through its long-term collaboration with Rolls-Royce is addressing the complex interaction between machine tools and the workpiece to improve the manufacture of aero-engine discs and shaft components.

Vibration control

Sheffield's research into process damping, a useful but poorly understood machining phenomenon that can be exploited to mitigate chatter, has generated insights applicable to difficult-to-machine metals such as titanium and superalloys. To maximise both stability and speed, Sheffield investigated the relationship between vibration and machining feed rate using numerical models and experimental tests. Accurate feed rate selection for machining was achieved through development of a time-domain model of milling chatter that considered process damping forces due to interference between the tool flank and the just-cut workpiece surface **[R1]**. Through extensive experimental testing, the influence of tool edge geometry on vibration and consequently production time revealed that variable helix/pitch angles and increased cutting edge radius increase process damping performance **[R2]**.

Chatter due to the dynamic flexibility of the tool-holder-spindle-machine assembly can reduce cut depth; this is complicated further when a spindle speed-dependent preload is applied. Sheffield's research developed an experimentally validated stability model that incorporates both tool speed-dependent frequency response functions and cutting force coefficients. This allows a more accurate stability prediction to be made for the tool and tool holder assembly **[R3]**.

Cutting tool design

Cutting tool design has a dramatic effect on both the life of the cutting tool and the resultant workpiece surface integrity, a key factor in determining the high cycle fatigue limit of rotating aero-engine components. Sheffield's research into the effects of cutting tool preparation, cutting speed, and feed rate on tool wear/life for a range of different cutting tool geometries and materials has led to an understanding of the effects of operating parameters on surface integrity **[R4]**. Building on this research, Sheffield has produced specific tooling models for milling and turning operations.

For milling, variable pitch and variable helix cutting tools impart non-standard forces into the system and have to be optimised to minimise chatter. Sheffield developed and experimentally validated a method to optimise tool helix and pitch angle, resulting in a 5-fold increase in chatter stability compared to traditional milling tools **[R2]**. Research into tuning vibration absorbers developed a new analytical solution, which demonstrated that a 40–50% improvement in the critical limiting depth of cut, compared to the classically tuned vibration absorber, was achievable. Specifically for turning and boring operations, it showed that passive vibration absorbers could be tuned using this technique **[R5]**.

Residual stress management

In a drive to reduce raw material costs and minimise wastage, forgings can be supplied close to the shape of the component. Sheffield's finite element-based machining distortion model, validated using neutron diffraction data and post machining distortion measurements, calculates the redistribution of highly asymmetrical residual stress during machining and predicts component distortion **[R6]**. This approach optimises material removal strategy and achieves required part tolerances whilst minimising cycle time.

Combined, Sheffield's insights across the aforementioned areas have underpinned the development of advanced technologies and optimised manufacturing processes.

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

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

R1. **Sims, N. D.,** & **Turner, M. S.** (2011). The influence of feed rate on process damping in milling: modelling and experiments. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225*(6), 799–810. https://doi.org/10.1243/09544054jem2141. Cited by 11.

R2. **Yusoff, A. R.,** & **Sims, N. D.** (2011). Optimisation of variable helix tool geometry for regenerative chatter mitigation. *International Journal of Machine Tools and Manufacture, 51*(2), 133–141. https://doi.org/10.1016/j.ijmachtools.2010.10.004. Cited by 62.

R3. **Ozturk, E.,** Kumar, U., **Turner, S.,** & Schmitz, T. (2012). Investigation of spindle bearing preload on dynamics and stability limit in milling. *CIRP Annals, 61*(1), 343–346. https://doi.org/10.1016/j.cirp.2012.03.134. Cited by 31.

R4. **Hughes, J. I., Sharman, A. R. C.,** & **Ridgway, K.** (2004). The effect of tool edge preparation on tool life and workpiece surface integrity. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 218*(9), 1113–1123. https://doi.org/10.1243/0954405041897086. Cited by 36.

R5. **Sims, N. D.** (2007). Vibration absorbers for chatter suppression: A new analytical tuning methodology. *Journal of Sound and Vibration, 301*(3–5), 592–607. https://doi.org/10.1016/j.jsv.2006.10.020. Cited by 126.

R6. **Bilkhu, R., Ayvar-Soberanis, S., Pinna, C.,** & **McLeay, T.** (2019). Machining Distortion in Asymmetrical Residual Stress Profiles. Procedia CIRP, 82, 395–399. https://doi.org/10.1016/j.procir.2019.04.346. Cited by 1.

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

Rolls-Royce is globally renowned as an aero-engine manufacturing powerhouse, with over 13,000 civil engines and 16,000 military engines in service around the world. The increased global demand for the Boeing 787, Airbus A350, and Eurofighter Typhoon, created an urgent need for optimised manufacturing capabilities to deliver vastly greater volumes of key aero-engine components **[S1]**. However, these components use titanium, nickel super alloys, or high-alloy steel, which are traditionally difficult to machine, and require complex manufacturing processes.

Sheffield's research into vibration control **[R1, R2, R3]**, cutting tool design **[R2, R4, R5]**, and residual stress management **[R6]** has resulted in step-change manufacturing process improvements that have been utilised by Rolls-Royce to enhance and scale-up production of aero-engine discs and shafts and so consolidate their market position as the world's second largest aerospace manufacturer. Chief of Manufacturing Technology, Rolls-Royce Rotatives stated, "*The new manufacturing processes have proved very successful in delivering well over £135m savings and providing competitive advantage and security for Rolls-Royce"* **[S1]**. This was realised through Sheffield's research in the high-performance machining of aero-engine disc and shaft component work streams as part of the Rolls-Royce led SAMULET Manufacturing R&D Programmes [text removed for publication].

The subsequent national and international impact, achieved during the assessment period, also includes:

Economic impact

Sheffield's research directly realised substantial productivity gains for Rolls-Royce. The new manufacturing technologies and processes of aero-engine discs, linked to better vibration control, cutting tool design, and elimination of manual processes, has also reduced manufacturing variation, according to the Chief of Manufacturing Technology, "*reducing the cycle time for the manufacture of aero-discs 50%, boosting output by 100% and increasing the right first time number from ~85% to >99%*" **[S1] [R1, R2, R3]**. This was only possible through re-engineering machining processes and identifying the critical paths for improving manufacturing efficiencies.

[Text removed for publication].

Without these gains, Rolls-Royce would have been unable to meet increased demand for turbine discs for their Trent family of aero-engines. Opened in June 2014, and fully operational in 2015, Rolls-Royce's new UK aerospace disc manufacturing facility in Tyne and Wear was able to significantly reduce start-up costs using Sheffield's novel manufacturing capabilities. The new machining processes halved the number of set-ups required to produce the component and equate to a 30% reduction in the machine tools needed within the factory environment **[S1]**. This facility has boosted regional productivity levels and supported the UK economy. Rolls-Royce's Chief of Manufacturing Technology stated that the impact directly accrued from Sheffield's research includes, "*Protecting 350 jobs at the Sunderland factory, guaranteeing the ongoing production of aero-engine discs in the U.K.*" **[S1]**. To date, Rolls-Royce has also implemented these new manufacturing capabilities at their Derby plant in the UK and overseas production plants in the USA and Germany **[S1]**. Rolls-Royce's Chief of Manufacturing Technology stated, "*This has supported the manufacture of over 2,500 fan and turbine discs per year*" **[S1]**.

Separately during the REF assessment period, the High-Performance Shaft Machining (HPSM) technology based on Sheffield's research has been implemented at the Rolls-Royce Sinfin D-site facility in Derby **[S1] [R4, R5, R6]**. Cycle times for machining of mainline and stub shafts were reduced by 30%, manual interventions were reduced by 80% against a target of 50%, and feature right first time was raised to 99.6% **[S1]**. Rolls-Royce's Chief of Manufacturing Technology stated, *"This technology has enabled marked productivity increases and underpinned the response to an ongoing increase in load maintaining manufacturing of shaft components. Consequently, there was a £35m investment in a new HPSM Cell within Rolls-Royce Inchinnan* [Scotland]*, safeguarding 50 jobs and enabling Rolls-Royce to meet the required load for Trent aero-engines"* **[S1]**.

Impact on practitioners within the aerospace industry

Sheffield's research has directly engineered a catalogue of knowledge enhancement, new processes, and technology solutions for the manufacture of key aero-engine parts. This has enhanced capabilities and expertise within Rolls-Royce, resulting in new technical standards, best practise documentation, and the uptake of new methodologies. For example, *"The selection of a standardised multi-axis machine tools (at a cost of £1m each) as the platform of choice, with close to 100 in place across Rolls-Royce, providing greater flexibility and agility to deliver the growing portfolio"* **[S1]**. The Rolls-Royce Chief of Manufacturing Technology commented that Sheffield's research has "*enhanced capabilities and expertise within Rolls-Royce, leading to new* *technical standards and best practise guidelines. High Performance Manufacturing, which was seeded within the AMRC is now the backbone of the methods used within the global Rotatives business and has positively impacted our engineers in the UK and America in terms of new skills and standardised working processes*" **[S1]**.

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

S1. Confidential testimonial from the Chief of Manufacturing Technology, Rolls-Royce Rotatives (2020). Corroborates claims around a) requirement for increased production volume, b) corporate & economic impact, c) specific productivity & quality improvements, d) jobs safeguarded & e) wider application within R-R.

S2. [Text removed for publication].

S3. [Text removed for publication].