Institution: Imperial College London

Unit of Assessment: 13B Metallurgy and Materials

Title of case study: Improved performance of a jet engine through improved materials manufacturing processes

1. Summary of the impact

Rolls-Royce has been able to reduce manufacturing scrap rates significantly, better control the single crystal growth process for nickel superalloy blades and more confidently understand production issues in Ti blades. The lower bound saving for the Imperial contribution to the work is estimated at £100M p.a. This has contributed to the production of a jet engine with better fuel efficiency, increased cost effectiveness due to lower scrap rate and improved time on wing for fleets in service.

Jet engine modifications account for over half the fuel efficiency improvements in modern aircraft, with the industry accounting for a large share of UK visible exports. Improvements in gas turbine technology offer jet fuel (cost and CO_2) savings and support UK employment. Titanium alloys in the cooler sections and nickel alloys in the hot sections are the subject of this case study.

The engines consist of Ti or Ni alloy discs attached to a series of shafts which are turned by aerofoils (blades) in the gas stream. Incoming air is accelerated by the fan section then compressed, mixed with fuel and burned, with the energy then being extracted by the turbine. Turbine blades operate in a gas stream at 1800+ K, 200 K greater than the alloy melting point, and extract up to 700 kW per blade to power the fan and compressor. Each disc holds around 60 blades, with around 9 turbine stages in a large engine. In titanium, failure of a fan blade or multiple blades is extremely costly (£5M per event) and of course poses safety issues. Research in the Department has focussed on a) predicting the microstructure of nickel superalloys and b) understanding defect formation in titanium and superalloys.

2. Underpinning research

The Department of Materials at Imperial College London carries out a large body of research in the area of solidification and microstructural analysis of alloys. The specific research insights that have had significant impacts on the science and technology of jet engines are as follows.

1. Predicting the microstructure of nickel superalloy blades: porosity, grain orientation and the effect on creep

With the support of an EPSRC Grant GR/L05433/01 (Dec 1996-Sept 2000) Dr Shollock and Professor McLean investigated the effects of well-controlled directional solidification conditions on the microstructures of nickel-base superalloys. The combination of controlled directional solidification and detailed crystallographic characterisation provided the most comprehensive information at that time on the correlation of solidification conditions with microstructure. Specifically it was found that:

- increasing the solid-liquid interface allowed better grain orientation control,
- stability of grains depended on their orientation and
- minor differences in alloy composition can affect the stabilisation of grains [1].

In follow-on work in 2002/3, led by Professors McLean with Lee and supported by Rolls Royce, Special Metals Wiggin and Wyman-Gordon, a combined cellular automaton-finite difference (CA-FD) model was developed to simulate the solidification process. It was found that for nickel superalloys the dendrite spacing selection (achieved by branching and dendrite competition) exhibited hysteresis. It was found that perturbation of the growth velocity affects both the primary dendrite arm spacing and tip undercooling - the primary dendrite arm spacing has a much narrower distribution after perturbation. The upper limit of the distribution of primary dendrite arm spacing is about twice the lower limit. Thus, the primary spacing was found to be dependent not only on the current growth conditions, but also on the way in which those conditions were reached [2].
These research findings were successful in allowing model-based casting design to be employed, so as to minimise stray grain formation and to control primary and secondary orientation in single

crystal castings. Extension of this work was carried out with EPSRC grant EP/R78992/019 (Oct2002-Mar2006) led by Professor Lee and Dr Dye, which introduced a methodology (weighted interval rank sort) that allowed the spatial variation of composition (microsegregation) to be more accurately estimated [3]. In linked work Professor Lee also determined that porosity was a major crack initiator and large pores close to the surface played an important role determining the fatigue life of cast components. It was established that the average size of pores as well as their spatial and size distribution in a component are also important. A statistical model was developed which successfully predicted fatigue life due to porosity population [4].

In 2006 research resumed on creep in superalloys, based on the historical activity in this area by Professor McLean, using support from an EPSRC platform grant, GR/T26344/01 (Feb 2005-Jan2010) and a further grant, EP/C536312/1 (Oct 2005- 2009). Of specific relevance is the development of a truly physically-based model by Dr Dye allowing the features of superalloy creep to be recovered i.e. dependence upon microstructure and its scale, effect of lattice misfit, internal stress relaxation, incubation phenomena and the interrelationship of tertiary and primary creep, and vacancy condensation leading to damage accumulation. The model provided predictive capability of the microstructural factors accounting for creep.

2. FIB-SIMs, O interstitials and degradation of alloys

Dr Shollock developed a combination of O isotope exchange, focussed ion beam milling and secondary isotope mass spectrometry (FIB-SIMS) in the late 90s, primarily to develop insight into the oxidation mechanisms of nickel superalloys [5][6]. This allowed depth profiling of O at the nanoscale, elucidating the mechanisms by which multi-layer and multi-phase oxide scales grow, in what order and understanding which are truly protective. In addition insight was gained into the formation processes of the brittle intermetallics in the secondary reaction zone and the porosity (vacancy accumulation) at the interfaces. More recently, this has been extended to the use of FIB-SIMS to measure and quantify interstitial concentration profiles in titanium alloys, in a PhD thesis published in 2013 “Controlling the interstitial element concentration in Ti-6Al-4V using Calciothermic Reduction” by Moorhouse (supervised by Dr Shollock). It was determined that with careful selection of the FIB-SIMS parameters one could correctly quantify the interstitial concentrations in titanium alloys and obtain oxygen concentration profiles.

3. References to the research * References that best indicate quality of underpinning research.

1. *N D'Souza, MG Ardakani, M McLean and BA Shollock, Directional and single-crystal solidification of Ni-base superalloys: Part I. The role of curved isotherms on grain selection, Metall Mater Trans A 31(11):2877-2886, 2000. DOI: 10.1007/BF02830351.
2. *W Wang, PD Lee and M McLean, A model of solidification microstructures in nickel-based superalloys: predicting primary dendrite spacing selection, Acta Mater, 51(10):2971--2987, 2003, DOI: 10.1016/S1359-6454(03)00110-1.
3. M Ganesan, D Dye and PD Lee, A technique for characterizing microsegregation in multicomponent alloys and its application to single-crystal superalloy castings, Metall Mater Trans A, 36(8):2191-2204, 2005. DOI: 10.1007/s11661-005-0338-2.
4. *JZ Yi, Y.X Gao, PD Lee, HM Flower and TC Lindley, Scatter in fatigue life due to effects of porosity in cast A356-T6 aluminum-silicon alloys. Metall Mater Trans A 34(9):1879-1890, 2003. DOI: 10.1007/s11661-003-0153-6.
5. D Garriga-Majo, BA Shollock, DS McPhail, RJ Chater, JF Walker, Novel strategies for evaluating the degradation of protective coatings on superalloys. Int J Inorg Mater, 1(5-6):325-336, 1999. DOI: 10.1016/S1466-6049(99)00047-1.
6. AA Alibhai, RJ Chater, DS McPhail, BA Shollock, Use of isotropic tracers and SIMS analysis for evaluating the oxidation behaviour of protective coatings on nickel based superalloys. Appl. Surf. Sci., 203:630-633, 2003. DOI: 10.1016/S0169-4332(02)00780-8.

4. Details of the impact

UK based Rolls-Royce Holdings Plc is the world’s second-largest manufacturer of jet engines in wide body civil aircraft [A], in competition with the largest industrial company in the world and US defence contractor, GE. It is the only non-US based company with significant operations in this sector and employs 42,800 people worldwide with 22,800 based in the UK [B]. Manufacture of civil aerospace jet engines generated revenue of £6,437M in 2012 with £727M of underlying profit for Rolls-Royce [B]. Rolls-Royce is one of the UK's largest manufacturing exporters, with 75% of its revenue coming from overseas [C]. Rolls-Royce, unsurprisingly, wish to retain competitive advantage, hence their interest in research that will a) reduce the probability of blade failure and b) allow a 10K higher operating temperature that saves fuel and reduces emissions. The impact of our research lies in two key areas:

1. **<u>The microstructure of nickel superalloys: casting, porosity, grain orientation and creep prediction</u>**

Nickel superalloys are used in the manufacture of jet engines blades due to their excellent mechanical strength and resistance to creep (tendency for solids to slowly move or deform under stress) at high temperatures; good surface stability; and corrosion and oxidation resistance. Optimising these properties via composition or manufacturing process is key to the successful manufacture and sale of jet engines and to the continual improvement of fuel efficiency in aircraft. Because of the significant fuel cost and CO_2 savings realised, they are replaced every 10,000 h (around every 2 years). Relatively high volume manufacturing of these blades is therefore essential and the cost of manufacture has a significant impact on airline service costs and aero engine manufacturer profitability. The optimisation of properties is achieved through the reduction or elimination of crystal grain boundaries (i.e. single crystal growth) and the appropriate selection of the grain orientation to reduce deformation (creep) from the centrifugal stresses in the engine. This is exactly what the research insights outlined in section 2 allows one to control.
The FIB-SIMS work has also been helpful in understanding the mechanisms of high temperature oxidation of the melt and its interaction with the mould wall. This has enabled casting surface scale to be tackled, allowing larger single crystal castings to be used in new engines at an economically acceptable cost without suffering from excessive scrap rates.
The FIB-SIMS technique development has also enabled the role of Y in bond coats to be quantified in follow-up work at Imperial. These are the interlayers that act as Al reservoirs and diffusion barriers between the metallic blade and the insulating ceramic thermal barrier coatings. This has enabled improved PtAl-based bond costs to be implemented in production, enabling further life/ temperature improvements to be achieved.
A Materials Technologist at Rolls-Royce Plc notes:
"*the research collaboratively with Imperial College addressed the mechanism for the formation of stray grains … [and] was instrumental in the design of a novel grain selector that successfully enables the "filtering" of these stray grains and ensuring casting conformance. This has resulted in publications in peer reviewed journals…as well as two granted patents for the grain selector….The collaboration with Imperial College has been important in identifying the role of the as-cast oxide that forms during solidification and that plays a crucial role during solutioning."* [D].

<u>Quantitative Estimate of the impact</u>
Scrap rates in the production of these type of blades due to non-conformance in 1993 were ~50% and are now reduced to ~10%. This improvement leads to a ~£300m/yr savings in waste material and processing (based on a cost per blade of £100 and typical production rates). A lower bound on Imperial's contribution to this of 5% gives a saving of >£100m over the last decade attributable to the casting research. The ability to grow single crystals with an improved yield made it economically feasible to manufacture larger single crystal castings, leading to the ability to raise turbine entry temperatures, which impacts on fuel burn and consequently fuel cost and CO_2 emissions, improving competitiveness. A 10K increase in temperature capability equates to about 0.5% increase in fuel efficiency. A Rolls Royce specialist in nickel alloys notes that:
"*It has been estimated that an increase in compressor discharge temperature of 30C produces 0.3% less specific fuel consumption per engine. For a large twin engine aircraft flying from London to New York, a 0.3% SFC equates to a 700kg reduction in fuel consumption, which translates to a reduction of ~2.25tonnes of CO2 emissions per flight. "* [E]

The 2012 estimated fuel costs of the airline industry were $210bn, and as Rolls-Royce has ~40% of the market their increased temperature capability allows a saving of $420m/year in fuel, or 2.6 million tonnes of CO_2 equivalent. This reduction in running costs makes Rolls-Royce engines

attractive to airlines and has allowed the company to grow its market share. The improvement in 10K material capability and the subsequent saving of $420m/yr can be assigned to developments across Ni superalloy research. The importance of this improved casting process has had a significant impact on the fortunes of Rolls-Royce Plc - this was highlighted in an Economist article on April 21st 2012, which states:
"But some things are not for sharing because they are too important to preserve a product's competitive advantage. For Rolls-Royce, turbine blades are one of those key technologies. The magic that creates them depends on a deep understanding of materials science and production technology. When metals solidify after casting they normally contain lots of microscopic crystals. That would still leave them strong enough for most things, but it is a potential weakness in a turbine blade. So Rolls-Royce uses a unique system which casts the blade in a nickel-based super-alloy with a continuous and unbroken crystalline structure. This ensures there will be no structural defects." [F]

2. <u>FIB SIMs: O interstitials in titanium</u>

The compressor and fan blades of a jet engine are made of titanium alloys because of their superior density-normalised fatigue strength. Hollow fan blades are made by diffusion bonding and vacuum brazing processes that can be difficult to control. As near-final manufacturing processes they are impossible to non-destructively inspect and therefore any variability must be tightly controlled. This has been enabled by the techniques developed by Shollock and used by Dye to understand and help improve the production process. A Rolls-Royce Fellow provides details of fuel consumption savings and CO2 emissions and explains how oxygen diffusion measurements and the development of an algorithm to predict the thickness of oxidation damage as a function of time and temperature were "*beneficial to Rolls-Royce plc."*

"The use of FIB SIMS depth profiling of interstitials in 'good' and 'bad' microstructures enabled the root cause for variability in the manufacturing process to be defined as nucleation driven from surface topography rather than via a chemistry change. … Whilst the benefit associated with this work is difficult to quantify in direct financial terms, the manufacturing changes are being implemented in order to reduce the probability of fan blade failures in service. The direct cost to the company is ~£5M per failure event."[G]

5. Sources to corroborate the impact

A. Corroboration of Rolls Royce's position in jet engine market – http://www.marketwatch.com/story/rolls-royce-raises-dividend-8-after-profit-rise-2011-07-28 *(Archived at* https://www.imperial.ac.uk/ref/webarchive/wvf)

B. 2012 Annual Report of Rolls-Royce Holdings plc. Corroboration of employees - page 34; corroboration of civil aerospace profits - page 2 http://www.rolls-royce.com/Images/rolls_royce_annual_report_2012_tcm92-44211.pdf Archived here on 28/10/2013

C. Corroboration of level of Rolls Royce exports from the UK http://www.rolls-royce.com/careers/working_for_us/our_locations/united_kingdom/ *(Archived at* https://www.imperial.ac.uk/ref/webarchive/j8f *)*

D. Materials Technologist, Rolls-Royce to corroboration the changes to casting process and Imperial input: Private email communication 5 June 2013.

E. Rolls Royce corporate specialist in nickel alloys will corroborate the estimation of fuel saving and CO2 emission.

F. Corroboration of the importance of the casting process: "Forging ahead- Manufacturers are increasingly working with new, game-changing ingredients" The Economist" Apr 21st 2012 http://www.economist.com/node/21552895?zid=293&ah=e50f636873b42369614615ba3c16df4a *(Archived at* https://www.imperial.ac.uk/ref/webarchive/dwf)

G. Rolls-Royce Fellow to corroborate that the work at Imperial enabled improved durability Private email communication from. 17 May 2013.