Rolls-Royce today is an increasingly global business, supplying integrated power systems to a wide variety of customers for use on land, at sea and in the air. Its reputation for ‘delivering excellence’ to these customers has been built largely on its gas turbine technology portfolio, and this reputation relies on the quality of the company’s expertise in design, manufacture and delivery of services. This paper sets out to examine a number of examples, such as the high-pressure turbine blade, of the company’s reliance on precision design and manufacture, highlighting how this precision contributes to customer satisfaction with its products. A number of measures the company is taking to accelerate its competitiveness in precision manufacture are highlighted, not least its extensive relationships with the academic research base. The paper finishes by looking briefly at the demands of the company’s potential future product portfolio.

Keywords: gas turbines; measurement; wear; marine; nuclear; fuel cells

1. Introduction

This paper was produced by Rolls-Royce plc to support a conference on precision engineering held at The Royal Society in London on 21/22 March 2011. The company has relied on precision engineering and advances in tribology throughout its 100 year old history; so it was appropriate to provide examples from this experience as a mechanism for furnishing some context for the academic papers.

Rolls-Royce today is a business providing high-integrity power systems and services for use on land, at sea and in the air, and has succeeded over the past 20 years in establishing a strong position in four global, intensely competitive, markets—civil aerospace, defence aerospace, marine and energy. As a result of following a consistent strategy, Rolls-Royce today has a broad customer base comprising more than 600 airlines, 4000 corporate and utility aircraft and helicopter operators, 160 armed forces, more than 2000 marine customers, including 70 navies, and energy customers in nearly 120 countries, with an
installed base of 54,000 gas turbines. The company employs over 38,000 skilled people in offices, manufacturing and service facilities in 50 countries. In 2009, Rolls-Royce invested £864 million on research and development, two-thirds of which had the objective of further improving the environmental performance of its products, in particular the reduction of emissions. Although the company is progressively diversifying its activities into low-carbon technologies, such as tidal generation and fuel cells, and into the exploitation of its extensive naval nuclear propulsion expertise into the civil nuclear power arena, the gas turbine remains its core technology base, with approximately 70 per cent of its resources devoted to gas turbine products, services and research.

2. Rolls-Royce and precision engineering

Historically, Rolls-Royce has enjoyed an enviable reputation for quality and precision engineering that was built originally on the Rolls-Royce motor car (figure 1) and of course, Henry Royce’s passion for excellence. A recent advertisement bears testimony to this reputation and to the affection in which the marque is held:

This is a concours car in as-new condition. You have to see the car to believe how good she is and how close to new. Mechanically, she is in incredible condition and drives like a new car. Her engine is silent and starts first time every time. Her oil pressure settles down to 30 psig which is well above the manufacturer’s specification of 25 psig. Her water never goes above 70°C. She drives with the kind of silence and precision for which Rolls-Royce are justly famous.

Once the company had started to produce aero-engines for the first time in the First World War, this passion and innovative spirit arguably found its ultimate expression in the Merlin engine (figure 2), the liquid-cooled, 271, V-12
The invention was nothing. The achievement was making the thing work
Frank Whittle

reciprocating four-stroke engine, which became a British icon in the Supermarine Spitfire during the Second World War and whose scale of production essentially launched Rolls-Royce as a major aero-engine manufacturer.

Up to this point in its history, largely based on reciprocating engines and cars, the company’s engineers had to possess mechanical engineering skills and, in particular, a very sound knowledge of tribology. However, with the invention of the gas turbine (figure 3) by Frank Whittle, and the company’s adoption of the new engine’s development in November 1942, the skills that grew rapidly in demand were those of aerodynamics and materials. The two engine types can perhaps be contrasted by observing that, in a reciprocating engine,
practically every component comes into sliding or rolling contact with another, a characteristic that is addressed by extensive lubrication, whereas in a gas turbine, such mechanical contact is largely avoided.

The adoption of the gas turbine by the company led to the technology becoming the dominant core expertise. The new machine stimulated comprehensive and sustained research activities as it was developed for both military and civil applications; this was provided by government research facilities (e.g. the National Gas Turbine Establishment), and by the highly capable academic research base available in the UK. The latter was progressively rationalized from 1990 with the creation of a network of university technology centres. These have now been extended to address the growing technical challenges facing Rolls-Royce, e.g. fuel cells, tidal generators, CO2 compressors and a wide variety of marine products. Introducing new technology to the market remains, however, very challenging as is illustrated in the simplified diagram (figure 4). This shows that it has taken at least 10 years to progress from the basic research on a new disc material, called RR1000, to its certification for flight in the Trent 1000 engine. At every point in this process, careful and precise measurements are required, from the material composition, the laboratory testing, the forging trials, the inspection techniques and through to the manufacturing technology.

Finally, though there are a plethora of examples of precision engineering in an aero gas turbine, one that illustrates how accurately the overall power system has to be made to operate is its oil system. Typically, in a large Trent engine (figure 5) at cruise on a long-range flight, the oil circulates every 16 s, is heated to approximately 200°C and cooled to approximately 10°C and rejects approximately 250 kW heat through the cooler. The engine's usable oil
capacity is approximately 23l, compared with the aircraft’s fuel tank capacity of approximately 168200l, and the loss rate of engine oil through the breather is less than 0.11h$^{-1}$.

3. Tribology at Rolls-Royce

Surfaces are one area where very small changes in topography and chemistry can have a major impact on the function of a component. Tribology deals with the impact of such changes on components in contact. In a gas turbine, which comprises thousands of components, the vast majority of the contact between them is essentially static. However, the gas turbine is an intrinsic generator of high-frequency excitation, arising from the interactions between the airflow, the rotating blades and the static vanes. Although the frequency response of the aerofoils can these days be predicted with considerable accuracy, it remains very difficult to assess the level of any given excitation and the damping that can be expected from static mechanical contact, typically between the blade root and the disc. Such fretting contact gives rise to wear. As a consequence, wear is one of the major factors affecting the life of engine components and is a significant cost element encountered during the life cycle of a gas turbine engine. In its marine and static land applications, wear can be exacerbated by the presence of sea water or by airborne sand.

The subject of wear mechanisms in engineering materials is very complex and one that has been investigated extensively in academia, a knowledge and skills base upon which the company draws heavily. However, the numerous material properties and surface finishes encountered, together with the variety of engineering applications, lead to widely differing behaviours at the contacting surfaces. Tribology therefore is extensive in scope and can be challenging to apply with the levels of precision required in modern technology such as the gas turbine engine.

As is well known, wear is characterized by a number of different mechanisms: sliding wear (generally gradual), adhesive wear (can be a very aggressive mechanism), abrasive wear, fretting wear (the most difficult type of wear to
predict) and impact wear (again difficult to predict). Few of these mechanisms are precisely understood and are very specific to the materials involved, making behaviour in complex engine running environments in some cases very difficult to predict with a reasonable level of certainty. Lubricants are extensively used wherever possible, but many parts of the engine design do not lend themselves to this type of solution. In these cases, protective coating systems are often employed to produce contacting surfaces whose wear characteristics are at a manageable level. Advances in measurement capability allow much improved inspection of the surface topography but place the challenge back at the door of the designer to define the topographical features that impact function. For example, surface furrows can help retain oil or control boundary layers, but random asperities may be ineffective or even be detrimental. Traditional surface finish definitions do not distinguish the two. Nevertheless, as gas turbine designs evolve to meet the ever-increasing demand for performance and reduced emissions, unanticipated wear scenarios can arise. This stretch in design capability with ever-reducing lead times for service introduction and limited engine testing opportunities places great pressure upon accurate prediction through modelling and laboratory scale verification.

4. Examples

(a) Measurement

Arguably, precision engineering translates readily to the measurement needed to ensure that precision. Generally speaking, more precision (accuracy) is needed to control variability, promote interchangeability and improve predictability. At the margins, this is economically driven. Interestingly, the ever-increasing ‘precision’ of analytical methods and design models is challenging the company’s ability to take the measurements needed to validate them; examples are material properties, computational fluid dynamics, aero-elastics and whole engine dynamics.

To take one of these, the characterization of the properties of materials and remaining useful life is the key to the safe and reliable operation of any of Rolls-Royce’s high-integrity power systems; the more accuracy (precision + bias) with which this can be done, the smaller the margins in design and operation can be made, thereby extracting the optimum performance from every piece of material. For example, if the residual useful life could be more directly assessed by measurement of fatigue in a part, the prognosis to failure interval could be extended, and costly surprises in service avoided. An experimental technique, called ‘nonlinear ultrasonic propagation’, is currently being evaluated by the company in a partnership between industry and academia. This involves two ultrasonic waves, one to stress the surface, the other to detect changes in the velocity of sound across a short distance; the principle is that, as the level of damage increases, the gradient of the velocity/stress line changes.

As illustrations of the importance of measurement, the company has recently almost halved the uncertainty of its experimental fan performance estimates by careful use of resistance temperature sensors in intakes in preference to thermocouples, and a unique whole-engine X-Ray capability to produce near real-time digital images of the internals of a running engine has been developed. In its
first use on a big civil engine, approximately 40 000 high-resolution images were obtained in a single evening’s testing (figure 6). This course has been followed because the precise position of the internal running geometry is so critical to reliable operation and is difficult to model with commensurate precision.

Similarly, the verification (inspection) of parts to the fine tolerances required in advanced manufacturing is extremely challenging both technically and in terms of the skills base required. This quest for improvement has lead to Rolls-Royce becoming one of the biggest users of coordinate measurement machines and to working closely with the UK’s National Physical Laboratory on the development of a training framework. Further, the control and monitoring of manufacturing processes brings its own needs for precision measurement. In this context, an interesting historical note here is that this need for precision sparked the innovative curiosity of David McMurtry while he was working at Rolls-Royce back in the 1960s, led to his invention of the touch probe and then to establishing the highly successful Renishaw plc.

To illustrate the importance of measurement to the company, an example has been taken from the National Measurement Office and Department for Business Enterprise and Skills [1], which examined the life cycle of an aero-engine compressor blade, of which there can be approximately 1000 in a typical Trent engine. To design such a component, the following lists the kind of information that is needed:

- knowledge of material properties;
- finite-element models of blade stresses;
- computational fluid dynamic models of the flows around the component;
- aero-elastic models linking the first two models;
— performance and whole-engine mechanical models describing the behaviour of the component as part of the whole engine system; and
— models of the manufacturing processes, e.g. forging.

All of these models and simulations require thousands of exacting measurements to validate the design concept, for example:

— vibration testing of the prototype to assess the response in each of 20+ modes;
— construction and testing of a compressor test rig in which thousands of measurements are made over the operating range of conditions (and to avoid potential damage to the rig, hundreds of additional indirect measurements are monitored); and
— the final validation of performance will be through a range of tests in a full engine, where again, thousands of measurements of the performance, thermal and mechanical behaviour will be made.

Broadly in parallel with the design validation process, the manufacturing processes must be defined. A simplified representation of the manufacturing process for a blade is, from the raw material entering the factory to the finished blade leaving it, as follows:

— the raw material is pre-inspected for composition and properties;
— the forging process involves measuring 31 features at each of three process stages (93 features in total);
— machining involves the dimensional measurement of between 50 and 171 features on the most complex blades;
— all finished features are 100 per cent inspected (i.e. not inspected through sampling); and
— visual inspection is carried out at six stages through the process (including final inspection), and surface finish measurements are made on sample blades after finishing.

In total, there are between 150 and 300 feature measurements on each blade, and on average over 1 million such items are produced each year.

Measurement does not stop once the blade has been manufactured. Once in service, measurements of engine vibration are monitored for evidence of blade damage, and the blades themselves are inspected at intervals using flexible endoscopes. Finally, even disposal involves measurements of material composition to confirm the composition of the recycled material.

(b) Fan blade root

A challenging example of fretting wear, and thus an area where critical design and manufacture is very important, is that of the fan blade root-to-disc contact. The dovetail profile and socket design features enable the secure location of fan blades into the rotating disc (figure 7). The blades, rotating with tip speeds of approximately $450\text{ m s}^{-1}$, each experience a centrifugal loading of approximately 100 tonnes. At such speeds with centrifugal loading, the blades lock into position, but, at certain times during the operating range, the aerodynamic flow of air
can result in small amplitude movements with high loading. Clearly, dimensional tolerances for the manufacture of both blades and disc need to be specified and measured with a high level of precision.

To enable a satisfactory degree of bedding into the disc slot, and to control the eventual and inevitable wear to a functionally acceptable level, coating systems are applied to the fan blade roots. Typically, these can be plasma-sprayed alloys of copper–nickel–indium, together with dry film lubricants that lower the coefficient of friction at the contacting surfaces, friction being the key property that defines the rate of wear in the system. The reason why this mechanism has to be understood and managed with great care is that the fretting can lead to a deterioration of the fatigue properties of the two components’ materials in the contact region.

The approach to dealing with this problem involves the selection of new combinations of coatings and/or lubricants, and their practical assessment in a number of test rigs. In the early stages of testing new materials, an ‘in-line Dartec rig’ test is employed. This rig consists of a simple flat-on-flat specimen geometry oscillating with a representative set frequency and a normal force of at least 20 kN. Measurements of friction are made during the test, and the number of cycles at which the coefficient of friction rises to 0.3 determines the coating life. The next test in the hierarchy is a much more representative and accurate multi-axis test (figure 8).

This is much more complex with the test piece geometry designed to simulate the blade root dovetail coupling, which can be tailored to the specific engine type. Movement of the test samples within the rig is designed to resemble closely the motion within the engine. The data obtained from such tests can yield a clear discrimination between coating systems (figure 9).
typical test conditions:
- disc load = 120 kN
- blade load = 75 kN
- 7200 : 1 minor–major cycles
- temperature 200ºC max.
- dependant upon the CoF induced however equates to around 250 MPa

Figure 8. Fan blade root bi-axial test rig. The bi-axial rig is specifically designed for the fan blade root and has the ability to induce high- and low-cycle fatigue conditions under high loads. © Rolls-Royce plc. (Online version in colour.)

Figure 9. Fan blade root bi-axial test rig results. © Rolls-Royce plc. (Online version in colour.)

(c) Compressor blade erosion

Erosive attack, or impact wear, is another form of degradation that adversely affects aero-engine performance. Blade material loss by particulate media is very common with military engines that tend to operate in very sandy and dusty environments, but it can be a significant problem experienced in certain civil aircraft operations. Depending on the engine configuration, aircraft design and exact operating conditions, a wide range of particle sizes can be ingested into the fan and compressor sections, resulting in considerable wear of component aerofoils.
with a corresponding loss of efficiency. While separator systems have been used with success in some helicopter engine applications, such a solution imposes too high a loss penalty on civil aircraft. Thus, there is a need for surface protection of compressor aerofoils, especially in respect to large particle sizes, which can produce a high level of damage. A further form of erosive attack arises from the ingestion of water droplets.

A number of technology acquisition programmes have been established by Rolls-Royce to help define an optimum coating system to protect against erosive attack. It is well known that ductile and brittle materials behave in completely different ways when subjected to impact by erosive media. Hard materials provide good resistance to deformation when impacted by fine particles up to about 200 \( \mu \text{m} \), but for larger particles, these coatings have a tendency to crack and eventually fail. Increasing the thickness of single-layer hard coatings does not significantly improve their erosion resistance and can bring other problems. In order to combine the advantages of hard brittle materials and softer ductile materials, multi-layer coating systems (figure 10) have been developed in recent years. These essentially comprise hard ceramic-based layers alternating with metallic layers. This multi-layer architecture provides a tough resilient coating system that is capable of absorbing high impact energies without sustaining damage.

As the manufacturing deposition processes continue to improve, there has been a move towards finer detail, reducing the layer thickness and increasing the overall number of layers. It is now possible to produce layer thicknesses that are at a nanometre scale, although scaling up of the deposition methods to a cost-effective manufacturing process is yet to be fully overcome.

As with fretting damage, it is worth noting that the application of these coatings can lead to a reduction in fatigue properties of the parent materials. The particular challenge, therefore, for the designer is to find the appropriate compromise between these conflicting characteristics.
An example of ‘controlled’ wear used by Rolls-Royce is that of abradable coating technology. Compressor efficiency in the gas turbine engine relies upon a minimum dimension being maintained between the rotating blades and the static casing, typically approximately 0.35mm (figure 11). During different phases of the engine flight cycle, this dimension will change due to centrifugal loading and thermal changes in the system. Reducing the clearance too much can risk damaging the blades due to the possibility of contact with the casing, but widening the gap to allow fully for the dynamics of the compressor would inevitably compromise efficiency. The solution that has been used for many years is to incorporate a ‘soft’ abradable liner into which the compressor blades can safely cut, thus enabling the rotating blades to ‘cut’ the minimum clearance.

Interaction mechanisms and material behaviour within the rubbing zone where the blade contacts the liner are quite critical and determine the levels of blade wear. If the material systems are incorrectly chosen, the abradable liner material can be transferred to the rotating blade tips, a phenomenon that can result in high heat generation and excessive loss of sealing material, thus significantly reducing compressor efficiency.

Designing the optimum seal materials has been a taxing problem for many years. Some sealing materials perform exceptionally well. For example, aluminium-polymer-based liners work quite satisfactorily in the front or low-pressure stages of the compressor. However, as the compressor temperature increases, the material and mechanical property match becomes much more challenging. A further complication in the design of compressor sealing is the change in properties over time. This limits the life of seal material, and liner deterioration will eventually reach the point at which compressor efficiency is noticeably reduced. As this consumes the allowable engine maximum temperature margin, the engine will be prematurely rejected and removed for overhaul.

Thermal conductivity, thermal expansion and material modulus have been found to be key properties, with the optimum liner material being defined within a very narrow range of values.

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On the road to introducing new liner materials, rig testing is a very important step prior to engine validation. Much work has been carried out using test equipment such as the rig located at Sulzer Innotec in Switzerland. This rig concept provides a simple evaluation of cutting performance. Rolls-Royce is, however, currently developing more advanced abradability testing routes through the design of two new rigs due to be commissioned this year. A university-based rig will enable a relatively cheap and quick method to evaluate both liner materials and blade or seal fin tip cutting design, which are being developed through technology acquisition work. While simple in design, the rig will enable precision measurements at the cutting interface. Complementary to this will be the Dresden-based abradability rig, which offers a closer simulation of engine operating conditions. Although more costly to use, it will provide a valuable intermediary validation prior to engine testing.

(e) High-pressure turbine blade

At heart of any gas turbine lies the high-pressure (HP) turbine blade (figure 12) whose function is to extract power from the hot, pressurized gas downstream of the combustion chamber. In a typical Trent engine, the HP turbine blade is operating in a gas stream temperature of approximately 1600°C and generating approximately the same power as a Formula 1 racing car engine. Its tip speed is approximately 480 m s$^{-1}$, which is over five times faster than the Formula I car’s top speed, and the radial clearance between the blade tip and the static liner shroud is typically approximately 0.4 mm.

The blade is manufactured as a single crystal from a complex nickel alloy whose melting point is approximately 250°C lower than the gas temperature. To make this possible, the blade is cooled with HP compressor delivery air, which itself is at approximately 650°C, both internally by convection and externally by films. In addition, thermal barrier coatings (TBCs) are applied to the external surface of the blade; the characteristics of these TBCs are such that their thermal conductivity is a function of composition, structure (figure 13) and even colour.

The holes through which the internal cooling air is exhausted to form the external cooling films are typically 0.5 mm in diameter and, on the leading edge, angled to reduce the potential for blockage by gas-borne sand or other particles. The load on the blade’s root required to retain it in the approximately 60 000 g field is equivalent to three London double-decker buses. Getting the blade metal temperature wrong by an overall approximate 10°C can have a drastic effect on its life. However, today, owing to major advances in materials, modelling and precision engineering, such blades are routinely expected to run satisfactorily for some 35 000 h (4 years) operation, which equates to approximately $24 \times 10^6$ km. The HP turbine blade, then, is a remarkable component.

The design and manufacture of these components, needless to say, involves some remarkable engineering at every step. For example, the single-crystal material contains very accurately controlled trace elements (e.g. lanthanum, rhenium, ruthenium and yttria) to achieve the required combination of creep and thermal fatigue properties, and a major incentive for precision here is the price, and thus availability, of these materials. As noted, TBCs are used to shield the blade material from the gas stream. The TBC profiles are designed to tight tolerances to control the heat flux into the blade; bond coat compositions and
manufacturing methods are controlled to ensure that the ceramic TBC remains attached to aerofoil surfaces and leading edge geometries under the blade’s extreme operating conditions.

The component design process thus sets out to control the interface temperatures for a given ceramic coating distribution by precision engineering of the inner surfaces to give optimum heat transfer conditions. Externally, the ceramic surface is micro-polished on a micrometre level to achieve optimal aerothermal performance and to control the external heat-transfer conditions. Internally, at the interface between the bond coat and the TBC, a thermally induced oxide develops in service. This oxidation, whose growth rate is controlled by bond coat structure and composition, actually promotes adhesion between the bond coat and the ceramic TBC. This is engineering on a very small scale, and the oxide thickness will grow from a fraction of a micrometre to 5 μm, a thickness...
that signals the end of life for TBC adhesion. Design tools have been developed to allow the time to ceramic spallation to be predicted and linked to the component design so that the blade life is managed safely.

Rolls-Royce’s Trent engines are noted in the industry for their continued adoption of shrouded HP turbine blades. However, a considerable body of research has been invested in a shroudless design (figure 12). This requires even greater precision of the control of running tip clearance, which will need to be maintained over the life of the turbine to approximately 0.12–0.25 mm. An active tip clearance control system has been designed, and great attention is being paid to the blade tip and static liner material systems, and to their cooling systems. The former challenge is being met by the use of a high-temperature, sinter-resistant, ceramic outer coating and a traditional zirconia-based material at the interface to promote bonding (figure 14); the latter is being addressed by the application of cascade impingement cooling to the external surface of the liner.

This improved segment design uses an optimized outer coating with controlled porosity to allow a track to be cut when contacted with an abrasive tip applied to the HP turbine blade.

(f) Fuel cells

The foregoing has focused on the company’s gas turbine technology. The brief background to the company’s engagement with fuel cells is that, having begun researching fuel cell technologies for commercial application in 1992, it was decided in principle to pursue the potential commercialization of this growing expertise in 2002. By applying its aerospace technology skills, Rolls-Royce designed an electrical power system that integrates a solid oxide fuel cell with a micro-turbine. This power system promises to be significantly more efficient...
efficient than any conventional gas turbine or reciprocating engine, with far less impact on the environment. The objective was set to develop a stationary, 1 MW power-generation system.

The fundamental architectural element at the heart of the system is the fuel cell ‘tube’ (figure 15). This is constructed in magnesia magnesium aluminate (MMA) ceramic, has a flat rectangular cross section and is approximately 25 cm long. Each tube is screen-printed with 60 cells (on both sides of the tube), each of which produce 0.5 W at 0.85 V and 0.5 A. A reformed natural gas fuel passes through the inside of the tubes, and air is passed transversely through the gaps between the stacked tubes, i.e. over the external surface of the tube. The MMA ceramic acts as the structural support but is also porous, which allows the fuel to diffuse to the anode, and the air passing across the outside of the tube comes directly into contact with the cathode. More than 20,000 tubes are required to generate the 1 MW rating.

This project has taken the company into a fascinating new world: mass production and electro-chemistry. The tubes are manufactured from powder, whose starting grain size has to be carefully controlled, and are required to achieve high degrees of flatness, both for the screen-printing of the chemically active layers and for subsequent assembly into ‘stacks’. For example, both warp and
curvature in any plane have to meet tightly defined limits. The screen-printing is required to lay down these active layers successively, and to achieve thicknesses as small as $15\,\mu m$ and linear separations measured in tens of micrometres. The printing comprises a specific and complex arrangement of five basic layers: anode, cathode, electrolyte, plus the anode and cathode current collectors; in addition, there are a number of dense and porous chemical barriers. All these need to be laid down accurately and repeatably while ensuring electrical continuity and avoiding parasitic losses. To achieve a stable and durable structure, both the strength and Young’s modulus are defined within specific ranges.

It continues to be a significant challenge to produce the desired mechanical and electro-chemical properties of the tubes, and subsequently the desired performance at the operating condition (typically, in the region of $850^{\circ}C$), particularly given that they need to be producible in large numbers. The types of measurement in which the company now needs to establish expertise embraces such metrics as electrochemical impedance spectroscopy, parasitic current density, polarization loss and area-specific resistance. In addition to their electrochemical characteristics, materials have to be carefully chosen to ensure they can integrate into a structure that can rise from ambient temperature up to its operating temperature without compromising the integrity of the structure. For this reason, particular care is exercised in matching their individual coefficients of thermal expansion.

(g) Nuclear engineering

In view of the relatively recent formation of a Nuclear Sector, and the intention to exploit the company’s naval nuclear reactor expertise in the civil nuclear power field, it is appropriate to take a brief tour around the precision engineering demands of this technology. In the nuclear industry, challenges to precision are often associated with large heavy components that see significant thermal and pressure loading and yet are expected to perform continuously and last for decades with little or no maintenance. There are thus a number of key requirements that dominate how a nuclear powerplant is made and how it is controlled. The following attempts to give a glimpse of the engineering challenges, based on the company’s experience in pressurized water reactor (PWR) technology (figure 16).
(i) **Fuel**

When a reactor is fuelled for life, it is critical (a word that is used with some precision) that it is known exactly how much fuel there is and where it is placed. This requires significant design and analytical work by physicists and engineers to achieve durability, reliability and safety targets. Precision in design must then be matched by precision in manufacture, for the material, material form and component geometry.

(ii) **Control**

The key component with regard to control of a PWR is the control rod. By placing a neutron absorber accurately within a core, the reactor can be controlled to assure long life and exemplary safety. This control is achieved by fabricating a control rod many metres in length that must be positioned accurately to within a few millimetres and must be able to be inserted quickly and reliably when required to do so. This control imposes tolerance, finish and alignment requirements on many components that range in weight (and thus size) from a few grams up to greater than 100 tonnes. For example, the alignment of the control rod has a ‘stack-up’ of tolerances that includes large, heavy components, such as the reactor vessel and its closure head, down to small components in the control rod drive motor. These tolerances are most challenging when large heavy components are being assembled together, with some location features controlled to fractions of a millimetre on a large diameter.

(iii) **Water**

Water is fundamental to the function and safety of a PWR and, as such, every characteristic is subject to very precise control.

— **Chemistry.** The quality and constituents of the water that passes through a nuclear reactor must be carefully specified and closely controlled in order to minimize accumulation of radioactive contaminants and to minimize corrosion of the wetted environment.

— **Surface finish.** Surface characteristics are very important to the wetted environment, with a long-established minimum finish requirement to ensure that rates of surface contamination and corrosion are managed to support the required operational and lifetime objectives.

— **Temperature.** Transfer of the heat energy from the nuclear reactor to a secondary fluid circuit is one of the prime functions of a nuclear plant. Thus, specification and control of water temperature is very important. Passive (automatic) monitoring and control assures a temperature high enough to extract heat but low enough to achieve safety and reliability targets.

— **Pressure.** A PWR maintains single-phase flow (i.e. no steam in the primary circuit). This requires pressure to be maintained and controlled within strict limits. Automatic monitoring and control assures a pressure high enough to prevent boiling but low enough to achieve safety and reliability targets.

— **Flow.** The uninterrupted flow of water round the primary circuit is an essential characteristic for a PWR. Large powerful pumps are required for
this duty, with close tolerances specified on bearing surfaces and clearances to ensure efficiency and long life. To achieve this, the surface form of one of the bearings in these machines is specified in units of wavelengths of light.

— **Cleanliness.** Hot pressurized water is an aggressive engineering environment that challenges many materials. The long life targets set for nuclear plants require a large number of chemicals to be controlled down to extraordinarily small proportions to avoid any form of environmental attack. In addition, some materials become radioactive when they pass through a reactor. These materials are also controlled to ensure that radiation exposure to maintenance workers is minimized. Cleanliness is therefore important for the full engineering life cycle of a nuclear reactor, from conception through to decommissioning. Cleanliness requirements influence design specifications, manufacturing methods and processes, assembly and build discipline and operability.

(iv) **Manufacture and build**

The form and fit of components and equipment often determines the success of the function. Thus, although it is incumbent on the designer to specify achievable limits, equipment and components must nonetheless be manufactured and assembled to achieve these close limits. In these instances, precision engineering includes establishing or developing production techniques and equipment assembly fixtures. Examples of the challenges to the manufacture and build of a PWR plant include the following.

— **Reactor vessel assembly.** A large thick-walled vessel with internal components that must be fitted and aligned precisely.

— **Reactor vessel head.** A large component that provides a removable end cover for the reactor, permitting simplified build and decommissioning (and refuelling, if required), but also providing a mounting point for the control rod drive motors. Alignment of these motors to the head, and of the head to the reactor vessel, must therefore be precisely controlled.

— **Pumps, control rod drive motors and valves.** Precision mechanisms that combine high temperature and pressure loadings with requirements for small clearances and contact surfaces, operating in a fluid that possesses very poor lubricating properties.

— **Pipework.** Large diameter pipes must be designed, manufactured and fitted between large components to small tolerances.

— **Boiler (or steam generator).** Large quantities of small diameter tubes are fitted and welded, requiring very accurate hole positioning and drilling and tube positioning and welding.

(v) **Maintenance**

Some maintenance activities that would be simple and straightforward in any other industry become challenging in the nuclear industry due to the presence of radioactivity. Every effort is made to minimize radiation, but the physics of radioactive decay imposes a need to carry out maintenance activities in the presence of radiation. As such, there is a self-imposed discipline to ensure that
the need for maintenance is minimized, and when essential, to ensure that it can be carried out quickly, efficiently and safely. This discipline has given rise to a plethora of precision machines designed to carry out remote inspection, maintenance and refurbishment of the nuclear plant.

In summary, all these challenges generate interactive features requiring multiple levels of precision, e.g. material control, geometry specification, manufacture and build and process control.

(h) Non-destructive evaluation developments

It is a truism to state that engineering structures have always contained defects, both in their original manufacture and arising during service operation. Engineering has sought to understand and control such defects, focusing particularly on those components whose failure would be catastrophic. Examples of such structures or components are nuclear reactor pressure vessels and their welds, gas turbine discs and ship rudder stocks. The non-intrusive detection of potential defects in materials, both on the surface and internally, has thus received a lot of attention, and both capability and precision have improved markedly. In some areas, this improvement has prompted the need for better analysis of local material properties, local stress levels and local crack propagation rates. These trends are apparent in both original manufacture and, increasingly, in service.

An example of a non-destructive evaluation (NDE) technique for original manufacture that has improved dramatically (figure 17) over the past 20 years is X-ray computed tomography (CET). The kind of detail that CET can yield today is quite extensive (figure 18). As can be seen, the three-dimensional presentation of the composite components is especially striking. This development is timely as the company is seeking to develop its first composite fan blade since the late 1960s.

An example for the in-service application of NDE is the detection of defects in HP turbine blades on-wing. This technique, the total focusing method, is based on the technology used in maternity scans, and it took approximately 7 years...
to develop and take the concept from TRL1 to TRL6. The challenge was that the use of ultrasonic inspection in a single-crystal material is distorted by the variation of the sound velocity with the direction of propagation (figure 19).

The trick was to correct for the crystal orientation via an understanding of its characteristics (e.g. Poisson’s ratio, lattice constants). The resulting physics was then built into a probe that could be inserted by a borescope port in the engine (figure 20).

Another technique to detect surface defects caused by sulphidation is based on the tried and tested method of dye penetrant; here, the company has developed a cunningly packaged device that fits down a borescope port and applies a squirt of in situ penetrant, the result being visually inspected under illumination (figure 21).

Probably the most practical and best known of the company’s in situ NDE techniques is that used for the detection of foreign-object-damage-induced defects in the leading edges of the fan blades in Pegasus engines. This requires the

Figure 18. X-ray computer tomography images of typical engine components. © Rolls-Royce plc. (Online version in colour.)

Figure 19. Ultrasonic inspection of a single-crystal material before and after reorientation. © Rolls-Royce plc. (Online version in colour.)
Review. Future propulsion systems

size of probe for *in situ* inspection, maximum height 8 mm

array size $4 \text{ mm} \times 8 \text{ mm}$

array design, 72 $0.5 \text{ mm}$ elements from sonaxis

Figure 20. Turbine blade ultrasonic inspection. © Rolls-Royce plc. (Online version in colour.)

inspector to crawl along the intake of the AV8B aircraft and run a pair of women’s tights along the length of the blade; reportedly, 10 denier gives the best results.

5. Looking to the future

Today, if such a general observation can be made, Rolls-Royce is arguably still living in the world where surface finishes are defined by the roughness (arithmetic mean of absolute surface height). This approach has served the company very
effectively for a considerable time. However, the increasing pace of competition, and the emergence of much more sophisticated technologies at an affordable price, herald that change is due. The current research portfolio contains quite a number of relevant examples that either demand or presage change:

— the development of organic matrix composite fan blades and static structures;
— the development of ‘lean burn’ combustion for reducing NOx emissions;
— the relationship between surface finish and performance (or drag) at the fan and compressor blade scale (figure 22);
— the potential reductions in noise generation by the removal of joints/overlaps in critical areas;
— the effects of surface finish on the propensity for fuel and oil coking in hot pipes and chambers;
— the active control of HP turbine tip clearances by direct measurement and pneumatic or electric actuation;
— the increased density of fuel cells screen-printed onto the ceramic flat tube;
— the evaluation of the nonlinear ultrasonic propagation technique for material damage detection;
— the influence that surface finish has on the dynamic behaviour of materials (e.g. mechanical and thermal fatigue), and hence on the assured lifetime of nuclear components;
— the development of coatings to resist the formation and adherence of ice crystals; and
— the requirement in new air-riding seals for surface finishes specified in units of wavelengths of light, running with axial gaps in the sub-100 μm range.

All of these might well lead the company to define surface finishes in a more sophisticated way than at present, e.g. ‘structured surfaces’, a trend that will place even greater emphasis on the ‘design/make’ relationship, which seeks to ensure that the demanded geometry is consistent with manufacturing capability.
Looking ahead, the company is positioning itself to be able to respond to society’s demands for cleaner, greener power in the air, on land and at sea. As a consequence, its product portfolio is currently expanding beyond the gas turbine and its marine and energy derivatives to electricity generation, e.g. civil nuclear, fuel cells, tidal turbines and reciprocating diesel engines (figure 23). There are growing opportunities to expand the marine portfolio, both in the reduction of its emissions and in energy exploration, and there are new technologies that are being evaluated such as energy storage. The company thus anticipates the doubling of its business over the next 10 years.

From a technical standpoint, this means that Rolls-Royce will continue to be a significant consumer of developments in surface engineering where advances can be demonstrably and affordably translated into customer benefit: better performance or capability, higher reliability or more predictable behaviour. Overall, the company aspires to retain and enhance the reputation for precision engineering and excellence inherited from our founders.

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Reference


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