Abradable coatings - From black art, to materials science.

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Abradable Coatings – From Black Art, To Materials Science

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DECLARATION

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Acknowledgements

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CONTENTS

1. Summary

Suck, squeeze, bang, blow! The efficiency and performance of a gas turbine engine relies on the ability to maintain high gas pressure ratios, throughout each stage of the compressor. To do this, engine manufacturers must minimise gas leakage over compressor blade and seal fin tips.

Increasing the efficiency of the gas turbine engine is an area of enormous importance to engine manufacturers worldwide. The rewards are obvious when it is considered that a modest improvement of 0.5 to 1% to the Specific Fuel Consumption (SFC) can translate to huge savings on fuel costs. One way in which engine manufacturers are looking to do this is through the use of abradable seals, which are used to help seal the engine and reduce air leakage over blade tips.

In an attempt to gain a fundamental understanding of abradable materials, this thesis discusses research carried out as part of an Engineering Doctorate. The research focuses on three key topic areas, identified as necessary for generating a robust understanding of the complete coating life.

The research carried out within this EngD programme has helped to generate a fundamental understanding of abradable materials by focusing on three key topic areas:

i) Development of Test Methodology
ii) Definition of Performance Drivers
iii) Implementation of Technology

Within these topic areas programmes of work have been carried out, which aim to fill gaps in current knowledge and provide the knowledge and techniques for future coating development. Significant advances have been made in all aspects of abradable understanding and the knowledge generated is now being successfully implemented within the Rolls-Royce Abradable Strategy.

As the demands from regulators and airlines for greater aero engine performance increase, the need for reliable and effective compressor sealing will become evermore critical. The knowledge and techniques developed within this EngD programme will enable further detailed understanding of the science of abradable materials.

2. Introduction

Maximising the efficiency of aero, marine and industrial gas turbines is an area of great interest to engine manufacturers worldwide. The advantages are obvious when it is considered that a modest improvement of 0.5 to 1% to the Specific Fuel Consumption (SFC) can translate to huge saving on fuel use. This in turn means a more environmentally friendly and economical engine and, in the case of an aero engine, a greater payload capacity (Walsh and Fletcher 2004). The fuel consumption of a Rolls Royce, Trent 500, civil aero engine is up to 15,200,000 litres/year. Therefore a reduction in SFC of 1% can translate to a saving in fuel of 152,000 litres/engine/year. To date over 750 Trent 500 engines have been sold, each with an estimated service life of 20 years. The resulting fleet saving from the 1% SFC would be a massive 2,280 million litres (Ghasripoor *et al* 1997 pp.328-30). Increased operating temperatures, improved aerodynamics and a greater materials understanding have led to huge improvements in engine efficiency. To further improve the efficiency and performance of new engines it is obvious that new, more innovative techniques must be developed in order to push the technology to its absolute limit.

Studies in the late 1980's revealed that losses in engine pressure, due to the leakage of air through the gap between the blade tip and engine shroud (clearance gap), increase linearly with the size of the clearance gap (Bindon 1989).

For over 35 years abradable seals have been used in gas turbine engines to reduce the clearance gap between blade tip and shroud, thus reducing 'over-tip leakage', which can lead to a loss of pressure and therefore a reduction in engine efficiency and performance.

Expansion and deformation, caused by temperature gradients and stress fields within engine components, and built-in manufacturing inaccuracies, mean the gap between blade tip and engine casing can never be completely alleviated (Nielsen 1984). An abradable coating can accommodate such deformation and inaccuracies by offering a relatively soft sacrificial layer, which is machined away by the blade tip itself, when the engine is accelerated toward maximum power. In addition to these abradable characteristics, seals must also be able to withstand the extreme conditions of the jet stream of a modern gas turbine (Schmid 1997). This thesis will specifically consider the abradable seals used in the compressor section of the engine, although abradables are also used in the turbine section of the gas turbine. The abradables discussed in this thesis are used principally in aero gas turbine engines as this is generally where cutting edge technology is first applied, although their use also spreads to marine and power generation gas turbines.

Rolls-Royce currently use a range of compressor abradables, which have been developed, with coating companies, through an ongoing programme of laboratory testing and materials development/selection. Although it is a well established industry the level of understanding of these materials is highly conceptual.

Thermal spraying has long been referred to as a 'black art' industry. Coating material properties are often not available, due to inherent difficulties in the generation of representative data. Thermal spray processes are highly dependent upon a seemingly endless number of parameters and variables, which make controlling these processes a huge specification challenge (Pfender 1999). Service experience throughout the gas turbine industry is a testament to the infantile maturity of the thermal spray industry, and the susceptibility of these coating materials to premature failure, when faced with the demands of a modern gas turbine engine. Abradable materials, whose basic functionality and performance drivers have never been quantitatively defined, are a classic example of reactive material development.

A literature review of abradable technology has been carried out to identify specific areas of research, which make a significant impact within this expertise.

3. Literature Review

3.1 Basic Principles of Abradables and Abradability

Abradables are used to reduce over-tip leakage of air throughout the compressor of a gas turbine engine. They function as seals between rotor blade and casing, between drum and stator and as labyrinth seals (oil and air). This helps to maintain the pressure within the combustor and thus increases engine efficiency (Schmid 1997).

This thesis will focus on the intermediate pressure (IP) and high pressure (HP) compressor abradables, which are thermally sprayed onto the rotor paths of the engine shroud. It is these materials, which have been the most problematic as far as in-service failures and manufacturing variability are concerned. Their role is to maintain a minimum compressor blade tip clearance, while also preventing the blade tip from making contact with the engine shroud (Saravanamutto *et al* 2001). Figure 1 shows the position of IP and HP compressor stage abradable seals on a typical Rolls-Royce civil aeroengine.

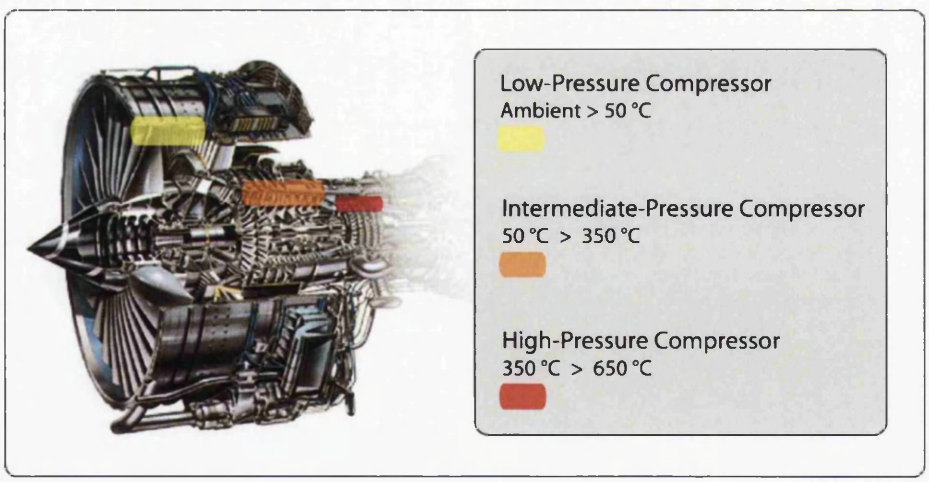

Figure 1. Location of LP, IP and HP compressor abradable seals on Rolls-Royce, Civil Trent Aero Engine

By wearing preferentially to the other engine components, abradable seals reduce pressure loss to a much higher degree than would be achievable by relying solely on mechanical tolerances (Uihein 1996). Figure 2 shows the principles of an abradable seal in a compressor rotor path.

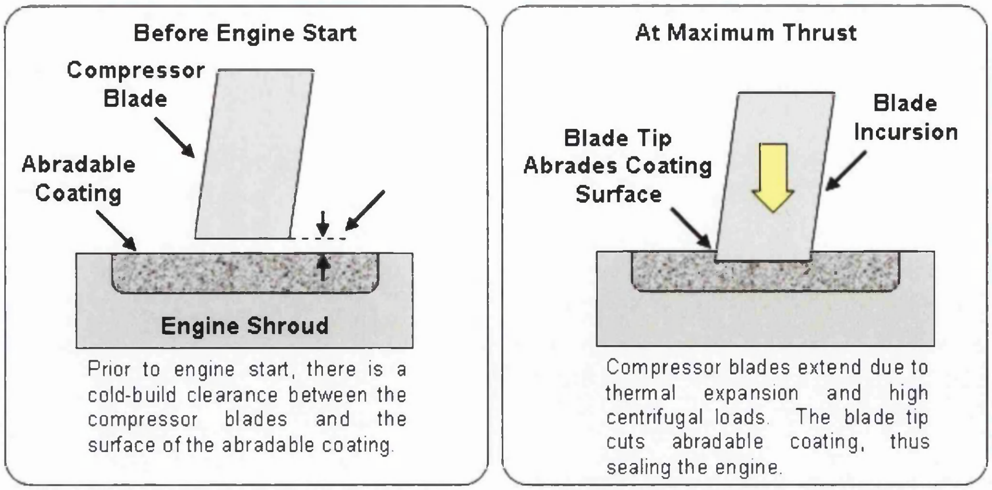

Figure 2. Compressor blade and abradable seal arrangement

Before entering service all gas turbine engines go through pre-service pass-off also known as running-in and handling. This gives the engine manufacturer confidence that the engine will perform as expected under various flight conditions such as a full-thrust acceleration. This is representative of the take-off and, to a lesser degree, landing parts of a normal flight cycle. During this the blades, which will be rotating at maximum velocities, will extend due to a combination of thermal expansion and elastic deformation as a result of centrifugal forces acting upon them (Zheng and Daubler 2002). In doing so they will come into contact with the abradable liner. At this point the blade tips will act as machine tool tips, cutting a path in the softer abradable material. The mechanics by which the abradable material is cut, or more accurately 'abraded', are quite complex and will be discussed later in this literature review. The depth of this path will be dependent on the in-built clearance tolerance of the stage and the extension of the blade during maximum thrust. As the engine decelerates the blades will elastically contract to their original length. The resulting path cut into the abradable will mean that, essentially, there will be a zero clearance between the blade tips and abradable during maximum thrust (Nielson 2005), and maximum high thrust engine efficiency.

As discussed above, the abradable material is required to abrade preferentially to other engine components. If the abradable is too hard or too abrasive then it will cause the blade to wear. Not only will this result in over-tip leakage and a resultant loss in engine efficiency and performance, but also in the case of titanium blades, which are used extensively in the compressor stages, may result in a titanium fire (Uihlein and Schlegel 1997).

3.2 Abradable Material Property Requirement

In addition to the aforementioned sacrificial properties, abradable coatings must display a number of additional characteristics in order to maintain their sealing properties in service. These can be summarised as follows:

Erosion resistance

While preferentially abrading by the action of incurring compressor blades and disc fins, an abradable must also be resistant to the erosive nature of the high-speed gas flow within the engine (Tilly 1979). This is made more challenging by particles of dust and debris, which are ingested into the engine and can increase the erosive characteristics of the gas flow (Smeltzer *et al* 1970). If the abradable seal is eroded, the clearance between blade tip and coating will be increased, resulting in a reduction in engine efficiency (Bindon 1989).

Oxidation resistance

Abradables are often exposed to moisture and/or high-humidity during service and storage, which could potentially cause the material to corrode. This would result in altered material properties and possibly material blistering and material drop-out, with adverse effects on engine efficiency and performance (Datta and Burnell-Gray 1996).

In addition, high-temperature oxidation resistance is also an important material requirement, particularly for abradables operating within the HP compressor at temperature up to 650°C.

Thermal Stresses

As the operating temperatures of gas turbine engines increase, ever higher, the requirements of all materials used are stretched to their limits. In addition to the high-temperature capability requirements of the HP compressor and turbine abradables, all abradables used must be able to withstand the cyclic thermal gradients imposed on the materials during each flight cycle (Kuroda and Clyne 1991).

Typically the coefficient of thermal expansion of the coating is greater than that of the substrate (sometimes by a factor of 2-3). Figure 3 shows the type of stresses, which are applied to a coating during a single engine cycle, where α_c is the coefficient of thermal expansion of the coating and α_s is the coefficient of thermal expansion of the substrate and $\alpha_c > \alpha_s$.

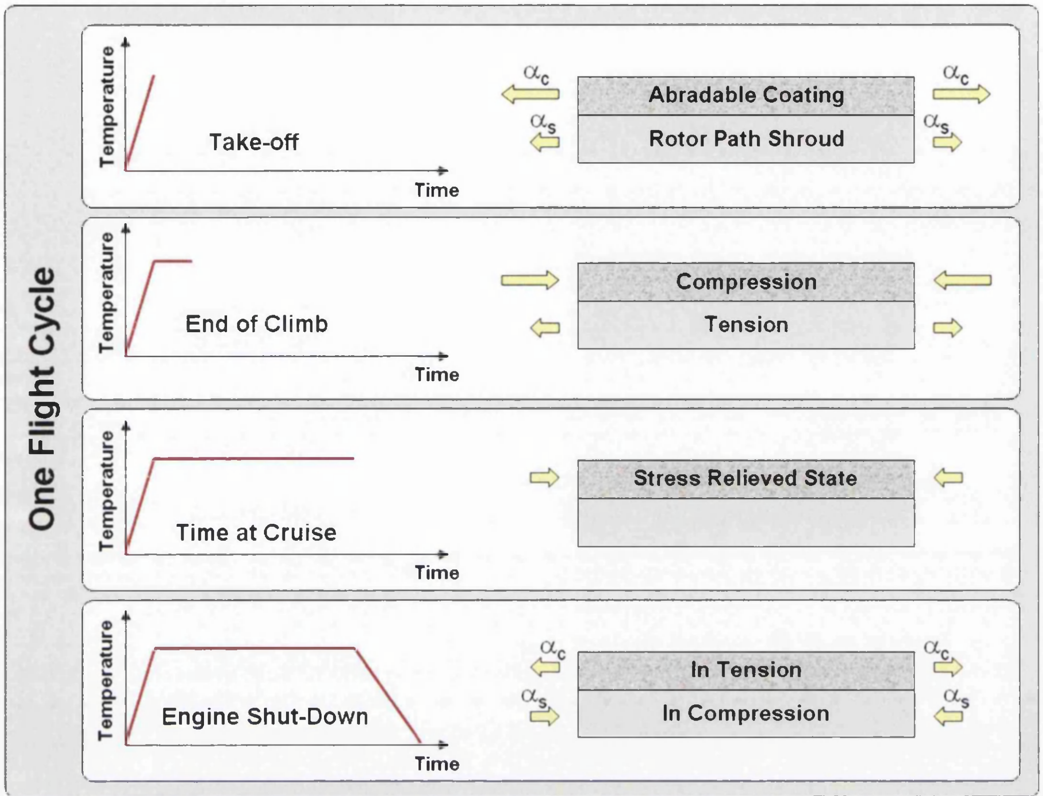

Figure 3. Thermal stresses on abradable coating during the engine cycle

When the abradable coating has a greater coefficient of thermal expansion than the substrate material (engine shroud), a tensile load is applied to the coating after one complete engine cycle. During engine start-up and take-off the temperatures of the abradable and substrate increase. As this occurs the materials expand proportionally to their respective coefficients of thermal expansion. Therefore, when $\alpha_c > \alpha_s$ the abradable will attempt to expand more than the substrate material. Abradable expansion is restricted by the substrate, which has a higher stiffness than the coating material. This causes the coating to go into a compressive stress state. During time at elevated temperatures (the cruise section of a flight cycle) the coating stress relieves and the compressive stresses are reduced. This continues until the temperature is reduced (engine shut-down), when the coating and substrate contract, causing the coating, which is approaching a stress free state at temperature, to go into a tensile stress state. As this occurs at lower temperatures it is much more difficult for the coating to stress relieve and so these tensile stresses are locked into the coating until the next engine cycle. As stresses accumulate with the number of cycles the engine completes they may reach a critical value, at which point the coating will crack. This type of cracking has been observed in numerous engine components to varying degrees of severity. It is believed that small cracks, which have little or no effect on the sealing efficiency of the coating, can be advantageous to the integrity of the coating as a whole as they act as stress relievers. Unfortunately when these smaller cracks eventually grow and coalesce they can cause loss of coating material (spalling). This type of failure has a dramatic effect on the clearance gap of the stage and on the effectiveness of the abradable seal.

Abradable debris

As the abradable is cut by the blade tips it is important that the resulting abradable debris is small and such that it does not cause any damage down stream of the rotor path (Zheng *et al* 2002). As discussed later in this thesis, dislocator phases within the abradable aid the fracture mechanics of the abradable material and ensure that the debris created is not problematic to other engine components.

A range of alloys and composites are currently employed to cope with these demanding and often contradictory material requirements. At present, abradables are applied by thermal spraying (Section 3.4) of the material in powder form onto the engine component. The resulting microstructures are defined by properties of the original powder and the spraying parameters used to deposit this onto the substrate. A typical abradable microstructure contains two or three distinct phases. There is always a matrix material, which may be a pure metal, an alloy system or, to a lesser extent, a ceramic. The role of the matrix material is to create a coherent structure, which usually has ductile properties. The second phase is known as the dislocator phase, which can be either a material phase (as in a fully dense coating) or simply regions of porosity within the matrix (as found in a porous coating). The dislocator phase acts as an initiation site for cracks and aids in the creation of fine abradable debris as the coating wears under the incursion of a blade tip. An additional third phase, sometimes used, is a binder, which increases adhesion between the matrix material and the dislocator phase, to ensure there is no segregation of material during spraying (Faraoun *et al* 2005).

3.3 Abradable Materials and Their Classification

Although the work discussed within this thesis will concentrate on the abradables used in the IP and HP compressors, it is important to understand the various abradable materials used throughout the whole of a modern gas turbine engine. The predominant factor governing material selection is the maximum operating temperature of the coating. In addition to these thermal properties, various engine stages demand further material capabilities.

The Coating manufacturer, Sulzer Metco, originally devised the concept of five abradable families, in order to classify the various types of abradable materials (Schmid 1997). These abradable families and respective operating temperatures are shown in Figure 4.

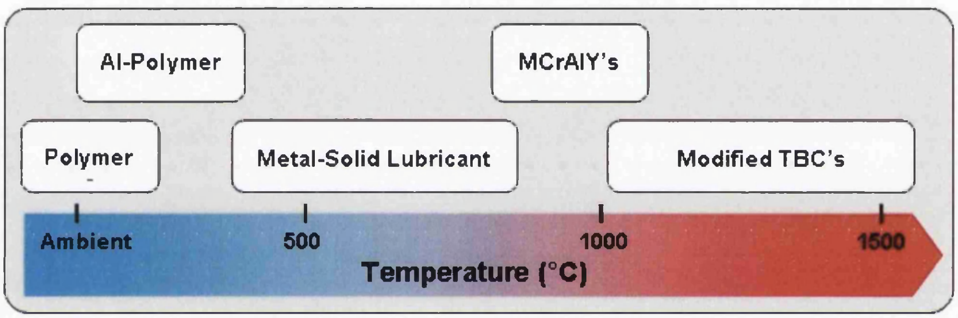

Figure 4. Temperature limits of the five abradable families

In addition to the three families of thermally sprayed abradables, Rolls-Royce also uses prefabricated abradable systems, which are then attached to the engine components.

Honeycombs and Feltmetals

Honeycombs form an alternative turbine abradable seal, manufactured from oxidation resistant metals and vacuum brazed to the engine components. Honeycombs are often filled with MCrAlYs or thermal barrier coating (TBC) ceramic powders and their abradable performance relies on their ability to collapse and deform, whilst maintaining a seal (Bondarenko and Khizhnyak 2005).

Feltmetals are abradable materials, which consist of thin oxidation resistant metallic strips or wires, pressed together to form an extremely porous material; these are then vacuum brazed on to the engine component. Feltmetals provide good abradability performance but high porosity limits their sealing ability. Feltmetals are usually used to prevent gas or oil leakage between compressor drum seal fins and stator ring shrouds (Tolokan 1980).

The IP and HP rotor path compressor abradables currently used by Rolls-Royce can be split into three distinct groups, as dictated by the operating temperature limits of the materials used. This is unsurprising when considering that the operating temperatures of an aero engine at cruise range from –50°C at the fan to 700°C at the rear of the HP compressor. These three groups are shown in the flow chart in Figure 5, and include a range of dislocator materials such as hexagonal boron nitride (hBN) and bentonite, which is an absorbent aluminium phyllosilicate clay.

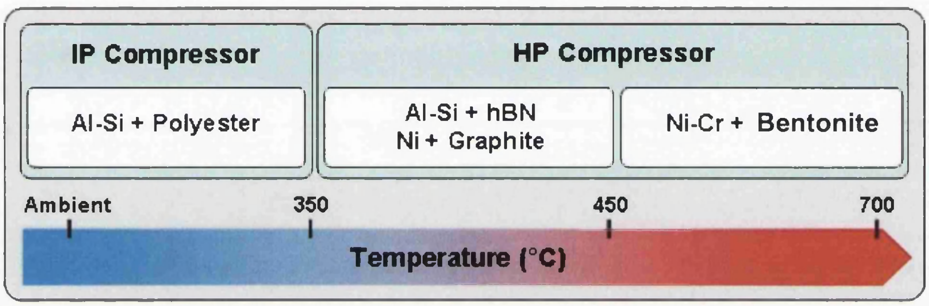

Figure 5. The three abradable groups currently used for IP and HP compressor stages

3.4 The Manufacture of Thermally Sprayed Abradables

A range of techniques is currently used in the manufacture of abradable materials and their bonding to various engine parts. Plasma spaying is the currently favoured technique for applying most compressor abradables, whilst others use the more traditional method of combustion spraying (Pfender 2004).

The majority of abradables require an intermediate bond coat, to ensure that the abradable material is well adhered to the shroud material. The bond coat has a roughened surface, which means that the abradable can bond to it through a mechanical keying effect; a plasma spraying process is often used for its application (Brindley 1997).

Since its invention by the Swiss engineer, Dr Max U. Schoop, in the mid 1920's, thermal spraying and its application for the production of coatings has grown enormously. Much of this growth has been driven by 'high-tech' industries such as jet engine manufacture (Sulzer Metco 2003). The basic principle of thermal spraying is shown in Figure 6. Coating materials, in the form of powder, are injected into a flame where they are heated and accelerated to high speeds; the molten or semi-molten particles are sprayed in a controlled manner onto a cooler substrate where they instantly solidify. In this way a coating can be built up to any desired thickness (Pawlowski 1994).

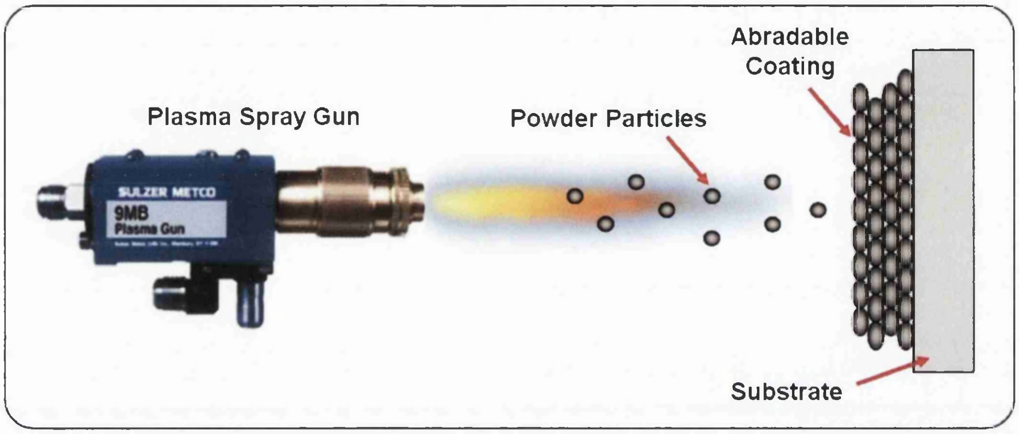

Figure 6. The thermal spray process

Two types of thermal spray technique, the Combustion Spraying process (CS) and the Air Plasma Spraying process (APS), are currently used for applying almost all current abradable coatings.

Combustion Spraying

In a CS system, powder is continually fed into an oxy-acetylene or hydrogen flame where it is melted by the heat of combustion and projected out of the spray gun, onto the component. The powder is transported to the spray gun by a carrier gas. Table 1 shows some of the process characteristics of the CS process (Sulzer Metco 2003), which produces coatings with porosity contents of 5-10%. It follows that the CS process is usually used to produce porous coatings i.e. coatings where porosity acts as the dislocator phase.

Table 1. Typical CS process characteristics

Characteristic	Typical Value
Flame Temperature	3,100°C
Particle Velocity	200-300 ms^{-1}
Porosity Content	5-10%
Oxide Content	5%
Bond Strengths	No bond coat 10-14 Nmm^{-2} Bond coat/One step materials 35 Nmm^{-2}

Figure 7 shows a simplified cross-sectional view of a typical CS gun, and a photograph of the flame generated.

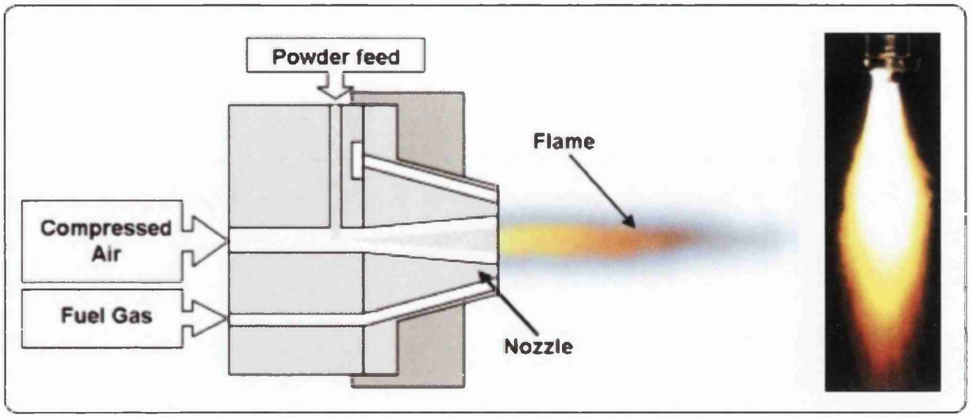

Figure 7. Cross-sectional view of CS gun and photograph of a CS flame

The CS process provides a simple, economical and reliable thermal spraying method, used for a number of coating systems. Abradable coatings sprayed using CS systems have been shown to demonstrate relatively large amounts of variability. This has led to the current drive towards the more reproducible coatings, made possible through the use of APS.

Air Plasma Spraying

In an APS system, powder is continually fed into an inert gas, which is then ionised by a D.C. electric arc, generated across the nozzle (anode) and an electrode (cathode). Electrons are ripped away from their gas molecules by the powerful electric arc, which results in the formation of an unstable plasma. Table 2, illustrates some of the process characteristics of APS (Sulzer Metco 2003).

Table 2. Typical APS process characteristics

Characteristic	Typical Value
Flame Temperature	8,000-16,600°C
Particle Velocity	600 ms^{-1}
Porosity Content	0.5-3%
Oxide Content	0.5-5%
Bond Strengths	35-70 Nmm^{-2}

As well as offering a more robust and versatile spraying method, APS also produces a much hotter flame than CS and better heat transfer to the powder particles (Sampath 1993). This can be explained by utilising the theory that plasma is actually a fourth state of matter (solid, liquid, gas, plasma). As electrical energy transforms the gas within the spray gun into plasma some of the energy goes into the change of state (rather than actually heating the gas or plasma). When the unstable plasma leaves the nozzle it loses energy, recombines with electrons and returns to the lower energy state of a gas. There is an energy release associated with this change of state, some of which is transferred to heat that subsequently heats the powder particles. The heat generated as plasma transforms to a gaseous state and can exceed the surface temperatures of the sun (Sulzer Metco 2003). Figure 8 shows a cross-section of a typical APS gun and a photograph of the flame produced.

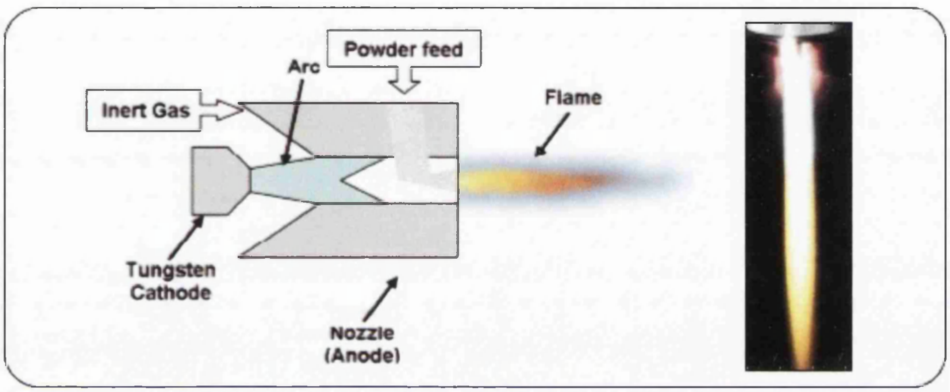

Figure 8. Cross-sectional view of an APS gun and a photograph an APS flame

Rotor path shrouds are sprayed as quadrants, halves or complete rings, depending upon the particular component. In all cases the component is rotated about the gun, which in turn traverses vertically in order to spray over a specified area. All modern spray systems are automated, with the gun mounted on a robotic arm. Spray programs are pre-programmed into a control console in order to ensure repeatability in terms of spray coverage and relative feed rates (Pfender 2004).

Prior to coating, the engine component must first be grit blasted. This is to ensure that the surface area to be coated is free of contaminants and any oxide build-up, also to improve mechanical adhesion between the bond coat or abradable and the substrate (Varcalle and Beitelman 2001). The time between the component being grit blasted and the coating being sprayed should be minimised to ensure that the part is not contaminated or does not oxidise prior to coating. Rolls-Royce specify there should be no more than 1.5 hours between surface preparation and the application of a coating. It follows that the time between bond coat and topcoat should be minimised, once again to prevent oxide or contamination of the surface

(Chis 2003). To further minimise surface contamination, the thermal spray gun will be used to heat the relevant component surface prior to spraying, thus burning off dust and superficial debris, often using a reducing gas such as hydrogen.

In addition to this surface treatment, components must be masked to ensure that only the rotor path or seal area is coated. This is often done using a high-temperature-capable masking tape or with a reusable metal or silicon mask. Separate masks will often be used to protect areas of the component during grit blasting and spraying.

Following the spraying process, components will require subsequent machining in order to remove any flash, which has been sprayed outside the rotor path or coating area, and to smooth the surface of the abradable coating. The exact details of the machining processes vary for different coating materials and the individual geometries of shrouds and rotor paths.

3.5 Abradability Mechanics

The primary design criteria for an abradable material in terms of its functionality within the engine, is its ability to abrade. Abradability performance under the type of operational condition associated with a modern gas turbine engine is a highly complex thermo-mechanical wear mechanism (Yi *et al* 1999).

A number of theories have been expressed, which attempt to explain the fracture mechanics by which an abradable seal is cut by a rotating blade tip. The most widely supported and referenced is the Schmid (1997) model. From the results of his model Schmid goes on to discuss deformation conditions and material properties, which should be obtained in order for an abradable material to abrade effectively. The model considers the interaction between the blade tip and the abradable coating and uses the following observations:

i) Debris produced should be released though a brittle failure mechanism

ii) Debris should disperse as much energy away from the blade interaction as possible

iii) Debris production should ensure that the coating is no longer in contact with the blade tip (no rub)

These are clearly simplifications of what actually occurs during abradable wear, but they are essential for the model to be effective. An important observation, which is also vital for the validity of the model, is that for blade speeds in excess of $100ms^{-1}$, debris will be released to the rear of the blade tip and the formation of chips ahead of the tip does not occur.

As a rotating blade moves parallel to the coating material it also incurs perpendicularly towards the coating, due to thermal expansion and mechanical deformation caused by centrifugal forces. Eventually, when the blade is rotating at a high enough velocity, it will impact onto the surface of the abradable coating. This results in a momentum transfer from the blade to surface protrusions of the coating (a perfectly smooth coating surface is not desirable). Initially this means that the surface particles of the coating are pushed away from the incurring blade tip and into the coating. The elastic energy, which is created in this interaction, then pushes the particle towards the surface of the coating, the blade now having passed. If the elastic energy is sufficient to overcome the bond between the particle and its neighbouring particles, it will be released as debris by the abradable coating, taking with it most of the initial impact energy.

The coating debris will have a larger volume than the original coating, which may cause problems if particles become trapped between the blade tip and the coating surface. This may occur if the blade tip is not sufficiently thin to have passed in time for the debris to escape behind it. The high contact pressure generated when debris becomes trapped under a blade tip can cause grooving of the coating, spallation, and over heating of the blade tip, which may lead to blade tip wear.

In order for individual particles to be released, there is a need for points of weakness at the particle boundaries. These can be in the form of release agents, coating of individual particles or porosity, which reduces surface area and thus adhesion, as well as acting as high stress points for crack initiation. Figure 9 shows the reaction between abradable particles at the coating surface and a blade tip as it passes over them.

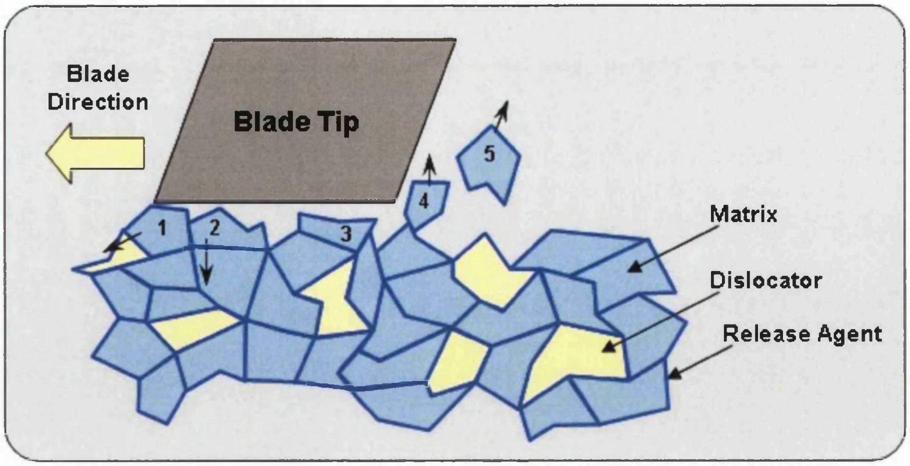

Figure 9. Blade tip and abradable coating interaction

By studying Figure 10, it can be seen that Particle 1 is being forced, elastically under compression into the coating material as momentum is transferred to it from the rotating and incurring blade tip. Particle 2 has been impacted by the blade tip slightly earlier and is still travelling into the coating but is no longer in contact with the blade. Particle 3 has stopped moving into the coating and has accumulated enough elastic energy to start moving back towards the surface of the coating. Particle 4 is accelerating away from the coating, due to the stored elastic energy of the abradable, and is about to de-bond from the coating. Particle 5 has already de-bonded and has been released by the coating as debris, to travel through the engine (Schmid 1997).

For this model to be valid for an effective abradable coating, all deformation of the coating material should be elastic, and cause minimum wear or deformation to the blade tip. In order for this to happen the force required to release the particles must be less than the force for their plastic deformation. It follows that the mechanical properties of the abradable coating dictate the necessity for use of a release agent. The energy to release a particle is also dependent upon the particle size, with smaller particles releasing easier than larger particles. Small particles also cause less damage to blade tips and are less likely to damage other components as they travel through the engine (Chupp 2002).

It is also important to recognise the importance of service conditions to the mechanics of abradability. Testing and service experience both show that the dominant mechanism of abradability during the interaction between blade tip and abradable is highly dependent upon the blade tip speed and the relative incursion rate. Geometry factors, such as blade tip thickness, are also important, particularly for the effective release of abradable debris (Schmid 1997).

3.6 Testing of Abradables

New abradable materials are continually being developed and tested by coatings companies and engine manufacturers. Much of the coating development (especially in the later stages, when the coating is used on engine rigs etc.,) is carried out by the coating company in partnership with the engine manufacturer (Sellars 2005). In this way coatings can be modified, spraying parameters set and specifications written, in order to obtain the optimum material properties from the abradable (Sellars and Hopkins 2005). As well as new coating development, service failures and manufacturing problems can prompt the need for further coating assessment. Not only can service failures be costly but also, especially in the case of an aero engine, there is always a risk of fatalities resulting from engine failure. For these reasons it is extremely important for Rolls-Royce and other engine manufacturers to use in-house testing methods in order to analyse abradable coatings.

There is currently a range of in-house and outsource test methods, which Rolls-Royce employ to study the thermal and mechanical properties of abradable coatings. This section will summarise these, highlighting the relevance of test methods to specific material properties and their limitations with respect to how closely they represent engine conditions, together with the simplifications and assumptions made.

Abradability Testing

As discussed in Section 3.6 of this thesis, the mechanisms by which coatings abrade are very complex. In almost all situations, where a coating is in contact with a blade tip, there is a combination of cutting, heating, plastic deformation and wear (Yi *et al* 1997). Modelling these mechanisms is therefore extremely difficult in a laboratory, where the extreme conditions of modern gas turbine engines are not easily recreated. There are a number of highly specialist abradability rigs, used by engine manufacturers and coating developers. These facilities have varied capabilities of recreating the service conditions in terms of blade tip speeds and incursion rates of a modern abradable coating. Sulzer Innotec, in Switzerland, own one of the most well established and representative abradability facilities and the

Innotec rig is constantly in use by engine manufacturers and coatings companies around the world. It has thus become an industrial standard for abradability testing.

In order recreate the service conditions of an abradable coating the abradability rig has to be able to generate the temperatures, blade velocities and incursion rates occurring in a modern gas turbine engine. The rig also requires the ability to operate over a wide parameter range, in order to model all possible engine and flight-cycle conditions. Figure 10 shows the arrangement of the Sulzer Innotec Abradability Rig.

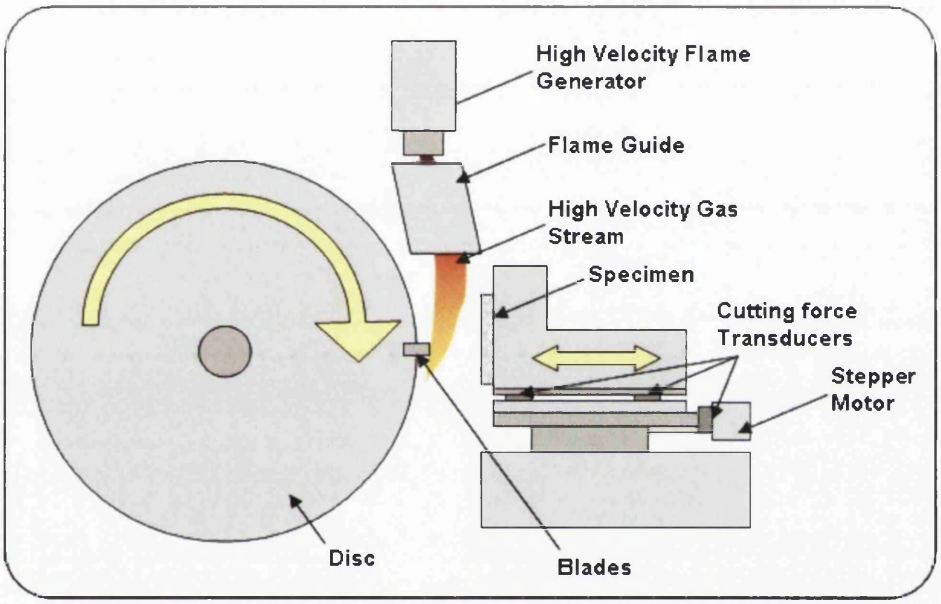

Figure 10. The arrangement of the Sulzer Innotec Abradability Rig

A 600mm diameter disc is driven by an electric motor, which rotates a rotor with two opposite blade slots, able to accept either dummy or actual blades. Sensors are used to monitor accurately any out of balance forces during rotation, which may be caused by a 'blade off', allowing corrective balancing. Blade tip velocities range from $100ms^{-1}$ to $500ms^{-1}$.

Specimens, which can be either flat or curved, are mounted on a specimen holder, which is able to incur and retract from the rotating blade at a range of controllable rates. These incursion rates are representative of the blade extensions seen in service, due to the centrifugal forces generated and thermal expansion of the blade. Incursion rates of $1mms^{-1}$ to $3000mms^{-1}$ are possible by using a high torque stepper motor. These conditions are representative of engine operation. Specimens are heated directly to temperatures up to 1,200°C via a high velocity gas stream (Ernst and Wilson 2005).

Abradability performance is measured as a function of blade tip wear, following a set of defined blade tip speed and incursion rate conditions. This relatively simplistic measure is an indication of abradability performance, but does not provide a fundamental understanding of the abradability mechanics and key performance drivers.

Due to the extremely high velocities and forces used, the rig is housed in a safety bunker. The current demand from around the world, and the high costs associated with running the rig (over £1,000 per test run), mean that abradability testing is only carried out when strictly necessary.

It is also important to recognise that although the Sulzer Innotec rig is capable of generating engine comparable blade tip speeds and incursion rates, any test rig only provides the confidence to proceed with engine testing, which is still required in order to approve a coating for service.

Erosion Testing (GE)

The GE erosion test is an industry standard method for quantifying the resistance of a coating to erosion, using a simple grit blasting technique. A test piece is positioned 4″ from the tungsten carbide nozzle of a grit blaster an angle of 20° (Immarigeon *et al* 1997). The equipment arrangement is shown in Figure 11.

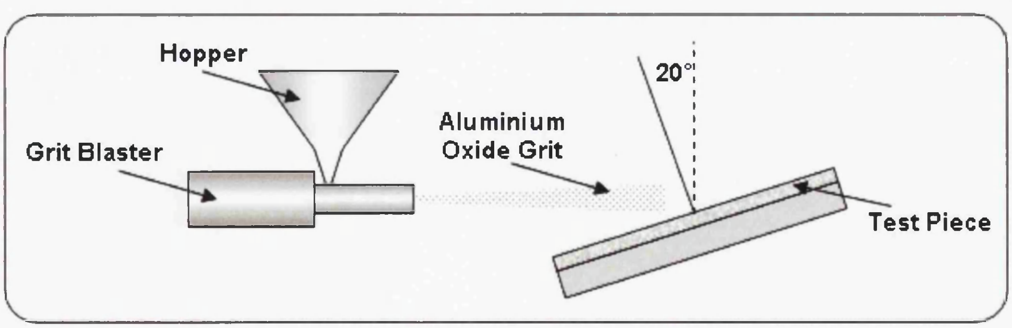

Figure 11. Arrangement of the GE erosion test equipment and test piece

The 20° impingement angle provides what is believed to be a representative, low angle, elastic erosive mechanism. Aluminium oxide grit is gravity fed through a hopper into the nozzle of the grit blaster, where it is projected towards the specimen surface and during each test 600g of grit is discharged. Before a test piece is used, a calibration run is carried out, using a test panel, and its weight and thickness are accurately measured, before it is blasted with 600g of grit. By weighing the test piece before and after grit blasting, and measuring the point of maximum erosion, a value for the erosivity of the material can be calculated (General Electric 1995).

The results of this test are useful when comparing various coatings, although the abrasive conditions of the test are much more aggressive than those likely to be experienced in service by an abradable coating.

Tensile Bond Strength Testing

A number of useful mechanical properties can be obtained through a tensile test. This is usually accomplished by machining a tensile test piece from a specimen, before applying a set strain rate, using a standard tensile testing machine. With thermally sprayed coatings, this is made more complicated by the substrate material, and especially problematic when testing abradable coatings, which are very weak in comparison to the steel, titanium or nickel substrates selected.

A compromise test procedure, known as the Tensile Bond Strength Test, has been historically used for a range of coating materials (Rolls-Royce 1994). This test can be used to quantify either the bond between coating and substrate or the strength of the coating itself.

The test method involves a tensile load being applied to a steel, titanium or nickel test button, perpendicular to the substrate-coating interface. After preparing the end of the test button by grit blasting, an abradable coating is applied by the respective thermal spraying process and its surface lightly grit blasted to aid mechanical adhesion. The test button is then positioned between two threaded loading fixtures, with grit blasted surfaces. A high-temperature, cure adhesive film is used to bond the fixtures to the test button and the abradable coating; this configuration is shown in Figure 12.

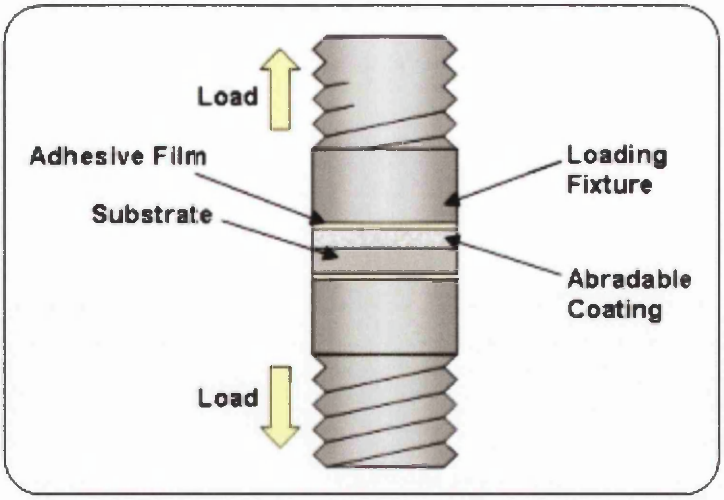

Figure 12. Loading fixture and test piece arrangement for Tensile Bond Strength Test

A tensile load is then applied to the test piece and loading fixture using a standard tensile testing machine at a strain rate of 0.75 to 1.25mm per minute. Failure will eventually occur in one of three ways; glue failure, cohesive failure (within the coating) or adhesive failure (at the interface between topcoat and bond coat).

A number of variations on this test procedure are used to generate relatively comparable loading conditions. However, there are certain limitations to this type of test method. Some abradable coatings, especially porous varieties, may absorb the adhesive, which can increase the strength of the coating, and confuse test results. It is also impossible to obtain a value for the elastic modulus of the material, as the extensions involved are extremely small.

Bend Testing

A Bend test can be used in order to study a coating's resistance to lifting, spalling (loss of coating) and cracking. The coating specimen is bent over a mandrel, 10 to 12.5mm in diameter, at a slow strain rate (Rolls-Royce 1994).

Test pieces are then evaluated for lifting, spalling and cracking, in order to assess whether the spraying parameters and manufacturing procedures are satisfactory and producing a coating to the correct specifications.

The test does not give a quantitative result and so it is often used as a comparative test, which does not directly represent particular engine conditions, but instead considers the material's failure behaviour.

The Split Bar Test Method

In an attempt to generate directionally representative material property data, the split bar test uses test pieces, which can be loaded parallel to the substrate surface. A bar containing a split line, is supported by a central locating pin and rotated during spraying. Coating is deposited onto the surface of the bar to the required thickness as shown in Figure 13.

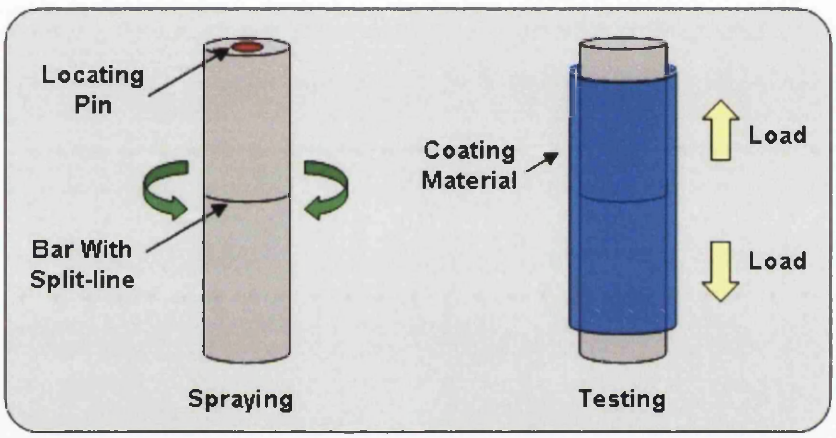

Figure 13. Bar test method test piece arrangement

Following spraying the locating pin is removed and the bar loaded into a standard tensile testing machine. Load is applied to the bar ends until failure of the coating is induced at the bar split line.

Although this test method is capable of generating representative loading modes (i.e. loading direction is parallel to the substrate surface), it is possible that the small bar diameter (1") could produce non-representative coating structures. During spraying, coating particles that do not deposit normal to the substrate surface may not form a representative structure and therefore produce variability in the mechanical properties of the bulk material.

Thermal Shock Testing

As discussed in Section 2.2, there is almost always a mismatch between the coefficient of thermal expansion (α) of the abradable coating and the substrate (Miller 1998). This means that when the engine heats up and cools down, the thermal gradients generate varying degrees of stress within abradable coatings (Zheng *et al* 2002).

In an attempt to model this type of cyclic thermal loading, a very simple Thermal Shock Test is used, which is designed to accelerate a similar type of cracking within a laboratory. Although there is no written procedure for this test method, it is used regularly to validate coatings during development and to measure the effects of variations in material properties, due to changes in spray parameters, for relevant manufacturing procedures.

The test uses small test coupons, which are heated in a furnace to temperatures above those they would normally experience in service. After a predetermined length of time (designed to allow stress relaxation to occur, typically 30 – 60 minutes) the coupon is removed from the furnace and immediately quenched in water. This aggressive cyclic heating and quenching usually causes cracking within a few cycles (Hopkins 2002).

The Thermal Shock Test only gives comparative results and in some cases has been seen to indicate a limited relationship to service conditions. As there is no Rolls-Royce written procedure for this test method it can be misleading to compare results from separate tests.

Corrosion Testing

During service, a combination of high temperature and moisture can produce a highly aggressive corrosive environment. It is therefore necessary to understand the oxidation resistance of abradable coatings (Borel *et al* 1989).

Corrosion Testing (Salt Solution Test Method)

The Salt Solution Corrosion Test is designed to induce accelerated corrosion of an abradable coating by subjecting it to a saturated salt solution at moderate temperatures. Currently this simplistic test method has no Rolls-Royce written procedure for abradable coating evaluation. As a result, experimental procedures have varied in the past, making comparing results from different testing programmes difficult and misleading. However, the basic principles of the test are constant.

The test involves partly submerging flat abradable test pieces in a saturated salt solution within an oven at a set temperature, which is above room temperature and below 100°C. This arrangement is designed to induce corrosion at an accelerated rate and specimens are subjected to these conditions for a number of hours before being visually, and where necessary chemically, examined for indications of corrosion. The procedure is repeated, with any observations recorded. There are no values obtained from this test method and so results are usually comparative.

Corrosion Testing (Fog Test Method)

A Corrosive Fog Test method is also used to assess the corrosion resistance of an abradable coating. In a similar way to the Salt Solution test, specimens are subjected to an aggressive environment, designed to induce accelerated corrosion. The specimens are placed inside a humidity cabinet, in which a humid salt saturated atmosphere exists.

As with the Salt Solution Test method, results are only qualitative and so it is difficult to compare different test results, therefore no quantitative values are obtained. There is no current, written procedure within Rolls-Royce for using the Corrosive Fog Test for the evaluation of abradable coatings.

Hardness Testing

As a relatively quick and non-destructive evaluation, hardness tests are often carried out as a source control method (on components) at manufacturing facilities. Hardness testing is also used as a simplistic mechanical test for quantifying the amount of dislocator phase contained within a coating material (generally, as the dislocator phase increases the hardness decreases). Standard Rockwell 15Y hardness tests are used for the hardness testing of abradable coatings.

The surface of the coating is first prepared with grit paper (120/220 grit) until smooth, ensuring no densification of the coating occurs. Once the surface preparation has been completed the coating is cleaned, using dry compressed air to remove any dust (Rolls-Royce 1994).

A number of hardness measurements (current specifications suggest 3-5) are usually required, as the heterogeneous nature of abradable coatings means there can be wide variations in hardness values from a single test piece. This is a limitation of hardness testing as a method of source control, since it is not always possible to conduct enough tests for a given component. A further limitation is the fact that hardness values of some abradable coatings change with time in service, due to various polymer or binder phases burning out of the structure. This means that a coating may pass a source control hardness test by falling within a hardness range, but after a number of cycles in service the same coating may be out of specification. A minimum coating thickness is required in order to obtain a true hardness value.

Micro Preparation

Abradable coatings can be very difficult to mount and prepare consistently due to their inherent abradable properties. This means that, even when sectioning a test piece or engine component, the coating material can become smeared or damaged in some way. For this reason a procedure has been written by Rolls-Royce to fracture, rather than cut, the abradable coating (Rolls-Royce 1994).

A slit is cut into the substrate of the abradable, up to the bond coat material and the coating is then fractured by applying a steady bending force, closing on the slit. This is shown in Figure 14.

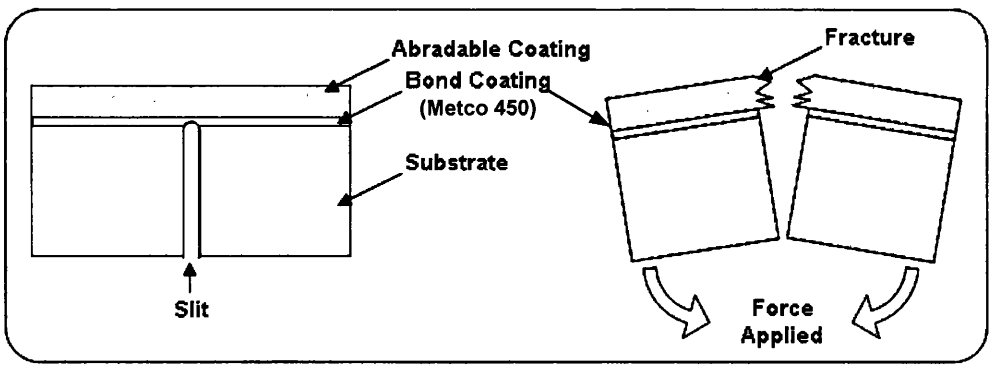

Figure 14. Fracture method for preparing abradables

The fracture surface produced also aids vacuum impregnation of the specimen when mounting. In order to ensure that the abradable is mechanically supported during grinding and polishing, the coatings must be vacuum impregnated with low viscosity resin. If the resin does not impregnate the coating sufficiently the dislocator phase may be pulled out during preparation, resulting in an unrepresentative microstructure.

When grinding and polishing it is important not to apply excessive pressure to the specimens and not to use grit papers <120 grit, as this can also lead to material pull-out and unrepresentative microstructures.

3.7 Current Compressor Abradables

A range of compressor abradable coatings are currently used by Rolls-Royce for both civil and military aero engines. This section summarises these materials, their properties, operational envelopes and limitations (Purdie 2001).

Aluminium - Silicon + Polyester (Metco 601)

Metco 601 contains an Al-Si matrix with a polyester dislocator phase, which accounts for around 48% of the volume of material. As one of the most widely used abradable coatings, Metco 601 finds applications in the LP compressors of a range of aero engines with operating temperatures up to 350°C. In common with all current abradable systems, Metco 601 is used with a Metco 450 (95%Ni-5%Al) bond coat (Sulzer Metco 2006). Figure 15 shows a typical microstructure for Metco 601. The lighter phase is the Al-Si matrix and the darker phase, the polyester dislocator.

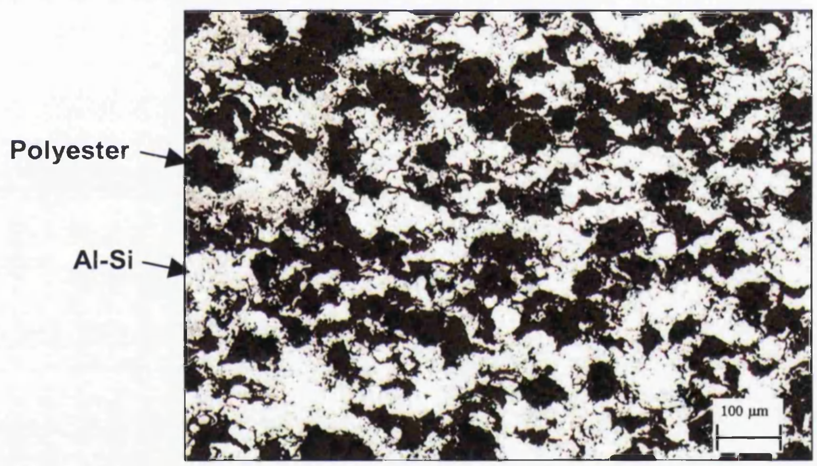

Figure 15. Microstructure of Metco 601

The polyester dislocator phase limits the material's operating temperature and variations in the amount of polyester have caused problems in service. If the polyester content drops then the material becomes harder and can cause blade-wear. If the polyester content increases then the coating can become too soft, wear too easily and be prone to erosion problems. These variations in the dislocator phase have been found to be linked to the spraying parameters used to deposit coatings.

Aluminium – Silicon + Hexagonal Boron Nitride (Metco 320)

Metco 320 is a plasma sprayed, fully dense Al-Si abradable, which contains a hexagonal boron-nitride (hBN) dislocator phase (Sulzer Metco 2006). The addition of an organic binder (self cross-linking acrylic latex), coated onto the hBN particle prior to spraying, protects the boron nitride, which can degrade during the spraying process (Purdie 2001). This is a relatively modern coating, which was first sprayed onto engine components in the late 1990's. Figure 16 shows the microstructure of Metco 320; the Al-Si matrix is shown as the lighter phase, with the hBN phase shown darker.

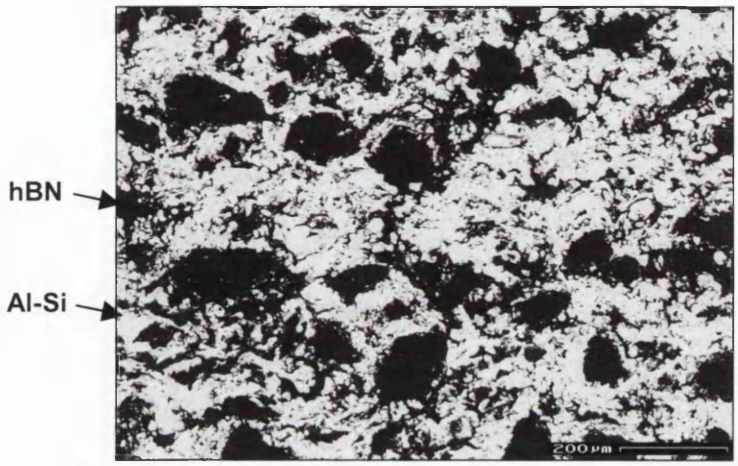

Figure 16. Microstructure of Metco 320

Metco 320 has displayed a number of failure mechanisms in service, the majority of which have been contributed to poor thermal shock resistance, or gramophone grooving, due to abradable pick-up.

Nickel – Graphite (Sherritt Gordon or Durabrade 2313)

Sherritt Gordon is a combustion sprayed, porous coating, containing a 50% Ni – 25% graphite matrix and 25% porosity. The porosity acts as a dislocator and helps to give the material abradable properties. Sherritt Gordon is sprayed onto a combustion sprayed bond coat known as Metco 405 with a composition of 80%Ni - 20%Al (Sulzer Metco 2006). Figure 17 shows the microstructure of Sherritt Gordon, with the lighter Ni-Graphite matrix material and the darker porous dislocator phase.

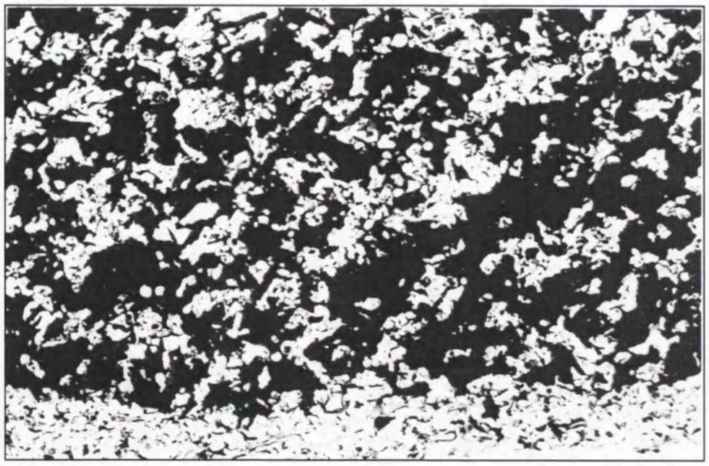

Figure 17. Microstructure of Sherritt Gordon

Metco 320 replaced Sherritt Gordon in the late 1990's, due to its poor erosion resistance. However, due to the gramophone grooving issues, which currently surround Metco 320, for some engines Rolls-Royce have reverted back to Sherritt Gordon.

Aluminium – Silicon + Graphite (Metco 313)

Metco 313 is plasma sprayed 70%Al – Si coating containing a 22% graphite dislocator phase and 8% porosity. This coating is no longer sprayed onto engine components as the graphite phase was found to cause galvanic corrosion (Sulzer Metco 2006). Figure 18 shows a typical image of the Metco 313 microstructure, with the lighter Al-Si phase and the darker graphite dislocator phase.

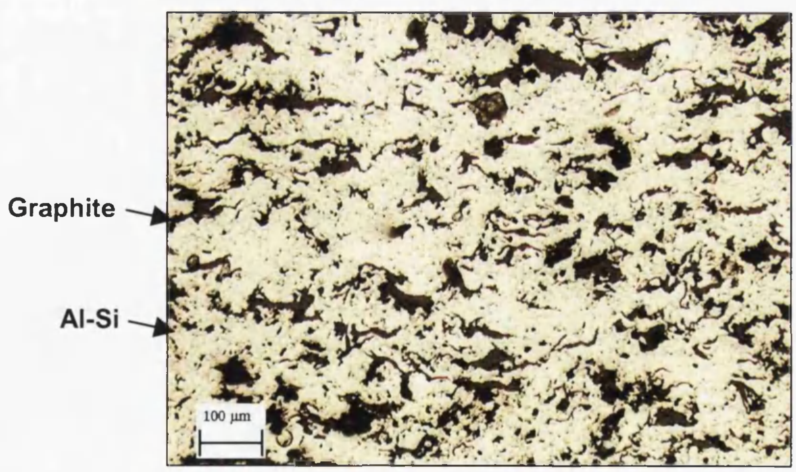

Figure 18. Microstructure of Metco 313

Nickel – Chromium + Bentonite (Metco 314)

Metco 314 is a relatively hard combustion sprayed coating for use in the HP compressor at temperatures above 450°C. It is comprised of a Ni–Cr matrix and a bentonite dislocator phase (Sulzer Metco 2006). The bentonite powder is clad in a Ni-Cr alloy prior to spraying. Figure 19 shows the microstructure of Metco 314 taken using an optical microscope, with the lighter Ni-Cr phase and the darker bentonite dislocator phase.

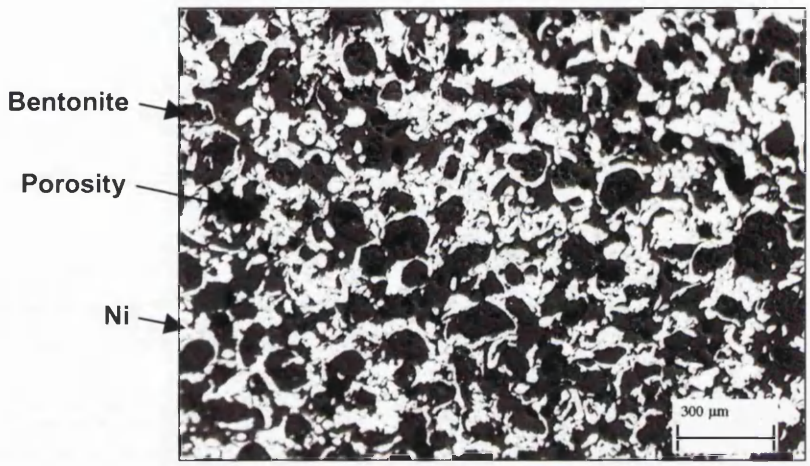

Figure 19. The microstructure of Metco 314

Since Metco 314 is combustion sprayed it does not have the controllability of the more favoured plasma sprayed coatings. Metco 314 cannot be used with titanium blades because it has been shown to increase in hardness when exposed to high temperatures, which increase the risk of titanium fires during service.

3.8 Failure Mechanisms of Abradables

A number of failure mechanisms are currently associated with in-service abradable coating failures. This section summarises these and highlights the material properties, which are currently believed to make some coatings more sensitive than others to this type of failure mechanism.

Thermal Shock

In Section 2.2 the need was discussed for an abradable coating to be able to withstand cyclic stresses, which are a product of the mismatch in the coefficient of thermal expansions (α) between the substrate and the coating. If these stresses are large enough they may cause the coating to fail in a tensile manner and cracks can initiate. This type of cracking is often specific to a particular component type due to stress concentrations caused by the geometric design of a shroud. Thermal shock cracking has also been shown to be dependent on coating thickness, where cracking is more prevalent in thicker coatings (Roth-F 2002). However, there are common initiation sites and familiar types of cracking, which are common across a variety of coating types and engine stages.

One of the most common types of cracking is known as 'mud-flat' or 'crazed' cracking. These cracks tend to start at the surface of the coating and propagate perpendicularly to the substrate, towards the bond coat. Figure 20 shows an image of a coating surface, which has suffered mud-flat cracking.

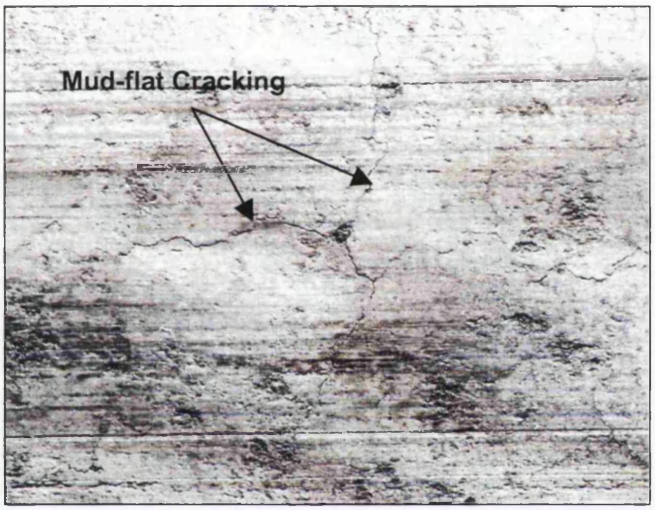

Figure 20. Image of typical mud-flat cracking on the surface of a Metco 320 abradable coating

This type of cracking is not necessarily a cause for concern. If the cracks remain small and are all in the same vertical plane (i.e. running from surface towards bond coat) then they act as stress relievers and can increase the service life of the coating. However, it is possible for this type of mud-flat cracking to cause spallation and liner loss. There are a variety of ways in which this is believed to occur. Some service evidence suggests that the cracks turn when they reach the bond coat, causing delamination. In other cases adjacent cracks coalesced, causing areas of coating to become severed. Depending on the severity, this type of coating loss can lead to a number of very serious engine problems, such as a loss in performance, stalled starts, or a surge event, where engine compression is lost, causing a sudden surge of pressure. Figure 21 shows an image of a particularly poor coating, which has experienced severe material loss during service.

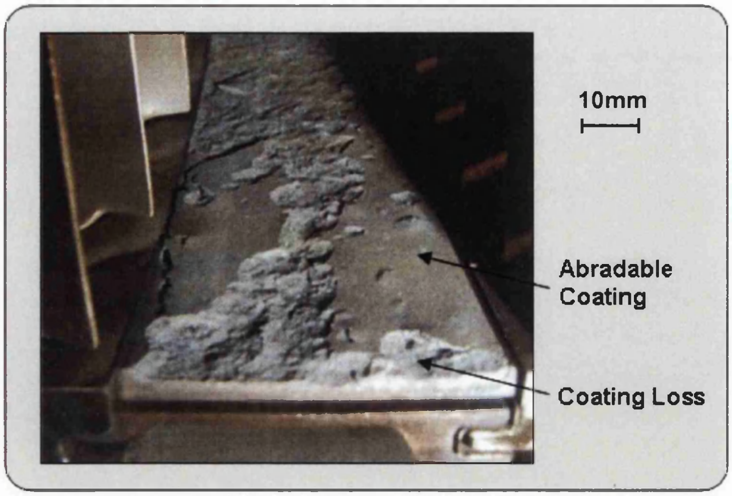

Figure 21. Metco 601 abradable coating, which has suffered material loss due to poor thermal shock resistance

Coating failure, due to thermal shock, has been observed on a range of abradable coatings after varying times in service and there is very limited understanding as to why some coatings appear more susceptible than others. A recent work project, which examined the effect of various spray parameters on the thermal shock resistance of coatings, suggests there is a correlation (at least in some coatings) between the size distribution of the dislocator phase and the degree of thermal shock cracking observed. This work is discussed in Section 6.1.

In some cases cracks concentrate around corners and edges, where stress concentrations, resulting from the geometry of a component, lead to crack initiation. This type of cracking can be more problematic than mud-flat cracking as it is difficult to detect and can lead to sudden delamination or spallation failures. Figure 22 shows a crack, which has initiated at a stress concentration within the coating.

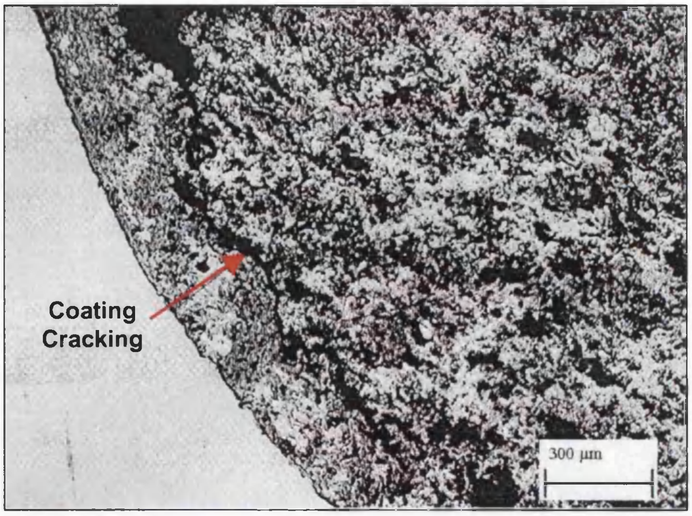

Figure 22. Cracking within a Metco 313 abradable coating due to thermally induced stress concentrations

Gramophone Grooving

If an abradable coating does not wear efficiently then, due to friction, the abradable material and blade tip can become exposed to much higher temperatures than normal. In some cases (particularly with aluminium based systems) this has led to abradable material melting and transferring to the blade tip, whereupon it solidifies, causing subsequent grooving of the coating on each succeeding engine cycle (Ghasripoorf and Schmid 1998). Figure 23 shows a coating, which has suffered gramophone grooving and a blade, which has some abradable pick-up on the tip.

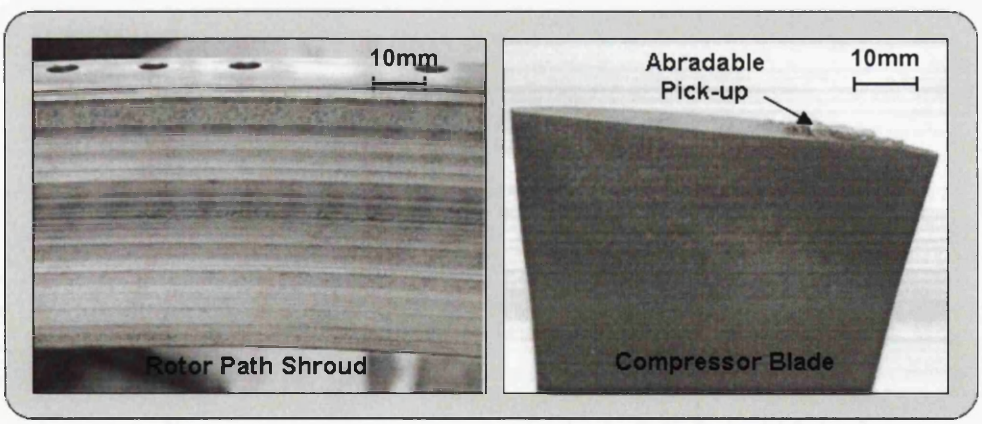

Figure 23. Gramophone grooving and blade tip pick-up

This type of grooving can have serious effects upon the performance of the engine, which may result in hung starts, engine stalls and engine surges.

Gramophone grooving is believed to be caused by a light rub condition, which is common on some aero engines during the climb stage of the flight cycle. The rub contact is not sufficient to cut or abrade the abradable coating but, due to friction, sufficient to cause the coating and blade tip to heat up until the coating melts.

Delamination

Delamination or coating loss is a dramatic failure, with equally dramatic effects upon engine efficiency and performance. It is usually caused by poor bond strength of the topcoat or bond coat. This can be the result of inadequate surface preparation or deficiencies when spraying, such as poor powder mixing or the inclusion of an oxide layer, due to a pause in the spraying programme. Figure 24 shows an example of a coating, which has suffered from a delamination failure. The image was taken using a specialist borescope camera, where a lens is positioned at the end of a flexible optic fibre in order to obtain an image of the coating in-situ with the blade. The image indicates that the clearance gap has increased considerably, due to the delamination of the abradable coating.

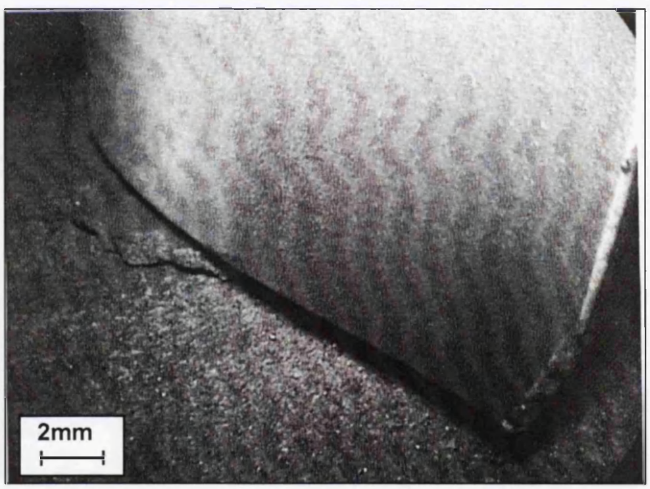

Figure 24. A coating, which has suffered a delamination failure

Delamination failures are often difficult to predict, sometimes only manifesting during service. Studies have previously investigated the use of scratch tests as a method of determining the adhesion of a coating (Bull *et al* 1988). However, there is no current standardised quantitative method for evaluating delamination during manufacture.

Erosion

Erosion is a less common failure mechanism, which is associated with Metco 313 and usually a result of the coating being sprayed too soft. This can be caused by poorly mixed powder or the use of incorrect parameters or procedures when spraying. For example the hardness of a coating is closely related to the amount of porosity or dislocator phase present in the microstructure.

Erosion is caused by the gas stream and particles within it as it flows over the abradable surface (Tilly 1979). There are often sand or salt particles within the gas stream (especially on landing and takeoff), which make the gas stream more erosive (Yi 1997). Figure 25 shows an abradable coating, which has suffered extremely serious erosion damage.

Figure 25. Erosion damaged Sherritt Gordon abradable coating

Erosion damage to this extent has equally dramatic effects upon engine performance, as discussed above under the heading of delamination.

Corrosion

Aqueous corrosion can initiate in abradables for a variety of reasons. In Al-Si matrix coatings galvanic corrosion can initiate, where the aluminium (anode) corrodes preferentially to the dislocator (cathode), resulting in the production of aluminium hydroxide (Jones 1996). This is especially true where a highly conductive graphite dislocator phase is present. The aluminium hydroxide can form layers, which may then cause delamination of the abradable coating. Alternatively the formation of aluminium hydroxide and the associated volume increase can cause the coating to swell, resulting in trapped blades.

Corrosion can have significant effects on performance of abradable coatings and eventually lead to serious failures, depending on the extent of the corrosion. Pitting, lifting, flaking and blistering are all associated with corrosion of abradable coatings.

3.9 Metco 320 (Al-Si + hBN) Case Study

Metco 320 (Al-Si + hBN) is a good example of a compressor abradable coating, currently used in a number of Rolls-Royce civil and military engines, which has suffered a series of in-service failures, resulting from a number of failure mechanisms. Metco 320 is a plasma sprayed Al-Si abradable with a hexagonal boron-nitride dislocator phase, both of which are coated in an organic binder (self cross-linking acrylic latex), which helps to protect the hBN powder particles during spraying and assists the binding of the coating. Figure 26 shows a Scanning Electron Microscope (SEM) image of a single particle of Metco 320 powder, containing Al-Si and hBN within the binder shell.

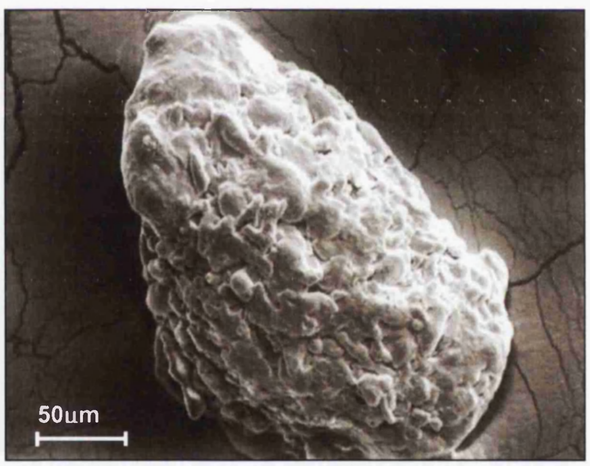

Figure 26. SEM image of a single particle of Metco 320 powder

In service Metco 320 operates up to 450°C and uses a 95%Ni - 5%Al bond coat (Metco 450), to assist bond strength to titanium, nickel or steel substrates (Sulzer Metco 2006). Figure 16 shows a Back Scattered Electron (BSE) image of the Metco 320 microstructure.

Metco 320 was jointly developed between the powder manufacturer Sulzer Metco and Rolls-Royce, to replace a number of problematic coatings, previously being used with various failure mechanisms. Figure 27 provides a flow diagram showing the coatings, which predate Metco 320, and the failure mechanisms associated with them.

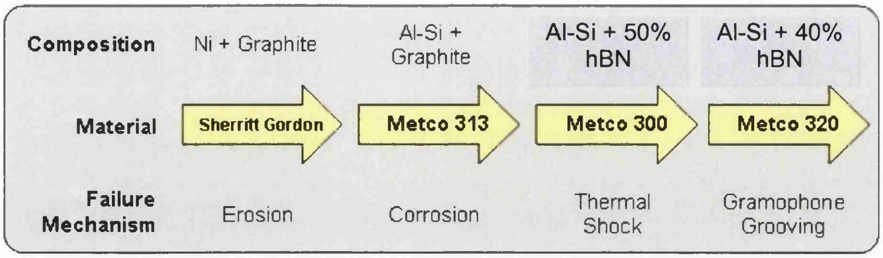

Figure 27. The predecessor materials of Metco 320 and associated failure modes

When each coating was validated the suite of testing methods used grew, as each new coating showed a new type failure mechanism. Validation of the latest coating was competed by ensuring it showed improved mechanical or thermal properties as indicated primarily by a laboratory test.

The testing program was conducted by Sulzer Metco and Rolls-Royce (Purdie 2001). In order to qualify Metco 320 as an abradable coating for use in aero engines, many of the test methods described in Section 3.6 were used and the results of these tests are summarised in Table 3. It can be recognised that for most tests a comparative result was achieved, showing that, for the various test conditions, Metco 320 outperformed its predecessors. Although this process ensured that, for the respective test conditions, Metco 320 showed improved thermal and mechanical properties, it did not account for the test methods being unrepresentative and only gave Metco 320 a ranking against other poor coatings.

Table 3. Metco 320's development testing for engine use

Test	Result
Erosion	GE 90 test showed that Metco 320 outperformed Sherritt Gordon
Corrosion	Fog Test method showed that Metco 320 did not produced aluminium hydroxide, no spallation or blistering were observed
Thermal Shock	Although cracking did occur after a number of thermal shock cycles, performance was much improved on Metco 300

Metco 320 is currently known to have failed by a number of mechanisms, including thermal shock cracking and gramophone grooving, which have had varied affects on the coating performance, some of which have meant engines being removed from aircraft for premature overhaul.

3.10 Alternative Abradable Systems

Whilst all gas turbine engine manufacturers understand the importance of sealing the engine, not all favour the abradable coating technology. This section of the thesis summarises alternative methods, currently used by engine manufacturers, to reduce over-tip leakage.

A number of abradable coatings are currently available but not used by Rolls-Royce. For example Pratt and Whitney use felt metal abradables for numerous stages on a range of their engines. Although Rolls-Royce use felt metal to a limited degree for sealing the engine drum to the stator vine fins, there are no applications for the material on engine shrouds to prevent over-tip leakage, since it was observed to allow unacceptable amounts of gas leakage through the seals.

Felt metal is an extremely porous (around 80%) metallic material, which is brazed to the substrate material. The metallic element is usually a nickel alloy e.g. Hastelloy X (Ni-22%Cr-18%Fe-9%Mo), whilst in higher temperature applications, e.g. >650°C, Fe-Cr-Al-Y felt metals are used. Felt metal is essentially comprised of turned machined cuttings with an added carrier, resulting in a loosely bonded structure. Material does appear more dense close to the interface with the substrate, as the braze material 'wicks-up' into the porous felt metal (Chappel 2004). Figure 28 shows an unusual microstructure of a felt metal, and the densification close to the interface with the substrate material. The lighter material is the nickel alloy, which is dispersed within the darker pores.

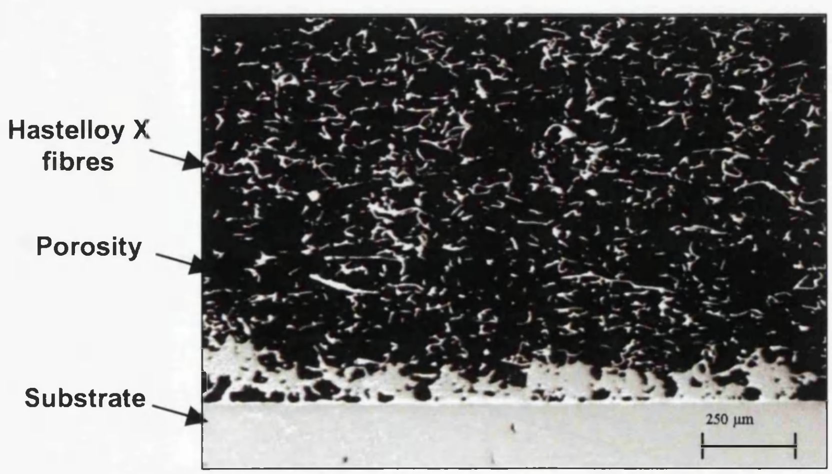

Figure 28. Microstructure of felt metal and brazed interface with substrate

If there is too much wicking by the braze material the felt metal can become too hard and wear the fins and/or blade tips.

Squealer Tips (Used By General Electric)

As an alternative to abradable coatings, General Electric (GE) use squealer tip technology in order to reduce over-tip leakage on a number of their engines. This technique involves reducing the tip section of the blade until there is very little surface area in contact with the engine shroud. These thin blade tips will then wear preferentially to the shroud material and will often be accompanied by a squealing noise (Key and Arts 2004). Squealer tips do not require an abradable layer as they lightly rub or narrowly clear the shroud material (Kontrovitz 2002).

3.11 Literature Review Conclusions

From the literature review carried out on abradable technology it is clear that a number of areas could benefit from fundamental material research. If we consider the life cycle of a thermally sprayed abradable coating, from development through manufacture and finally in service, it is possible to align specific design and material requirements. It is therefore clear that, to support these requirements, a fundamental understanding of these unique materials must focus upon three key topic areas; Material Property Data, Process Understanding and Service Experience, as shown in Figure 29.

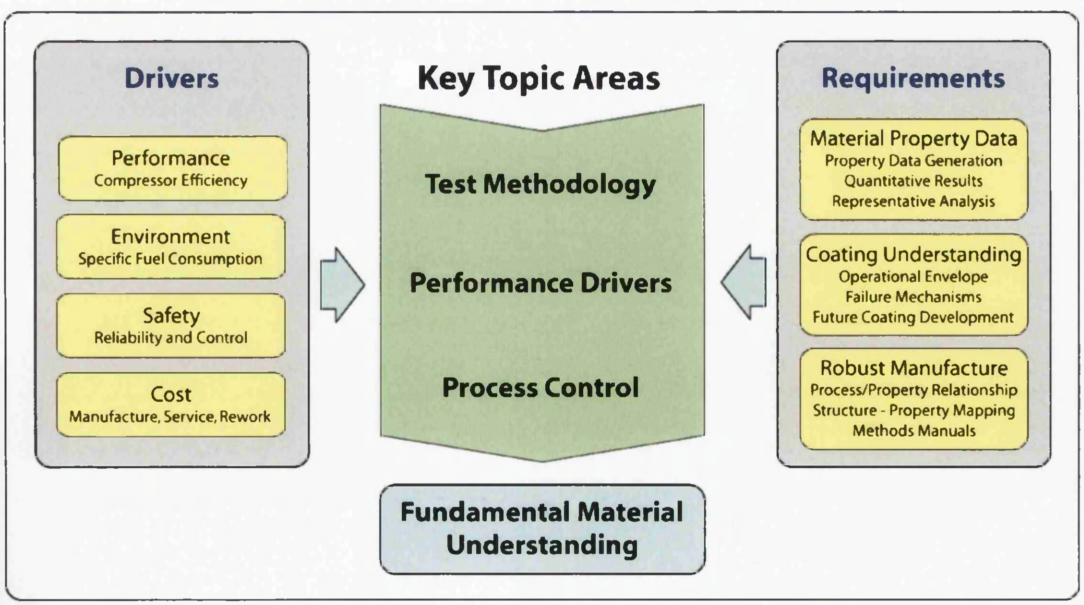

Figure 29. EngD Key Topic Area Strategy

Work carried out to generate a fundamental understanding of each of the key topic areas identified in Figure 29 will be discussed in this thesis. For each, specific advances will be highlighted, where materials science has provided a fundamental understanding of this black art industry.

4. Development of Test Methodology

The literature review discussed in Section 3 has highlighted a number of gaps within the understanding of abradable materials at a fundamental level. This is often the result of insufficient material property data due to a lack of quantitative test methodologies. Clearly it is necessary to develop specialist techniques and equipment for the robust testing and evaluation of abradable coating materials.

4.1 Thermal Shock Test Method

As shown in Figure 3, during the flight cycle of aero engines the mismatch between the coefficients of thermal expansions of the coating and the substrate material can generate significant thermal stresses within the coating (Kuroda and Clyne 1991).

A Thermal Shock Test method is currently used by Rolls-Royce, which involves the cyclic heating and quenching of abradable test pieces on flat substrates, in order to induce similar types of stresses into the coating to those that occur in service. Higher heating temperatures and faster cooling rates than those seen in service are used in attempts to accelerate the effects of thermal shock stresses on the coating (Clyne and Gill 1996).

Although a Thermal Shock Test method is currently used to assess in-service coatings, as well as to approve new or development coatings, until now there has been no formal procedure for the thermal shock testing of abradable coatings. This has meant that a variety of test parameters have been used, making it difficult and often misleading to compare results from different test programs. Some tests have caused uncharacteristic failure modes, which appear to be the result of differing stress fields to those observed in service.

4.1.1 Thermal Shock Test Method – Experimental Design

A package of work has been carried out to experimentally understand the key test parameters and to define a standard procedure for thermal shock testing of abradable coating materials. Experiments were completed to find the optimum test parameters to best mimic the type of thermal stresses applied to a coating in service. All tests were carried out on Metco 320 abradable coating and Jethete steel (16Cr 2.5Ni 1.8Mo steel) substrate material, with a thickness of 3mm.

4.1.2 Thermal Shock Testing Method – Heating Time Assessment

For the generation of tensile stresses within an abradable coating on engine shut down, the material must initially be at a high enough temperature for sufficient time to stress-relieve in compression (Roth-F 2002). Heating times as short as 20 minutes have been used in past laboratory experimentation to assess the thermal shock resistance of an abradable coating.

To determine the minimum time at temperature that an aluminium abradable coating requires in order to stress-relieve, five sets of thermal shock test pieces were subjected to five thermal shock cycles for a range of heating times before being quenched and analysed using binocular microscopes. All specimens were heated at 475°C before immediate quenching in water. Test pieces were 10mm x 35mm, with a coating thickness of 2mm. Table 1 shows the heating times used to assess the effects of various times at temperature on crack type and severity.

Table 4. Heating times used to assess the time required for an abradable liner to stress relieve at 475°C

Specimen Set Number	Heating Time (mins)
1	20
2	30
3	40
4	50
5	60

After 5 complete thermal shock cycles all of the specimens had suffered some cracking. Initially cracks initiated at the corner of each specimen and propagated parallel to the substrate. These cracks continued to grow with each subsequent cyclic thermal shock. This type of horizontal cracking is not characteristic of the thermal shock cracking observed in service failures. Only specimen Set 5, showed cracks initiating from the surface of the coating and propagating toward the bond coat in a typical mud-flat manner. Figure 30 shows binocular microscope images of test pieces from Sets 1 and 5 after 5 completed thermal shock cycles.

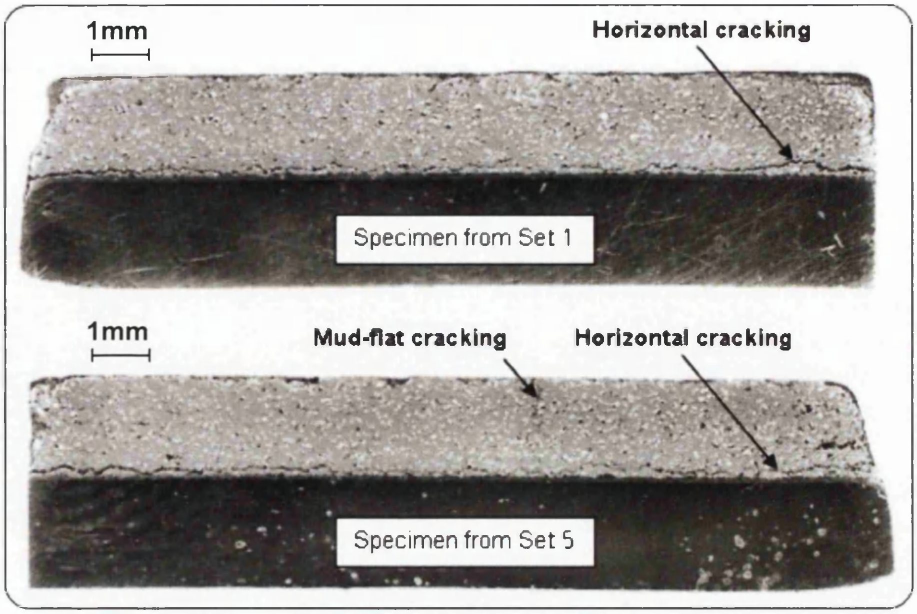

Figure 30. Thermal shock test pieces from Sets 1 and 5 following 5 thermal shock cycles

4.1.3 Thermal Shock Test Method – Water Quench Evaluation

Whilst accelerating the failure mechanism observed in service, due to the mismatch between the coefficients of thermal expansion of the coating and substrate materials, the Thermal Shock Test aims to mimic the thermal conditions experienced by the abradable coating in service. The water quench stage of the Thermal Shock test exposes the abradable material to a much more aggressive cooling rate than that observed during operation. Although the exact rate of cooling is not known, it is considered to be reproducible within the limits of the experimental procedure.

To assess the importance of the water quench to crack initiation, an experiment was carried out using two sets of test pieces. Set 1 were heated at 475°C for 1 hour and then water quenched; Set 2 were heated at 475°C for 1 hour and then air cooled. Test pieces were subjected to 5 thermal shock cycles to assess the effect of cooling rate on the type and extent of thermal shock cracking. Binocular microscope images were taken of the edges of each specimen in order to record the amount of cracking.

After 5 complete thermal shock cycles, the water quenched specimens had suffered from horizontal cracking. No cracking of any type was seen on the air-cooled specimens after the same amount of cycles. Figure 31 shows binocular microscope images of the water quenched and air-cooled specimens taken after 1 and 5 completed thermal shock cycles.

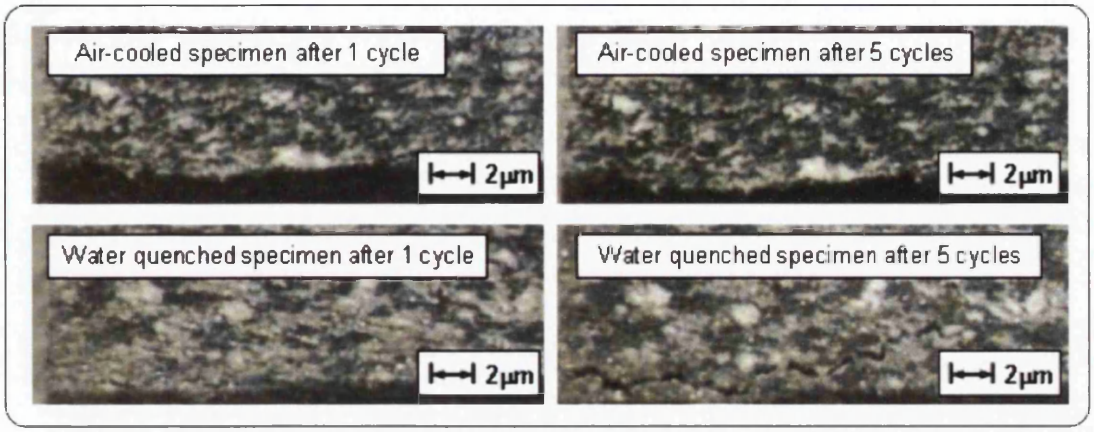

Figure 31. Thermal shock test pieces following water quenching and air-cooling

4.1.4 Thermal Shock Test Method – Literature Review

In order to further understand the influence of various test conditions on the type and severity of thermally induced cracking observed following laboratory testing, a literature review of Rolls-Royce test reports was carried out.

A study of the effect of coating thickness on the thermal shock resistance of abradable materials indicated that, as coating thickness increases, resistance to thermal shock cracking is reduced (Roth-F 2002). It is therefore important to ensure that coating thickness is defined as a test constant during the Thermal Shock Testing of abradable coatings. Following spraying, coatings should be skimmed down to a constant thickness using a slab miller, with a complementary cutting action and a slow feed rate to ensure that the coating is not damaged during machining.

From previous Thermal Shock Test programmes, it can be recognised that cracking often initiates at the corner of the coating or at a surface defect, which act as stress raisers (Shipton 2000). It is therefore necessary to carry out surface preparation on all Thermal Shock test pieces before testing.

4.1.5 Thermal Shock Test Method – Conclusions

From the experimental data and literature review investigating the Thermal Shock Test conditions and procedure for abradable coatings, the following test conditions can be issued as part of a Rolls-Royce Materials and Mechanical Methods (MMM) report, formalising the test method.

i) Abradable specimens should be heated for 60 minutes at 475°C in an air circulating oven

ii) On removal from the oven specimens should be immediately quenched in water

iii) Coating thickness should be constant across all specimens

iv) Test pieces should be flat, with a substrate thickness of >1mm and a coating thickness of 2mm

v) Specimens should be ground to a 2400 grit as specified in CME 5033 (Abradable Liner Preparation) (Rolls-Royce 1993)

A Thermal Shock Test procedure for abradable coatings, has been formalised and now forms part of the Abradable Coating Approval Process.

The Thermal Shock test method produces subjective results, which are heavily test operator dependent. Crack initiation is often the result of a surface flaw, which acts as a stress raising feature, leading to premature failure.

Clearly there is a need to develop quantitative test methods for evaluating coating integrity under specific loading conditions to support the observations of Thermal Shock Testing.

4.2 The Freestanding Coating Process

At a most fundamental level, materials science relies on material property data to make informed judgements upon the performance and reliability of an engineering component. The inability to generate representative coating property data has led to the perception within the aerospace industry of abradable coatings as a 'black art' as apposed to robust engineering solutions.

The properties of abradable coatings must be uniquely balanced; providing the strength to withstand the harsh gas turbine environment, and the wear characteristics to minimise compressor blade wear (Zheng *et al* 2002). Quantitative property data for thermal sprayed coatings is relatively sparse and inherently difficult to generate in an accurate and representative manner. As a result, the understanding of abradable materials remains at an empirical level despite over 30 years of service experience (Schmid and Dorfman 2000).

By definition, an abradable material has a much lower stiffness and strength than the substrate material onto which it is deposited (Malzbender and Steinbrech 1986). It is therefore difficult to accurately measure properties of the coating material, without the influence of the substrate material. The most effective method of distinguishing between the properties of a coating and substrate is to physically separate the two systems.

4.2.1 The Freestanding Coating Process – Introduction

The Freestanding Coating Process has been developed within Rolls-Royce as a method for the accurate generation of representative thermally sprayed coating property data. The process has initially been used to investigate the tensile properties of abradable coatings with a view to understanding failure mechanisms associated with thermally induced stresses, although potentially it can also be used for generating material property data for any thermally sprayed coating material.

The process relies on a polymer composite material (Aquapour), which has some important characteristics (Advanced Ceramic Research 2002). The material, which is supplied as a powder, can be processed to form solid moulds as shown in Figure 32. The moulds are capable of withstanding temperatures up to 200°C, and importantly they are also dissolvable in water.

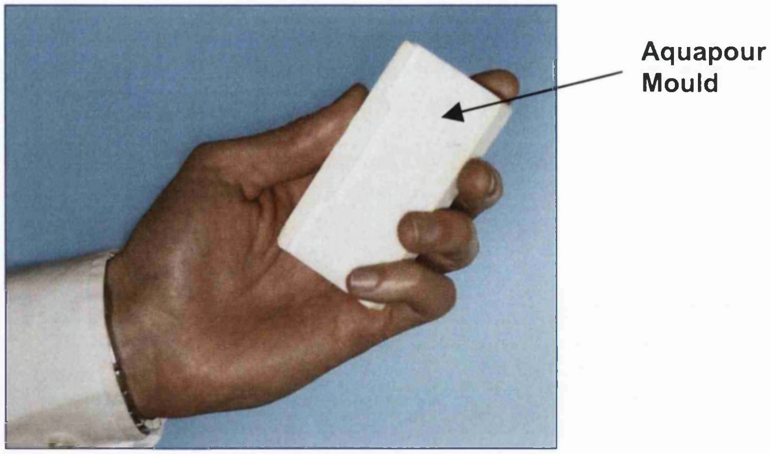

Figure 32. Example of Aquapour mould containing tensile test piece cavity

Moulds are produced containing cavities to accurate specified test piece geometries (Watts 2004). The moulds are then arranged on a rotating stage for thermal spraying, in order to replicate the manufacturing process of a compressor rotor path shroud. Abradable coating material is deposited onto the mould surface until the mould cavity is filled. Following spraying the mould material is dissolved in water leaving a freestanding coating material of near net-shape geometry. Minor machining and finishing operations are then carried out in order to improve the surface finish of the test piece, which can then be tested using standard mechanical test equipment as shown in Figure 33.

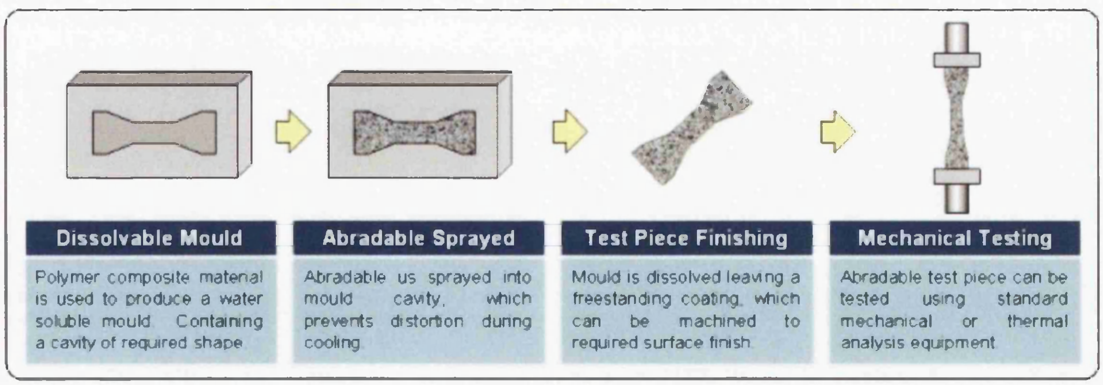

Figure 33. Flow chart of the Freestanding Coating Process

The low material strength and stiffness of the abradable coating material means that the freestanding forms are extremely delicate. In order to obtain reproducible results, a comprehensive validation study was carried out to optimise test piece geometry in addition to machining and testing procedures.

4.2.2 The Freestanding Coating Process – Experimental Design

A comprehensive development programme has been conducted in order to ensure the validity of the Freestanding Coating Process in terms of test variability and control. The validation work focused on the generation of tensile material properties from Al-Si+hBN (Metco 320) abradable coating material. In order to optimise the Freestanding Coating Process, the following key process variables were investigated:

Test Piece Geometry

With fully dense, plasma sprayed, abradable coating materials in particular, the residual stress locked into the coating during manufacture can cause deflection of the coating material. As the residual stress within a system increases with increasing thickness, it was found that for plasma sprayed abradable systems, a maximum coating thickness of 3mm is possible (Santana et al 2006). This provided enough material for final machining and finishing, but prevented significant deflection of the test piece geometry during spraying.

It is important with any tensile testing to ensure that test piece features do not influence the results of the test. Abradables are particularly sensitive to surface features, such as blend radii or machining roughness, due to the heterogeneous nature of the coating structure.

Freestanding Coating test pieces are sprayed on a rotating stage in order to mimic the spraying of a rotor path shroud. It is important that the test piece profile is wide enough to allow the coating material to be deposited within the mould cavity without creating turbulent gas flow. For example a narrow gauge width was found to generate unrepresentative microstructures due to turbulence during spraying, which resulted in a 'shadowing effect' along the test piece edge as shown in Figure 34. The resultant material displayed particularly low strength and was found to be extremely difficult to machine.

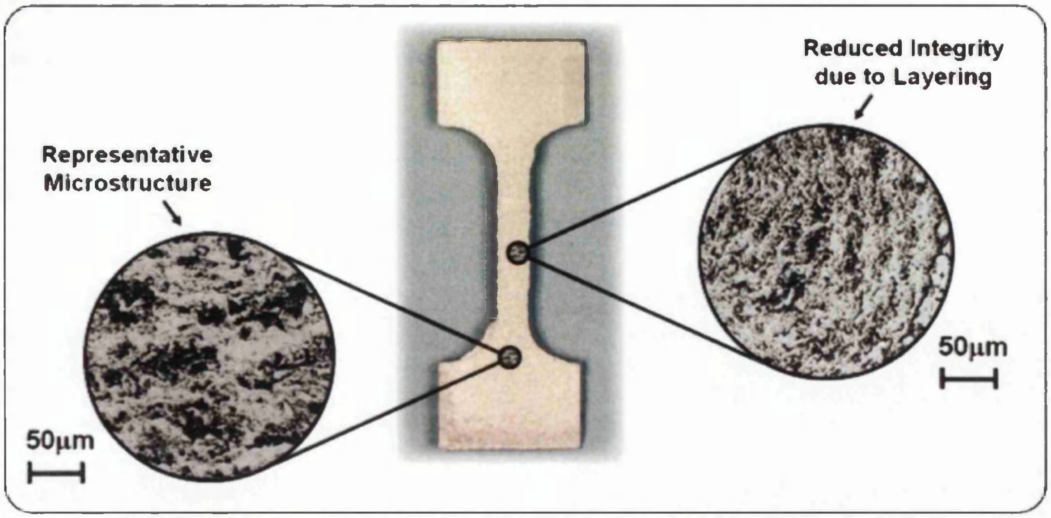

Figure 34. Edge shadowing as a result of narrow gauge width

Following the investigation of a number of test piece geometries a final test piece design was defined for the tensile testing of abradable coating, as shown in Figure 35.

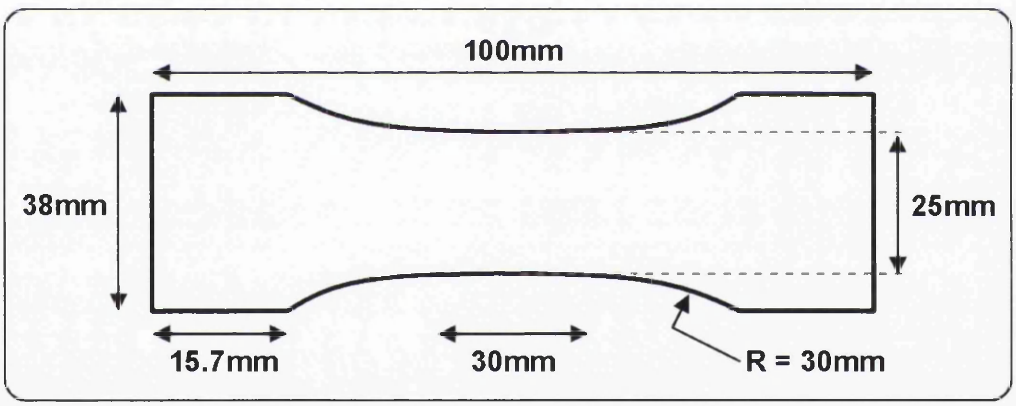

Figure 35. Schematic layout of the final Freestanding Coating tensile test piece design

4.2.3 The Freestanding Coating Process - Results

All validation testing was carried out at Swansea University, using a Hounsfield Testing Frame with a 10kN load cell (with a 1N or better resolution). A universal joint was added to the load train to compensate for any deflection within the test piece during loading. A number of methods of measuring test piece extension were evaluated, in order to determine the most accurate and reliable method:

The low strains to failure of abradable coating materials, means that strain readings calculated from cross-head displacement are inaccurate. Clip gauges can be used to accurately measure strain over a section of a test piece. However, it was found that the contact forces required to support the clip gauge were sufficient to influence the experimental measurements. Optical extensometry could be used to overcome this problem, although the laser extensometers available were discovered to be inaccurate over low strain ranges.

For fully dense abradable coating systems it was found that the most accurate and robust method for generating strain data was to use contact strain gauges, adhered to the surface of the gauge length. However, it is important to note that for porous coatings, such as those produced via combustion spraying, alternative methods should be considered in order to avoid infiltration of the adhesive into the coating material. Figure 36, shows three Metco 320 tensile stress versus strain plots and an image of the final freestanding test piece design. The test pieces were sprayed simultaneously at East Kilbride in order to generate a representative coating material.

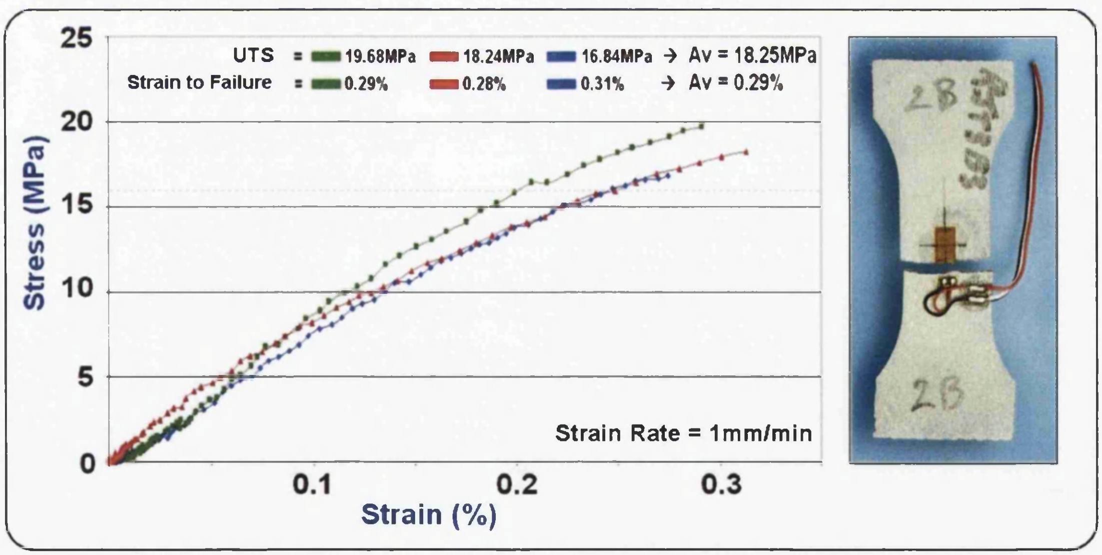

Figure 36. Stress Versus Strain plots for Metco 320 test pieces tested to failure at a strain rate of 1mm/min

The Metco 320 test piece data shown above is comparable to data generated during the validation programme. The average UTS for the three specimens tested was 18.25MPa (±1.5MPa) with a strain to failure of 0.29% (±0.02%).

4.2.4 The Freestanding Coating Process - Discussion

As the test pieces evaluated in Figure 34 were sprayed simultaneously, it is possible to use this data to assess the variability in the Freestanding Coating Process as a result of machining and testing tolerances. The UTS measurements from the three test pieces show a spread of less than 2MPa. The strain to failure ranges from 0.2% to 0.31%. From these results it is possible to measure stress and strain within approximately ±5% of the measured values.

A number of notable characteristics can be observed from the results shown in Figure 34. Clearly the coating material has a low strength and a low strain to failure, but the deformation modes during loading are also important. From initial loading until failure there is no apparent yield stress at the transition from elastic to plastic deformation. Instead permanent damage is apparent following very low loads at the onset of testing. This suggests that the coating fails in a progressive, low-ductility fracture as the various phases and interfaces within its structure crack and de-bond.

In order to better understand the failure mechanism associated with an abradable coating under a tensile load it is useful to consider the microstructure of these materials. Within the structure of the Metco 320 abradable tested, there is an Al-Si matrix phase, within which are randomly distributed particles of hBN as shown in Figure 16. hBN is an extremely low strength and highly lubricious platelet material with similar properties to graphite (Lee *et al* 1999). It is therefore reasonable to assume that it is the hBN phases within the material which plastically deform first.

The interfaces between the hBN particles and the Al-Si matrix, as well as adjacent Al-Si particles that would inevitably contain oxide layers and micro-porosity, form a matrix of weakening planes within the material structure (Padture *et al* 2002). It is therefore reasonable to assume that these interfaces fail ahead of any trans-granular crack formation within the Al-Si matrix.

4.2.5 The Freestanding Coating Process – Conclusions

The Freestanding Coating Process enables accurate and representative generation of coating property data. Although initial work has focused on abradable coatings, this process could potentially be used to generate property data for a number of thermally sprayed materials.

The initial development and process validation work has focused upon tensile testing of fully dense, plasma sprayed, abradable coating systems. Although only limited sized test programmes have been undertaken, the process has demonstrated a good level of consistency. The stress versus strain plots generated were found to indicate reproducible results with a ±5% variability for UTS and strain to failure for a given coating structure.

Under tensile loads abradable coating materials display a progressive failure mode, with no pure elastic behaviour or yield stress apparent. This unique characteristic is most probably due to the multiphase, thermally sprayed structure, which will inevitably fail over a range of stresses relative to the specific coating composition.

There is clearly the opportunity to investigate a range or specific failure mechanisms and stress modes using the Freestanding Coating Process. Compressive, fatigue and also high-temperature tests are of particular interest in terms of better understanding thermal stresses generated in service, due to the mismatch in coefficient of thermal expansion between coating and the substrate material.

In addition, Rolls-Royce is investigating the use of the Freestanding Coating Process for the material property data generation of thermal barrier coatings as well as other thermally sprayed systems. Companies including Corus, Sulzer Metco and General Electric have also expressed an interest in gaining an improved understanding of a range of coating properties.

4.3 Development of a Rig Strategy

Understanding the fundamental mechanisms associated with abradability is essential in order to optimise current abradable coatings and to design the systems of the future (Gasripoor *et al* 1997). Historically, abradability performance has been measured as a function of blade wear/pick-up. As the requirement for improved engine efficiency and performance increases, there is a demand for more quantitative scientific data, in order to enable the development of optimal coating systems.

Generating representative abradability data, comparable to that observed within the compressor of a modern gas turbine aero engine, requires highly specialist equipment (Ernst and Wilson 2005). Only a small number of abradability rigs exist around the world.

4.3.1 Development of the Abradable Rig Strategy – Introduction

To ensure that Rolls-Royce have the necessary testing capability, and to identify the most appropriate test facilities to provide knowledge and solutions to specific business requirements (Simpson 2005), an assessment of the abradability facilities around the world has been carried out. A three phase strategy has been completed in order to assess, classify and standardise the abradability facilities and subsequent testing described in Figure 37.

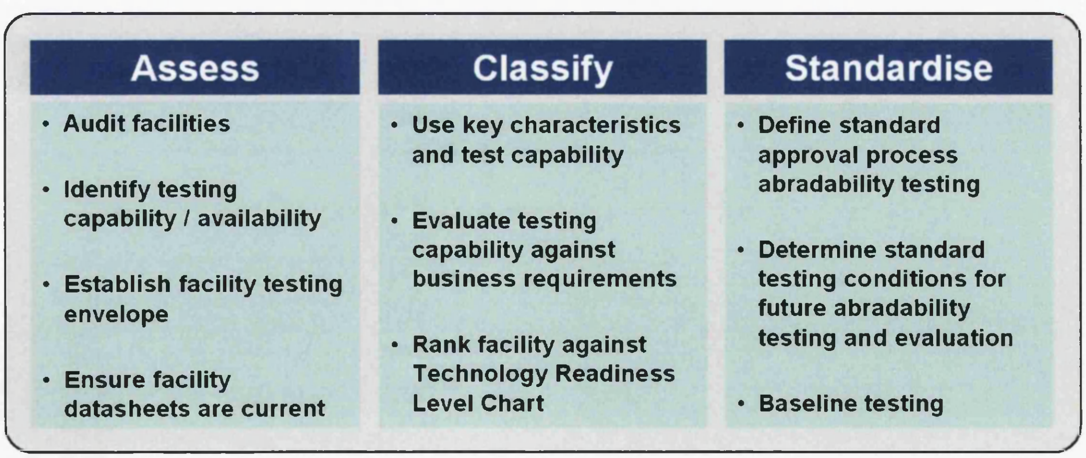

Figure 37. Three phase Rig Strategy overview

Assess

The global abradability facility assessment investigated the capability of abradability test facilities around the world, regardless of their commercial availability (Hopkins 2004). The aim of this study was to investigate the global capability of both Rolls-Royce and aerospace competitors.

Classify

The requirements of the Rolls-Royce business were gathered from Compression Systems and within the coatings community. These requirements formed the basis of the Rig Strategy document (Hopkins 2004), by highlighting strategic testing facilitating both in-service support and new coating introduction.

Standardise

Test facilities were then aligned to these specific business requirements in order to determine the most appropriate abradability test strategy. For example, where high-temperature testing was a requirement, the appropriate high-temperature rig has been selected, based on previous test data and capability.

The results of this study have been captured within a Rig Strategy Document (Hopkins 2004), which aligns test facilities against specific business requirements and the Abradable Approval Process for the introduction of all new abradable systems.

4.3.2 Development of the Abradable Rig Strategy – Assess

The testing capability of a range of commercially available and private venture abradability test facilities has been evaluated. From comparison, all the test facilities studied were classified as either room temperature or high-temperature abradability facilities. A summary of the global abradability facility assessment is shown below:

Room Temperature Abradability Facilities

i) Canadian National Research Centre Abradability Facility – Ottawa, Canada
The Canadian National Research Centre (CNRC) has a longstanding room temperature abradability facility, which is commercially available. Data available from the rig is limited to simple blade and shroud weight and

dimension changes. Some historic results have proved to be inconsistent with the Sulzer Innotec abradability rig data.

ii) Alstom Abradability Facility – Rapperswil, Switzerland

The Alstom Abradability Facility was recently developed under a Swiss government funded collaboration with the IPEK University in Rapperswil. Although the facility is not currently commercially available, Alstom will allow Rolls-Royce to use it under a pre-existing technology transfer agreement between the two gas turbine manufacturers. In addition to standard blade and substrate weight and dimensional changes, high-speed instrumentation enables detailed load and temperature rub data to be generated.

iii) General Electric Facility – Ohio, USA

General Electric (GE) is the world's largest gas turbine engine manufacturer. In addition to commercially available abradable coating materials, GE has developed a number of proprietary abradable coating systems. GE has an unusually designed spin-pit rig, with a vertical shaft, which is intended to simulate engine condition rubs including vibration modes setup during the flight cycle. As a competitor, little is known about the capability of the test rig and as such this facility is not available to Rolls-Royce.

High Temperature Abradability Facilities

Sulzer Innotec Facility – Winterhur, Switzerland

For over 20 years Rolls-Royce has used the Sulzer Innotec abradability facility for most of the abradability analysis for both compressor and turbine abradable systems. The facility, which is discussed in Section 3.6, is recognised as an international standard for abradability data by both engine manufacturers and coating companies.

There are however, a number of limitations associated with the Sulzer Innotec Facility. Testing is expensive and test slots are limited to one week per month. The rig has remained largely unchanged for a number of years with limited instrumentation.

Praxair Facility – Indianapolis, USA

Praxair Surface Technologies have recently commissioned a high-temperature abradability facility at their facility in Indianapolis. This facility uses similar technology to the Sulzer Innotec facility by heating abradable test pieces using oxyacetylene torches. However, there are limits to the possible blade tip speed, due to the amount of resistance generated by the unique four armed rotor, as shown in Figure 38.

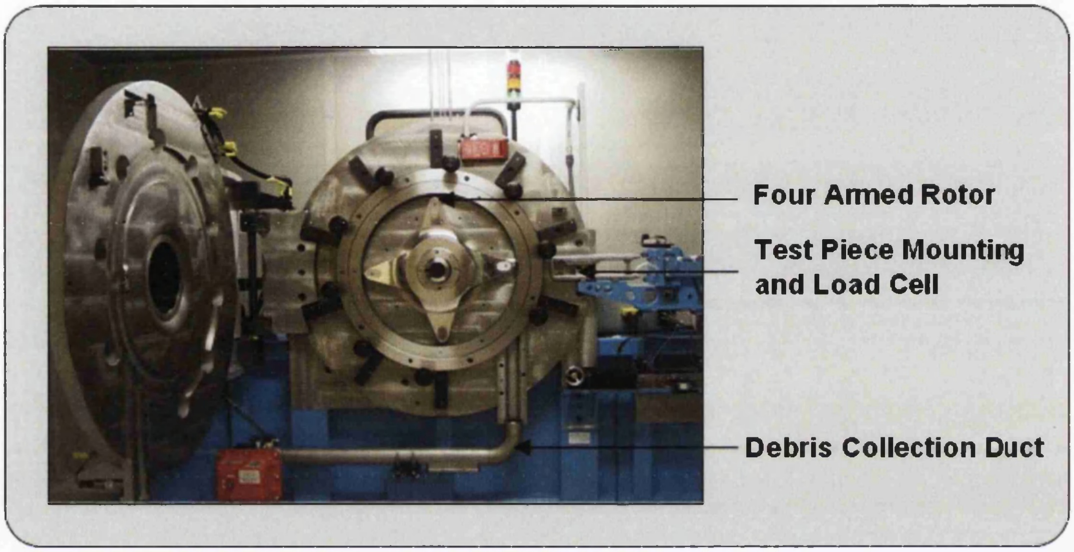

Figure 38. Praxair high-temperature abradability facility

Upgrades to the rig drive motor are planned to improve the blade tip speed capability of the rig. Load cell and infrared temperature measurements are available, together with a unique debris collection duct.

MTU Facility – Munich, Germany

An abradability facility at MTU allows engine components to be tested at elevated temperatures and representative incursion rates. Rotor path shrouds can be mounted within the closed rig as shown in Figure 39.

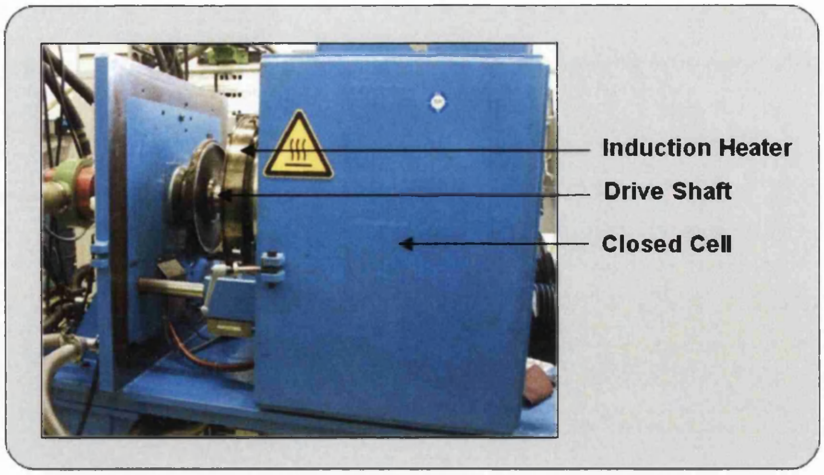

Figure 39. MTU high-temperature abradability facility

The MTU rig is capable of generating extremely high incursion rate rubs, representative of conditions observed during aggressive military engine manoeuvres. MTU use a combination of blade tip wear/pick-up and optical inspection for signs of excessive frictional heating to measure abradability performance (Zheng *et al* 2002). As a competitor, the MTU abradability facility is not available to Rolls-Royce.

Cranfield University Facility – Cranfield, UK

A rig is currently under construction at Cranfield University as part of a DTi funded programme, investigating rub induced titanium fires. The facility is unique in that it utilises a powerful peddle-bed heater in order to create a flow of hot air. It will be possible to generate representative compressor temperatures and pressures within the closed cell rig. The facility will also be capable of testing engine rotor path shrouds and compressor blades.

The costs associated with running such an advanced abradability facility will be substantial; however, the rig will have the ability to generate conditions comparable to those that exist within a gas turbine compressor.

4.3.3 Development of the Abradable Rig Strategy – Classify

The global assessment of abradability facilities highlights the capability and availability of these specialist test rigs and their value to Rolls-Royce is determined by the requirements of the business. The requirements of Rolls-Royce have been gathered through consultation with the Coatings Group and Compression and

Turbine Systems. A summary of the strategic business requirements for abradability research and testing is shown in Figure 40.

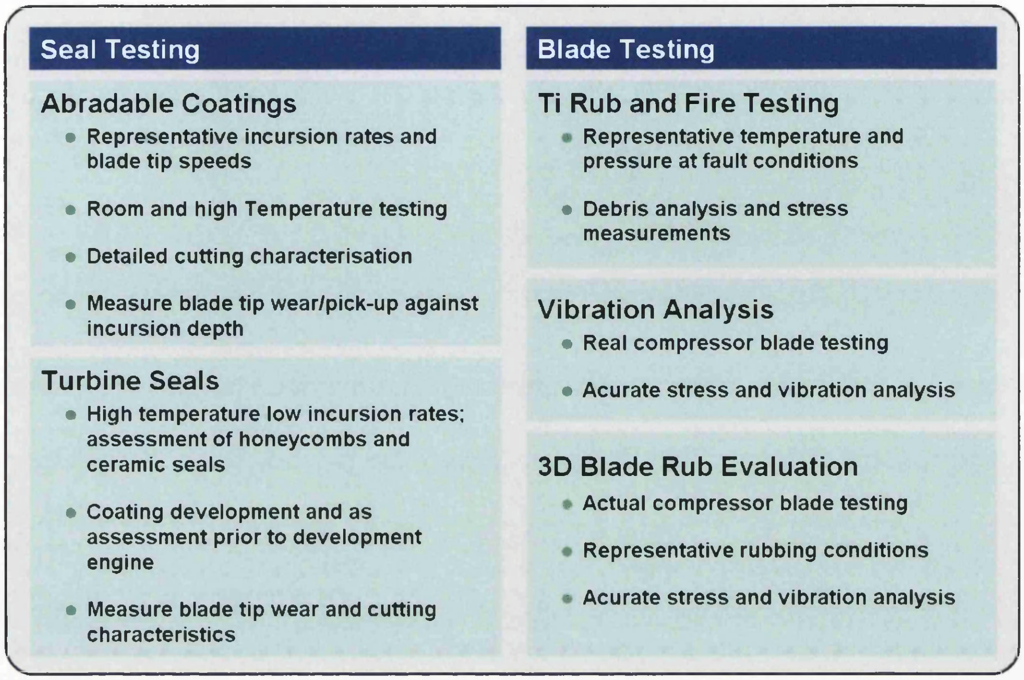

Figure 40. Rolls-Royce strategic business requirements for abradability capability

Not only is there a strategic requirement for abradable research and development and coating approval from within the Coatings Group, but also in-service support to both Compression Systems and Turbine Systems. It is essential that a robust testing capability is available for investigating abradability mechanics at a fundamental level in order to support early coating development, together with engine representative rigs, for mature systems and approval for engine testing.

From the global assessment and review of business requirements shown in Figure 38, the Alstom abradability facility has been identified as the strategic test resource for all fundamental abradability analysis. This will provide the majority of research and development support as well as the early, new coating approval stages.

The Alstom Abradability Rig, as shown in Figure 41, is driven by an 80kW electric motor capable of rotational speeds of >22,000RPM, which generate a maximum blade tip speed of 419m/s. A stepper motor, capable of incursion rates of between 1-7000m/s controls the position of the substrate relative to the rotating blade. Both axial and radial incursion rates are possible either individually or in combination.

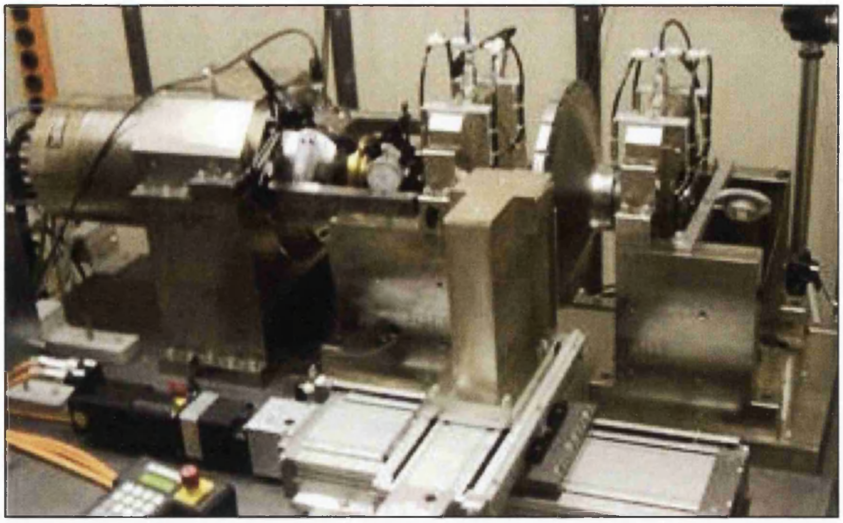

Figure 41. The Alstom Room Temperature Abradability Facility

Optical pyrometers activated by the passing blade are capable of taking temperature readings from both the blade tip and the abradable surface. Load cells attached to the substrate holder measure the load generated during corresponding rubs in the axial, radial and tangential directions. It is feasible to gather data at a rate of one point every 40th blade pass. In this way it is possible to generate extremely detailed maps of rub load and temperature, as indicated in Figure 42, showing a pyrometer voltage signal, which is later converted to the relative temperature.

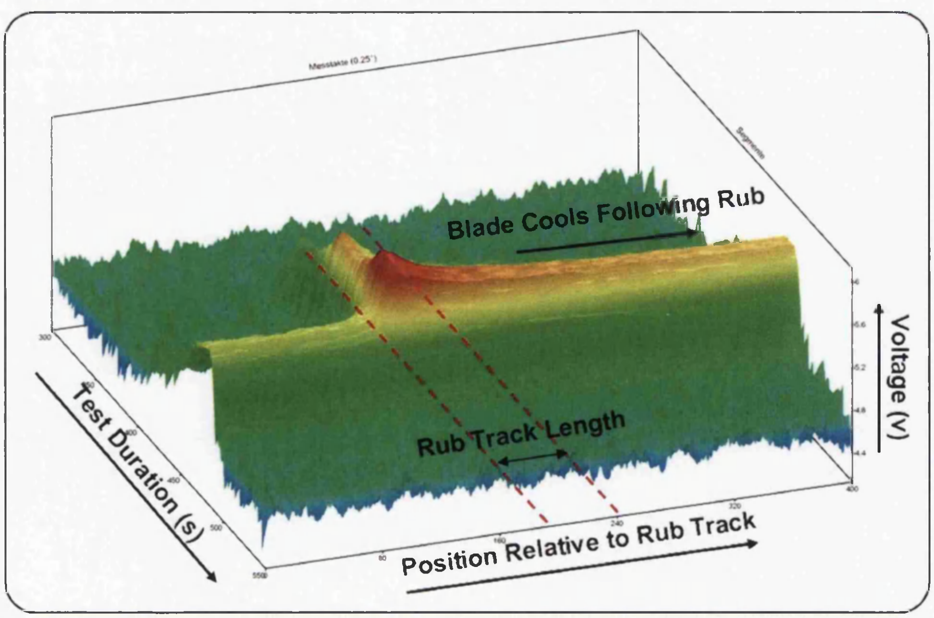

Figure 42. Pyrometer temperature measurements of blade tip during abradability test

The temperature plot shown in Figure 42 indicates a rapid increase in temperature from frictional heating during contact between the blade tip and abradable material. The subsequent cooling on the blade during the remaining rotation is also shown.

The Alstom abradability facility offers a unique test capability, which will enable Rolls-Royce to generate a fundamental understanding of the abradability mechanics of current and future abradables. However, the facility does not currently provide high-temperature capability, and is therefore not considered an appropriate facility for later stages of coating approval or generating engine representative conditions.

From the global abradability facility assessment and review of business requirements within Rolls-Royce it is clear that at present the Sulzer Innotec abradability facility provides the most robust high-temperature testing capability. The Sulzer Innotec facility does not offer the specialist load and temperature measurement capability of the Alstom rig. However, the high-temperature testing and representative disc geometry provides more representative blade and abradable test data. This is important, particularly when approving new coating systems for development engine testing. At present Sulzer Innotec provides this unique capability, of which Rolls-Royce has considerable experience.

There are however, significant differences between the test conditions of the Sulzer Innotec facility and those of an aero engine compressor. Pressure ratios and gas stream flows are currently outside the capability of any commercially available abradability facility. The Cranfield Abradability Facility will move closer to the compressor environment, with the pebble bed hot gas stream generator, and it will therefore be appropriate to review the current rig strategy once this facility becomes operational.

4.3.4 Development of the Abradable Rig Strategy – Standardise

The Rolls-Royce Abradable Rig Strategy has been defined using the results of the global abradability assessment and business requirements. Figure 43 shows how the Alstom and Sulzer Innotec Abradability Facilities will support the research and development of abradables and also the Abradable Coating Approval Process.

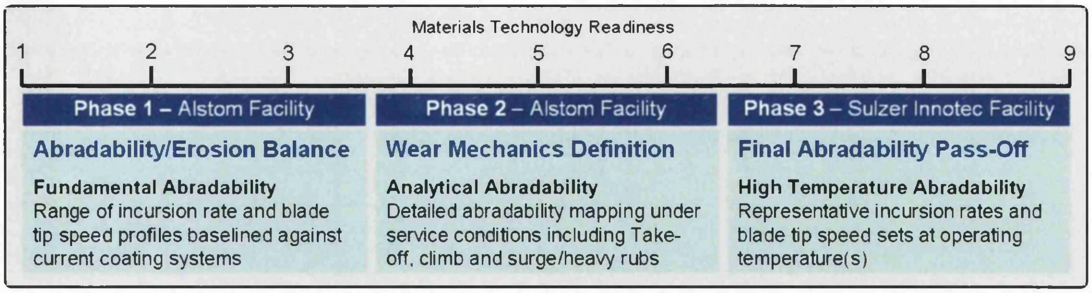

Figure 43. Abradability testing for future research and new coating approval

In Figure 43 abradability testing is classified into three gated phases. Each phase is aligned against the Materials Technology Readiness Level (MTRL), which is a Rolls-Royce standardised scale, providing information as to the maturity of a material system. Specific material and manufacturing requirements associated with the various MTRL's must be achieved in order to reach MTRL 9, at which point the material is eligible for engine testing. Abradability data generated during the 3 phases of testing will provide the technical evidence to allow a coating material to proceed along the MTRL scale.

The 3-phases shown in Figure 43 are also aligned to specific abradability facilities due to their specific testing capability:

Phase 1

As discussed above the Alstom abradability facility provides unique fundamental testing capability. Load and temperature data provided by this facility will be useful during early stages of coating development and initial approval. Availability of the facility means that abradability screening trials can be carried out and combined with coating erosion performance as initial pass/fail criteria.

Phase 2

In order to generate a comprehensive understanding of coating abradability, performance over all service conditions phase 2 testing will also be carried out at the Alstom Abradability Facility. The relatively low test costs associated with the facility mean that it is possible to carry out a large number of abradability tests. This will allow the generation of detailed abradability maps showing both blade tip wear/pick-up and time-dependent load and temperature rub data.

Phase 3

Once a coating material has satisfied all Phase 2 criteria it is necessary to perform a selection of high temperature abradability tests prior to full demonstrator engine tests. The Sulzer Innotec Abradability Facility will be used for Phase 3 testing, allowing representative rub temperatures to be generated over a range of service conditions.

4.3.5 Development of the Abradable Rig Strategy – Conclusions

The Abradability Rig Strategy provides a generic specification for the abradability testing of coating systems during research and development and as part of the coating approval process. The strategy was used to select commercially available abradability testing facilities from around the world capable of supporting the requirements of the business.

Of the facilities evaluated, those of Alstom and Sulzer Innotec were found to provide the necessary testing capability to support the current research and approval process requirements of Roll-Royce.

The Cranfield University Abradability Facility, which is currently under construction, will provide additional and unique test capability. It is therefore necessary to review the Abradability Rig Strategy on a regular basis in order to ensure that the most appropriate facilities are used and that there is capability available to meet the technical requirements of the Rolls-Royce Coatings Group.

4.4 Seal Coat Abradability Model

As highlighted within the literature review, the complex mechanisms associated with abradability performance are difficult and often costly to investigate. Abradability facilities such as the Sulzer Innotec and Alstom rigs are able to provide experimental data, which can be used to better understand coating performance during specific rub conditions. Ultimately, in order to design a robust abradable coating system, capable of operating over many flight cycles and over a range or operating conditions, it is necessary to simulate its performance using computational models. This allows much larger and more detailed abradability maps to be generated for a range of operating temperatures at a fraction of the cost (Maozhong *et al* 2002).

In an effort to develop a predictive abradability model, Rolls-Royce has collaborated with eight partner companies and research institutes in a European funded research programme called Seal Coat.

4.41 Seal Coat Abradability Model - Introduction

The Seal Coat Programme utilised modelling expertise, engine manufacturer service experience and coating supplier knowledge in an effort to develop an abradability model capable of simulating wear as a result of specific rub conditions (Chandler 2006). Laboratoire d'Etudes et de Recherches sur les Matériaux, les Procédés et les Surfaces (LERMPS), the modelling and thermal spray specialist department at the French university of the University of Technology of Belfort Montbéliard (UTBM), coordinated the modelling activities, and was responsible for generating the abradability software based upon test data and engine experience supplied by Rolls-Royce. Sulzer Metco has been responsible for the supply of coating materials for testing, metallographic analysis and available coating property data.

Various aspects of abradable coatings and abradability mechanics were investigated within the Seal Coat programme (Faraoun *et al* 2004). Two complementary approaches for modelling of abradability mechanics have been developed in parallel, using a variety of commercially available and specifically developed software tools, which contribute to a comprehensive simulation of abradability. Figure 44 shows a flow chart overview of the relevant modelling processes associated with the two approaches and the software required.

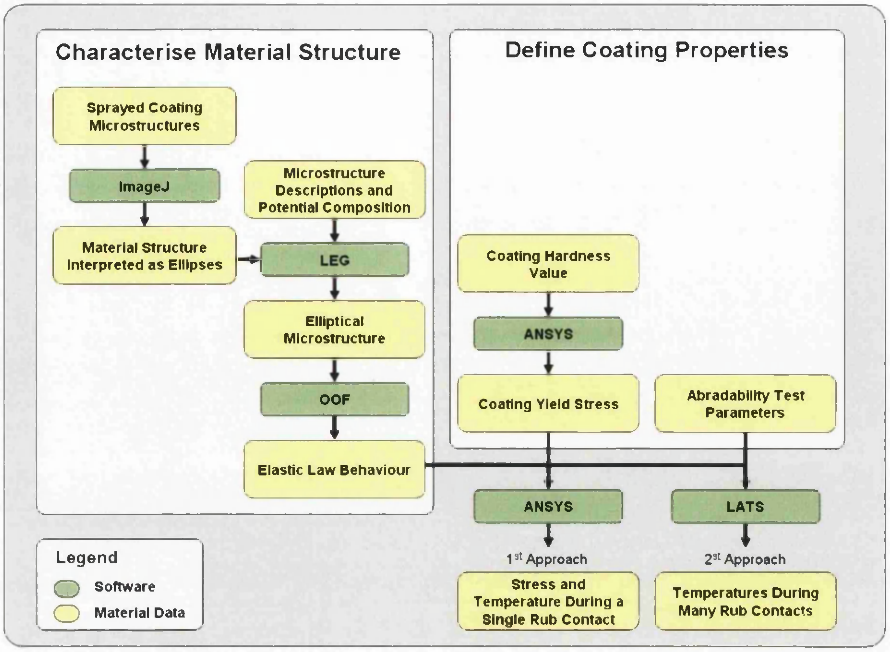

Figure 44. Flow chart of modelling processes and software used in Seal Coat abradability model

1st Approach – Metallographic Route

An image analysis process has been implemented using the ImageJ software, to achieve a representative description of an abradable coating microstructure (Faroun *et al* 2005). The image analysis process identifies the various phases within the material structure and the associated key characteristics including; area %, aspect ratio and size distributions from an electron microscope image of the material microstructure (Zwick *et al* 2005).

Specially developed software, LERMPS Ellipse Generator (LEG), is then used to create a simplified microstructure based upon the input characteristics, constructed from an arrangement of ellipses. A finite element (FE) mesh is generated over the elliptical structure, allowing specific material properties to be assigned to the various phases of the configuration (Faraoun *et al* 2005). The process of converting an abradable microstructure to a representative meshed elliptical representation is shown in Figure 45.

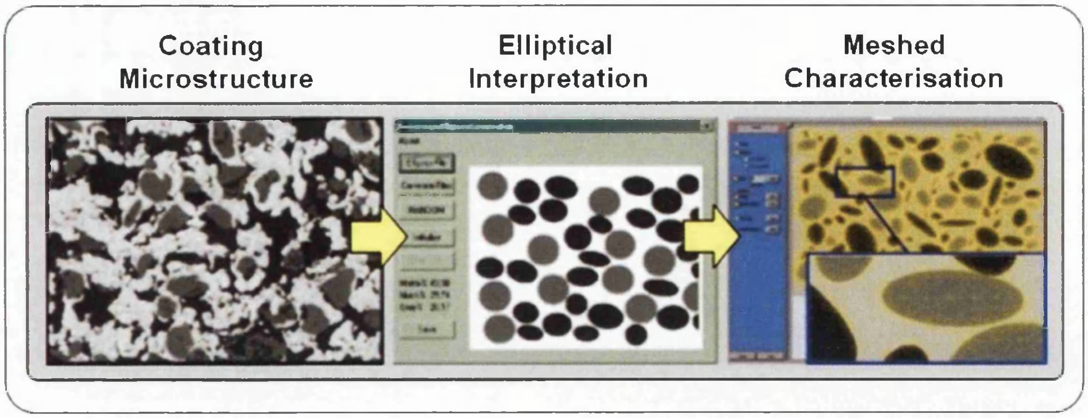

Figure 45. Microstructure interpretation using LEG software to create ellipses

From the FE model it is possible to estimate the elastic modulus of the bulk structure as a result of the relative proportions of the various phases. Due to the lack of material property data available for the abradable coating materials studied, a value of yield stress has been estimated from the hardness of the coating material (Cao and Lu 2004).

These parameters and structural characteristics are then used as inputs for an FE simulation of a single blade-to-coating rub contact, resulting in calculated stresses and temperatures. The commercially available FE code ANSYS has been used to perform the contact simulation between a simple blade geometry and flat abradable coating surface (Seichepine *et al* 2005).

The properties of both the blade and coating materials are key input variables. Blade materials are assumed to be classical isotropic and linear elastic. For the coating a linear elastic orthotropic behaviour is assumed, with parameters defined using the LEG and FE modelling techniques previously described.

The contact between blade tip and coating surface is modelled for a constant incursion rate (V_{inc}) over a single rub, moving with linear speed (V_{rot}) as shown in Figure 46.

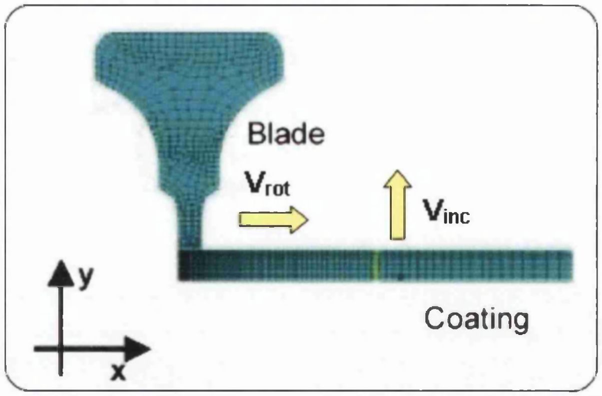

Figure 46. Relative blade and coating velocities resulting in contact forces and frictional heating

The resultant combined velocities generate frictional heating at the contact area between the blade and coating, proportional to the effusivity (a heat transfer property, which dictates the interfacial temperature of two objects at different temperatures) of each material.

2nd Approach – Global Thermal Simulation of the Abradability Rig Test

The aim of this simulation is to adjust the theoretical laws from the 1st Approach with empirical observations from abradability rig tests. This is to allow for limitations due to calculations from the 1st Approach only accounting for single blade contacts. For example, cyclic variations in temperature over the duration of a rub test are sometimes observed due to the melting and transfer of abradable material to the blade tip. Comparison of rig data, with the calculations from the FE model, will allow improvements to be made to the abradability model.

The LERMPS Test Simulator (LATS) has been developed to estimate temperature evolutions during a rig test. LATS is an analytical approach, considering a large number of blade contacts, each comprised of three parts as shown in Figure 47.

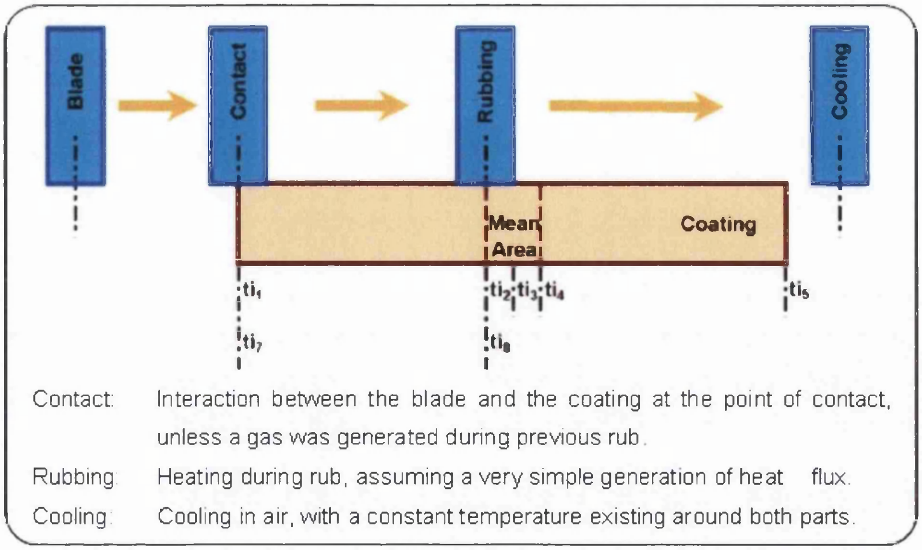

Figure 47. LATS analytical approach for multiple rub conditions

LATS relies on range of input parameters for the blade, coating and geometry of the system.

4.42 Seal Coat Abradability Model - Discussion

Models developed within the Seal Coat programme have taken existing abradability data and service experience in order to provide predictive load and temperature data for a given set of rub conditions. Due to time restrictions within the Seal Coat programme, only limited model validation testing has been carried out. Further development and validation work is planned within a separate DTI funded research programme.

Although limited validation data is currently available, a number of key elements of the modelling capability developed within the Seal Coat Programme have been demonstrated. These will assist with coating development and form the foundations of future abradability modelling activities.

An image analysis process has been established using the ImageJ software, which is able to achieve a representative description of an abradable coating microstructure. The software uses microstructural images to identify individual phases within a coating material structure and associated characteristics including; area %, aspect ratio, and size distributions. As well as providing a key step in the accurate modelling of abradability mechanics, this process has wider benefits as a tool for assessing the influence of process parameters on coating properties.

LEG software is used to create a simplified microstructure, based upon the input characteristics and constructed from an arrangement of ellipses. This technique allows a simplified combination of material properties to be generated for the composite structure. The process could also benefit stress calculations used to evaluate operational conditions, which depend upon accurate material property data.

The Seal Coat Abradability Model used the LEG elliptical structure to generate a FE mesh. This enables accurate evaluation of the load and temperature gradients through the coating structure upon contact with an incurring compressor blade tip (Faraoun *et al* 2005). Validation of this approach is necessary before the technique can be used to model abradability performance in place of more expensive and timely rig testing. The LATS model for abradability also requires further validation before the tool can be used to generate representative abradability data.

4.43 Seal Coat Abradability Model - Conclusions

The Seal Coat European funded research programme aimed to generate a predicative abradability model using service experience and material property data. Two complimentary approaches for modelling of abradability mechanics have been developed in parallel.

Techniques for the characterisation of the complex abradable coating microstructures have been developed. Established image analysis techniques have been successfully used to determine key coating structure properties. Specially developed LEG software generates a simplified elliptical representation of a given microstructure, which can be used to create detailed FE computational meshes. These techniques will provide valuable data for spray process analysis and future abradability modelling activities.

FE simulations using standard laws of friction equations generate temperature and load data for a given set of abradability conditions. From the FE model it is possible to calculate an elastic modulus for the coating structure as a result of the relative proportions of the various phases. Together with additional material property data, including a value of yield stress deduced from the hardness of the coating, their constants are used as inputs for an FE simulation of a single blade-to-coating rub contact, resulting in calculated stresses and temperatures.

The commercially available FE code ANSYS was used to perform the contact simulation between a simple blade geometry and flat abradable coating surface. Blade materials are assumed to act in classical isotropic and linear elastic behaviours. For the coating, a linear elastic orthotropic behaviour, with parameters defined using the LEG and FE modelling techniques previously described, is assumed.

The models developed within the Seal Coat programme are clearly dependent upon the material property data provided. Where possible coating property data was generated or sourced from literature. However, some key coating properties, including yield strength and compression behaviour data, was not available. It is therefore essential that a detailed validation programme is carried out to identify any inaccuracies within the model as a result of the lack of available material property data.

Future abradability test programmes will be used to generate load and temperature data over a range of test conditions for a known coating structure and blade tip geometry. The Seal Coat Abradability Model will be run using comparable dimensions and specific coating characteristics in order to validate the load and temperature data generated.

Seal Coat Abradability Models currently generate load and temperature data as a result of the frictional behaviours of respective blade and coating materials at representative engine conditions. The generation and dissipation of heat as a result of coating loss and blade tip wear/pick-up are not included in these calculations. Further work could build upon the techniques developed and the availability of a highly instrumented abradability facility, for example the Alstom Abradability Rig, in upgrading the models to account for these complex mechanisms.

4.5 Abradable Coating Approval Process

Generating representative coating property and abradability data is essential in providing a fundamental understanding of existing abradable materials, also for the development and approval of new coating systems. The techniques and processes discussed in Section 4 have been formalised within the Rolls-Royce Abradable Coating Approval Process. The 3-phase gated process is designed to provide the necessary evaluation techniques and pass/fail criteria to approve a new abradable coating system as shown in Figure 48.

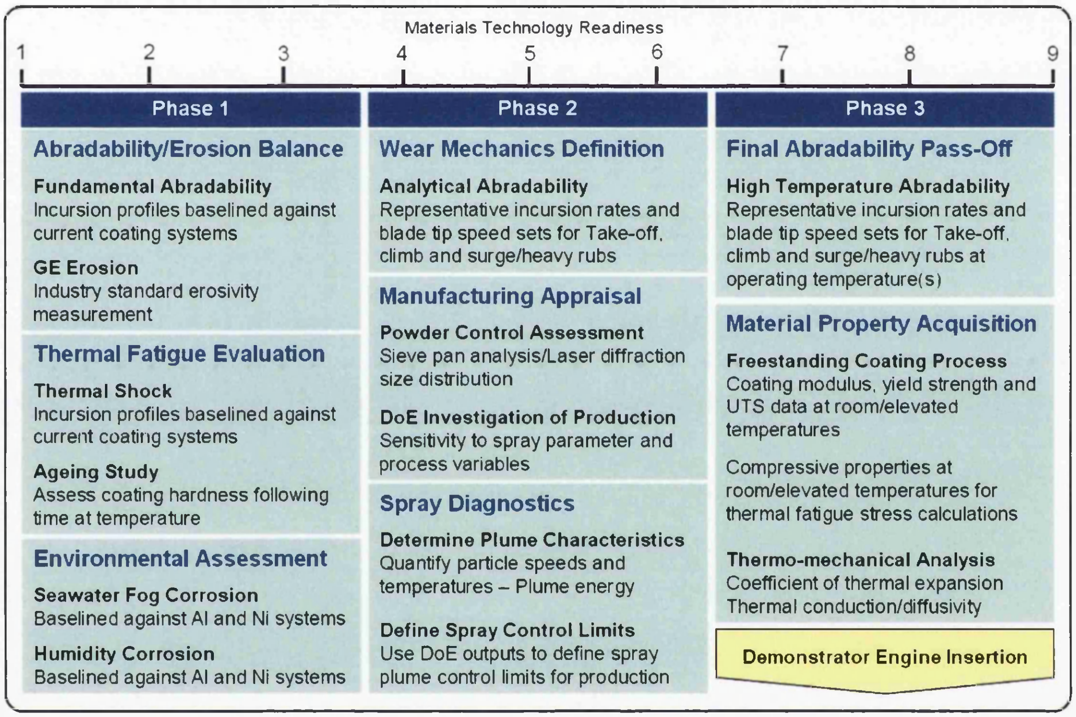

Figure 48. 3-Phase Approval Process for Abradable Coating Materials

Within each phase of the Approval Process there are a number of specific tests. Each of these has a formal procedure and pass/fail criteria, which must be achieved by a new coating system in order to progress to the next phase of testing:

Phase 1

As an initial evaluation of coating functionality, Phase 1 testing provides an assessment of the critical balance between abradability and erosion resistance. In addition, thermal shock and corrosion testing determine a coating's resilience to thermal stress and aggressive environmental conditions.

Phase 2

A comprehensive abradability investigation is carried out in Phase 2, generating detailed abradability maps over representative service conditions. A manufacturing appraisal evaluates the manufacturing processes and quality control of a coating to ensure the system is robust. Spray diagnostics equipment is used to analyse spray plume characteristics in order to identify the optimum spray parameters.

Phase 3

A final high-temperature abradability study provides confidence that the system will operate at service temperatures. A range of coating property data is also generated using the Freestanding Coating Process, together with additional laboratory techniques. Property data can then be used by design engineers to model service stresses on component geometries prior to engine testing.

The Approval Process phases are aligned to Rolls-Royce Materials Technology Readiness Levels (MTRL), a corporately recognised maturity scale for any new technology, which was discussed in Section 4.3.4. Once a material has reached MTRL 9 it is possible to begin demonstrator engine testing prior to entering service.

5. Definition of Key Performance Drivers

To design a robust and reliable abradable coating system it is essential to have a clear definition of the key performance drivers, which influence the coating behaviour during service. The Corporate Approval Process discussed above aims to quantify new abradable coatings against specific performance criteria. It is therefore necessary to identify and understand the material properties and service conditions driving performance.

A number of programmes of work have been undertaken, focusing specifically upon the identification of key performance drivers, for a range of abradable systems. The findings of these studies have been captured within a single document – The Abradable Blueprint of Understanding (Sellars and Hopkins 2005). As a design guide, this document will be used to design future generations of abradable coating materials.

5.1 Metco 320 Binder Burnout Investigation

Metco 320 abradable coatings have proved to display a significant decrease in hardness with time in service (Woodward 2003). Material softening is believed to be due to burnout of the organic binder at the elevated operating temperatures of IP and HP compressors. In addition to this, service data suggests that 'gramophone grooving', as a result of coating melting or softening, and transfer to blade tip occurs following as few as 50 engine cycles.

Historical rig data and service experience suggests that maximum rub temperatures are observed during low incursion rate rub conditions ($<10\mu ms^{-1}$), witnessed during the climb section of a civil flight cycle. There are two possible conditions, which could lead to such a low incursion rate or light rub conditions. Generally, low incursion rate rubs are the results of the thermal expansion of various parts of the engine core and casing. These usually follow higher incursion rate rubs, as a result of engine thrust events. A more subtle condition, which may generate low incursion rate rubs, results from variations in the operational environment: As the aircraft increases in altitude the air pressure decreases allowing the compressor blades to rotate at higher velocities. As the rotational speed of the engine gradually increases the disc and blade slowly expand resulting in a low incursion rate rub or even dwell condition.

5.11 Metco 320 Binder-Burnout Investigation - Introduction

An abradability study was carried out to investigate the influence of the organic binder within Metco 320 upon the abradability performance of the coating; namely its tendency to transfer material to blade tip during low incursion rate rubs. If conclusive, the results could be used to introduce a heat treatment process following the thermal spraying of production parts. The binder material within Metco 320 is a self, cross-linking acrylic latex, designed to hold Al-Si and hBN particles together during the spray process (Purdie 2001). There are no known benefits of the residual binder following spraying.

The investigation used test pieces sprayed at two UK manufacturing thermal spray facilities. Half of the specimens from each facility were then heat-treated in order to simulate time in service and burnout of the organic binder. All test pieces were subsequently sent to the Sulzer Innotec abradability rig in Switzerland to investigate the occurrence of gramophone grooving during low incursion rate rubs. To ensure that heat treatment did not have any adverse effects on other material properties, comparative corrosion and thermal shock tests were carried out at Rolls-Royce on all specimens.

5.12 Metco 320 Binder Burnout Investigation – Experimental Design

The Metco 320 Binder Burnout Investigation involved two sets of experiments to first determine a suitable binder burnout process and subsequently study its influence on abradability performance under low incursion rate rubs:

Binder Burnout Study

In order to investigate the effects of a binder burnout heat treatment on Metco 320, a suitable heat treatment needed to be designed, which would burn out most if not all of the binder within a reasonable length of time, without having any adverse effects upon the rest of the coating structure. For the heat treatment to be used as part of the manufacturing process it had to be carried out over a reasonably short time period, without causing oxidation or degradation of the abradable matrix material.

Metco 320 test pieces were heat treated at a range of temperatures (225°C-450°C). Each test piece was weighed periodically to quantify the amount of binder removed following time at temperature. From these results a suitable heat treatment cycle was defined.

Abradability Performance

To evaluate the abradability performance of Metco 320 coatings under representative conditions, the Sulzer Innotec abradability facility was used to carry out the investigation at elevated temperatures. Temperatures, blade tip speeds and incursion rates were selected to reproduce a range of service conditions associated with gramophone grooving.

In an attempt to simulate representative low incursion rate (light-rub) conditions witnessed on some large civil engines during climb, three incursion rate profiles were designed. Figure 49 shows these profiles with the respective incursion rates and incursion times or incursion depths.

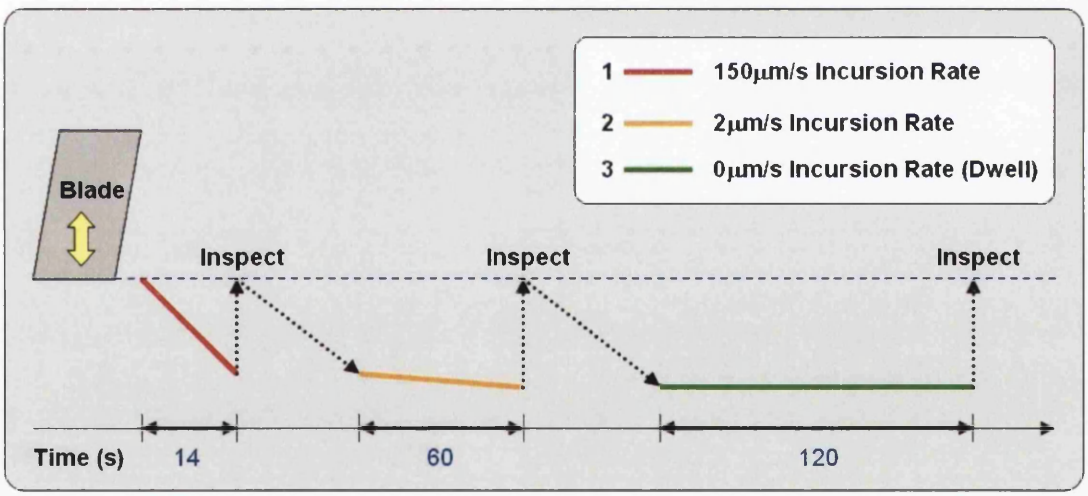

Figure 49. Incursion rate profiles for abradability investigation

Profile 1 represents the running-in handling (engine pass-off cycle) of an engine. A high incursion rate ($50\mu ms^{-1}$) was used in order to cut an arced path in the Metco 320 abradable coating. Test run 2, which was carried out on a separate test piece, repeated the high incursion of test 1, before the piece was retracted for inspection. The second part of the test run involved a slow incursion rate of $2\mu ms^{-1}$, for 1 minute to represent a climb condition. Test run 3 involved a duplication of test run 2 with a new test piece and an additional dwell period (no incursion) of 2 minutes to represent the cruise condition of the flight cycle.

Inspection of the blade tip and coating surface was carried out following the completion of each profile. All abradability tests where carried out at 350°C and with a blade speed of $370ms^{-1}$. The blades used were titanium 6/4 and had a wedge shaped tip ranging in thickness from 0.7mm to 2.5mm, in an attempt to understand the influence of blade tip thickness.

5.13 Metco 320 Binder Burnout Investigation – Results

Binder Burnout Study

It was discovered that >85% of the binder was burnt out in a relatively short period of time, whilst the remaining 10%+ burnt out at a much slower rate. Figure 50 shows a plot of % weight loss against time (min) for a range of heat treatment temperatures.

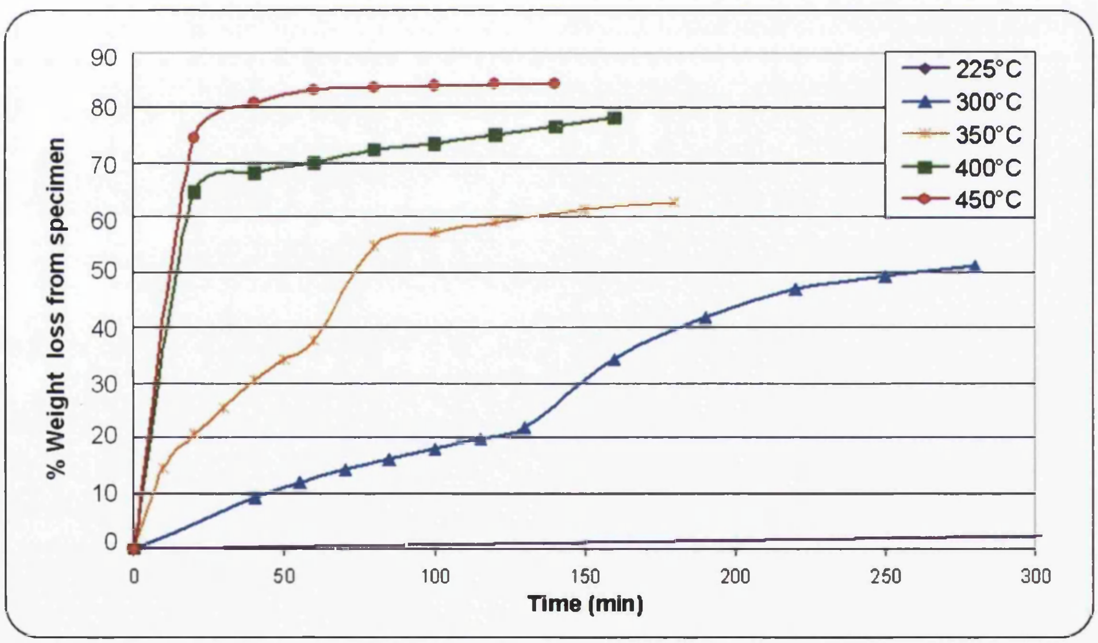

Figure 50. % Weight loss of Metco 320 specimens as a result of binder burnout following time at a range of elevated temperatures

From these results a heat treatment of 400°C for one hour would be sufficient to burn out approximately 70% of the binder. Over 80% of the binder was removed at 450°C, however, there were concerns that oxidation of the aluminium may become an issue. A one hour, 400°C heat treatment was then applied to half of the test pieces from the two UK spraying facilities, before being submitted for abradability testing at Sulzer Innotec, and corrosion and thermal shock testing at Rolls-Royce.

Abradability Performance

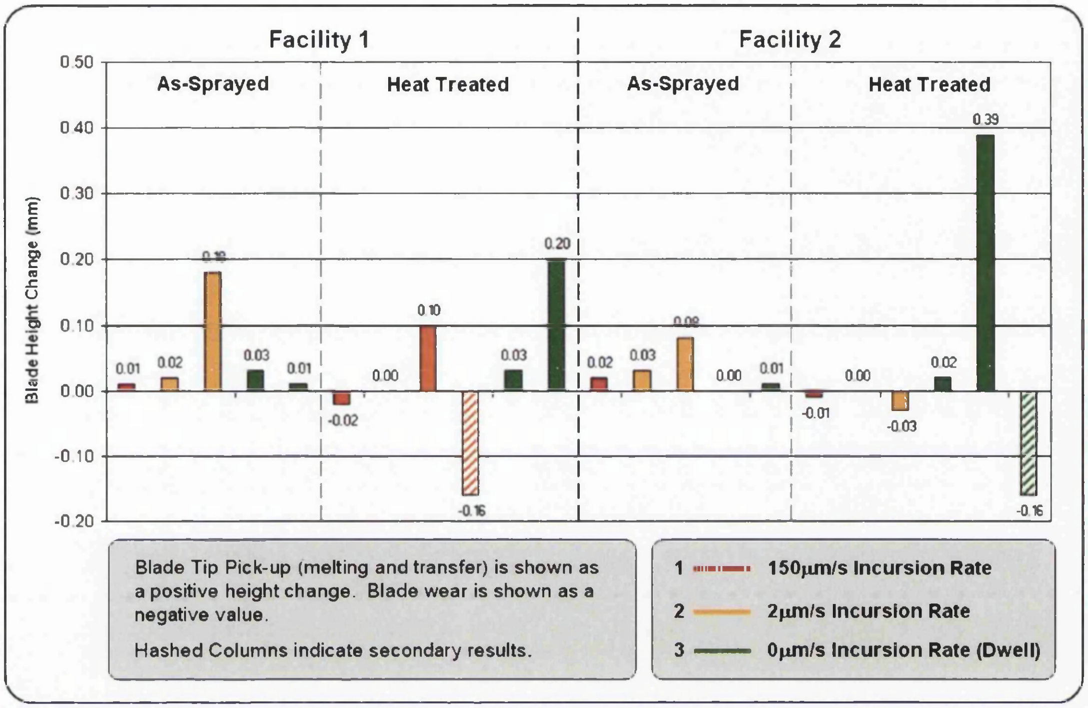

Figure 51. Blade height change measurements following abradability testing of as-sprayed and heat treated Metco 320 test pieces

From the results shown in Figure 51 it is apparent that the abradability behaviour of coatings sprayed at the two manufacturing facilities is comparable. Inevitably there is some scatter within these results, due to the cyclic nature of the melting and transfer mechanism associated with blade tip pick-up. Indeed, video footage of the abradability testing indicates the extent of the heating and cooling cycle associated with pick-up and gramophone grooving.

There was no significant pick-up or blade wear following the 50µm/s incursion rate rub for both the as-sprayed and heat treated abradables sprayed at the two manufacturing facilities. However, the 2µm/s incursion rate of Profile 2 (orange bars) did show significant blade tip pick-up, particularly for the as-sprayed coatings. Pick-up was also observed on all Profile 3 (green bars) tests and was particularly prominent on the heat treated specimens. Sulzer Innotec reported concerns that the dwell period was difficult to set up and that other factors, like vibration, may have led to the accumulation of abradable on the blade tip (Zielinski and Zuller 2005).

Both blade tip pick-up and wear were observed on the heat treated specimens from Facility 1, tested under Profile 2, and Facility 2 under Profile 3. In both cases blade wear was observed on the thinner blade thickness, whilst pick-up was concentrated towards the thicker blade tip thickness as shown in Figure 52.

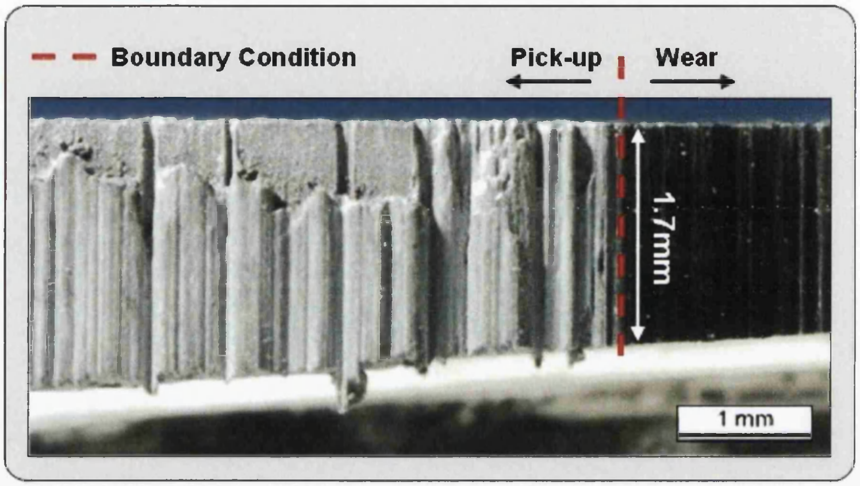

Figure 52. Blade tip displaying pick-up on thicker section and wear on thinner width.

The boundary condition between pick-up and blade wear, indicated in Figure 52 is at a blade tip thickness of 1.7mm. The greatest wear was observed at the thickest blade width and appeared to lessen toward the boundary condition.

The thermal shock and corrosion testing carried out at Rolls-Royce showed that heat treatment had no significant effect upon the thermal shock resistance or corrosion resistance of the abradable material. The heat-treated coatings were noticeably more friable and appeared to be more prone to hBN pull-out during the polishing process.

5.14 Metco 320 Binder Burnout Investigation – Discussion

This binder burnout study investigated the necessary time and temperature required to burn out the organic binder within Metco 320, as a potential production process. A heat treatment of 450°C for 1 hour in an air furnace was selected as a suitable process. This heat treatment was shown to burn out >70% of the organic binder by weight loss calculations.

Two batches of test pieces were sprayed at manufacturing facilities and half were heat treated as described above in order to burn out the organic binder. All specimens were then abradability tested to assess the influence of the binder upon the abradability performance of the material. The abradability conditions selected were designed to focus specifically on low incursion rate rub conditions associated with thermally induced, and climb operational conditions.

Following initial abradability testing at 50μm/s incursion to cut a rub track into each abradable test piece, a series of low incursion rate and dwell rubs were carried out. Inspection of the test pieces following low incursion rate rubs (2μm/s) indicated that heat treated coatings from both facilities produced less blade tip pick-up than the as-sprayed materials.

Profile 3 tests, which included a two minute dwell period were however, less conclusive. From the results shown in Figure 40, heat treated coatings appear to produce significantly more blade tip pick-up than the as-sprayed materials in both facility tests. Following testing, Sulzer Innotec raised concerns about the validity of these results, due to problems in setting up the dwell period accurately and rig vibrations observed during testing.

Significantly both blade tip pick-up and wear were observed on the heat treated specimens from Facility 1 tested under Profile 2, and Facility 2 under Profile 3. Examination of the tapered blade tips indicates that pick-up is evident between 1.7-2.5mm blade tip width and blade wear was concentrated between widths of 0.7-1.7mm. This suggests that, under low incursion rate and dwell rubs the pick-up mechanism associated with Metco 320 is also dependent upon blade tip geometry.

The Schmid (1997) model for abradability discussed in Section 3.5 describes an elastic mechanism of abradability as coating particles are released in the wake of the rotating blade tip. There is therefore a critical blade tip speed where abradability mechanics take over from classic chip formation ahead of the cutting tip, as in the case of a traditional machining operation (Schmid and Dorfman 2000). This critical value is therefore dependent upon the width of the blade tip. For abradability to be effective the blade tip must have moved clear of the releasing material. i.e. the compression or rubbing time for a given point on the surface of the abradable must be short enough to allow elastic material release.

Therefore, for a blade width (w), and blade tip velocity (v) it means that, for any point on the surface of the abradable, the time spent rubbing (t_{rub}) can be calculated as follows:

$$\frac{w}{v} = t_{rub} \qquad \text{Equation 1}$$

From the results of the low incursion rate abradability testing and Equation 1, it can be established that the time taken for the blade tip to pass a point on the abradable surface at the boundary condition between pick-up and wear is as follows:

1.7 / 370 = <u>4.60 ms</u>

As pick-up was not observed on any of the high incursion rate rubs (50μm/s), it is clear that pick-up and effective elastic abradability are dependent upon both the value of t_{rub} and the incursion rate. As incursion rate increases the value for t_{rub} at which pick-up and ineffective elastic abradability occurs.

There was no measurable degradation in coating properties in relation to thermal shock resistance or corrosion resistance. However, the inconclusive abradability results following testing with a 2 minute dwell period do not inspire sufficient confidence for a post spray heat treatment to be introduced into the manufacturing specification.

Further testing is required to gain a more fundamental appreciation of the pick-up mechanism associated with low rub conditions with a view to understanding the drivers associated with this melting and transfer mechanism. Testing should focus upon the boundary condition of the key performance drivers associated with melting, such as incursion rate, blade tip width and transfer of abradable material, which have been shown to result in pick-up of abradable on blade tips.

5.15 Metco 320 Binder Burnout Investigation – Conclusions

Metco 320 abradable coatings contain residual binder, used to bond Al-Si and hBN powder particles during the spray process. The binder burnout study revealed that a heat treatment of 400°C for 1 hour in an air furnace would burn out >70% of the organic binder by weight loss calculations.

The low incursion rate abradability performance of Metco 320 coating with this subsequent heat treatment was compared to as-sprayed coating materials, using the Sulzer Innotec Abradability Rig.

Under low incursion rate rub conditions of 2mm/s the heat treated Metco 320 coating showed less pick-up than the as-sprayed material. However, following incursion profiles, which included a 2 minute dwell period; pick-up was significantly higher after coating heat treatment. There were concerns over the validity of these results due to problems in setting up the dwell period tests accurately and rig vibrations observed during testing.

The inconclusive abradability results following testing with a two minute dwell period do not inspire sufficient confidence for a post-spray heat treatment to be introduced into the manufacturing specification.

Further abradability testing is required to understand how the dominant mechanisms of abradability change due to the influence of key parameters, for example blade tip speed incursion rate and t_{rub}.

5.2 Seal Fin Wear Study

Seal fins prevent gas and oil leakage between the rotating compressor drum and stator ring shrouds (Ross and Beckinger 2003). Unlike compressor blades, which are primarily designed for optimised aerodynamics, the exclusive purpose of seal fins within the gas turbine is to cut efficiently into an abradable liner in order to seal the compressor. Despite this dedicated design, service experience has highlighted a sporadic seal fin wear failure due to excessive frictional heating, resulting in material softening and, in extreme cases, melting and material transfer (Gilleland 2005). As such, there has not been a definitive solution to this problem. As a mitigating step, in most cases cold build clearance gaps between seal fins and abradable are increased to reduce the amount of rubbing during operation. However, this reduces the effectiveness of the seal with associated engine performance and efficiency penalties (Bindon 1989).

Commercially available abrasive tip treatments exist and these are designed to improve the cutting performance of seal fins. Rolls-Royce has limited experience of these technologies and has so far never used such a system on a compressor drum seal fin.

As operating temperatures increase within the compressor, materials engineers and designers are required to select materials with increased high temperature capability to ensure component reliability during service. Inevitably seal fin - abradable liner, material combinations are being used with less service experience. The unknown abradability characteristics of these sealing systems could increase the risk of seal fin wear issues during service. Experimental analysis of representative rub conditions is necessary to understand the conditions under which excessive heating is observed and to validate a robust engineering solution.

5.21 Seal Fin Wear Study – Introduction

Seal fin wear has been shown to result from excessive frictional heating of the seal fin and abradable material during normal service conditions. Wear is a result of material softening and in extreme cases melting, which often results in transfer of seal fin material to the abradable. Figure 53 shows the rub track within a feltmetal abradable created by a seal fin. A recast layer of nickel seal fin material is clearly visable at the bottom of the rub track.

Figure 53. Seal fin transfer as a result of excessive frictional heating during engine rub

Vertical cracking within the recast layer is a result of residual stresses, which form as the material cools and solidifies. This type of seal fin transfer results in a reduction in performance as a direct result of the loss of seal fin material (Gilleland 2005). In addition, any subsequent rubs may produce further transfer as a result of high friction between the seal fin tip and the recast layer.

The surface temperatures achieved due to frictional heating are a result of the following:

Sliding Velocity	Seal fin tip speed during rub, resulting from HP compressor RPM.
Contact Load	Contact force as a result of drum expansion, due to centrifugal loading and thermal expansion.
Friction Coefficient	Friction parameter resulting from the surface characteristics of the two contact materials
Heat Transfer	The ability of the two contacting bodies to effectively transfer heat from the source.

Clearly sliding velocity and contact load are a direct result of the blade tip speed and incursion rates generated within the engine. Both these parameters will vary over the operational envelope of the engine. The coefficient of friction and heat transfer properties of the materials are constants of a given seal fin abradable combination.

Increasing operating temperature within the compressor of modern gas turbine engines means that discs and blades, which were previously titanium, are being replaced by nickel components. Although nickel alloys have better strength at higher temperature it is important to note that the melting point of these is significantly lower than that of traditional titanium compressor alloys. Figure 54 shows the melting point of titanium and nickel alloys used in HP compressors, highlighting specifically the difference in melting points between Inco 718 and Ti IMI 834.

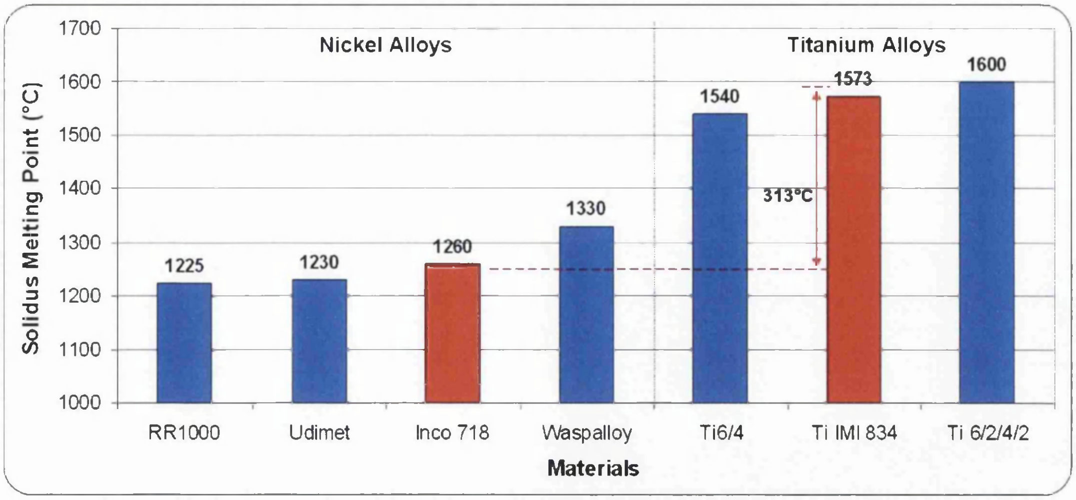

Figure 54. Melting point temperatures for a range of nickel and titanium alloys

Abrasive coating systems can be applied to seal fin components to improve the cutting characteristics of the seal fins and thus reduce the effects of frictional heating, resulting from inefficient cutting (Wallace 1977). TBT406 is an abrasive coating, developed by Praxair Surface Technologies. The coating relies upon extremely hard particles of cubic boron nitride, which are distributed within a multilayer coating of electroplated nickel and chrome carbide and cobalt as shown in Figure 55.

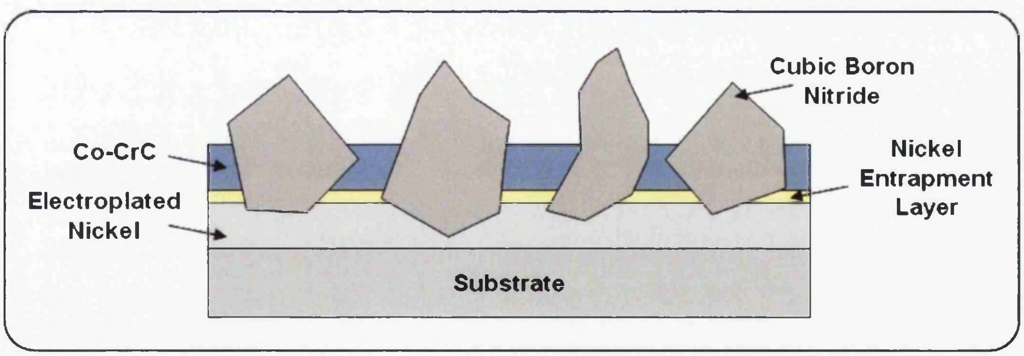

Figure 55. Schematic diagram of TBT406 abrasive coating

Cubic boron nitride particles protrude from the surface of the coating system, providing an abrasive wear resistant surface. On contact with an abradable material each cubic boron nitride particle will act like a cutting tool, efficiently cutting a track in the abradable and producing minimal frictional heating.

An abradability investigation of the characteristics of Inco718 seal fins rubbing against Hastelloy X Feltmetal abradables was carried out with the following objectives:

i) To generate seal fin wear as a result of significant frictional heating during engine condition rubs.

ii) To identify the conditions under which seal fin wear is prominent, due to excessive frictional heating.

iii) To evaluate a hard abrasive tip coating for reducing or preventing seal fin wear under service conditions.

5.22 Seal Fin Wear Study – Experimental Design

In order to identify the specific conditions responsible for excessive frictional heating of seal fins it is necessary to understand the operational envelope of the components during service. This experiment focused on the operational conditions of the Trent 900 aeroengine, stage 1-4 HP compressor drum.

The Trent 900 1-4 compressor drum is comprised of four forged Inco718 discs, which are welded into the drum arrangement following machining. Each disc has two sets of fins, which act as air seals on either side of the blade root and dovetail slots.

The range of incursion rates and blade tip speeds of the 1-4 stage HP compressor drum as observed in service were, were calculated using whole engine and disc stress modelling, which provide thermal and centrifugal loads to be evaluated. The values calculated were used to define an abradability test matrix for the investigation of rub characteristics associated with Inco718 and Hastelloy X feltmetal, as shown in Figure 56. All tests were carried out to an incursion depth of 1mm.

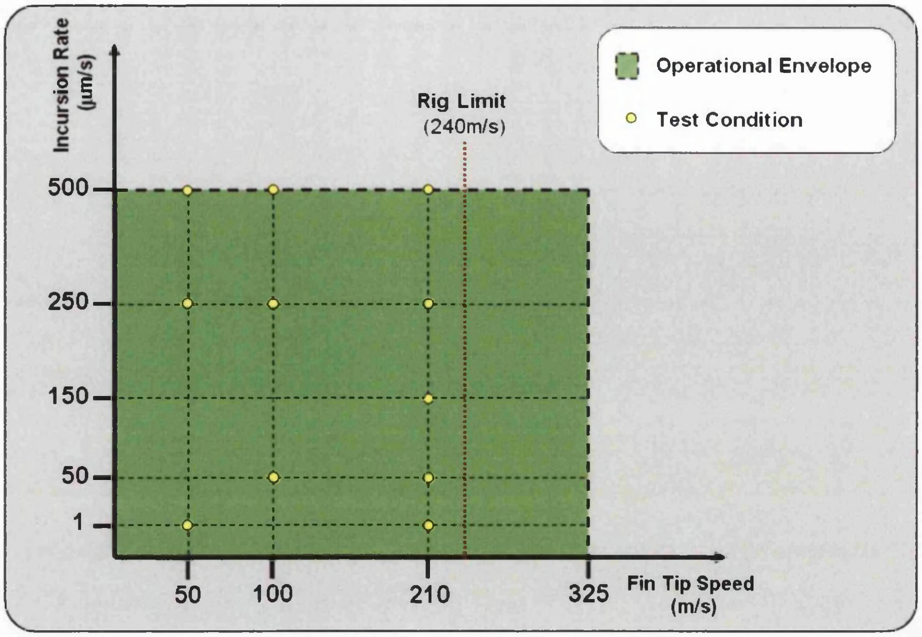

Figure 56. Trent 900 Stage 1-4 HP Compressor operational envelope and testing conditions

Five abradability tests were carried out at 210m/s fin tip speed, which corresponds to the fin speed at idle of the Trent 900 HP compressor seal fins. Additional tests were carried out at lower fin tip speeds to investigate the possibility of seal fin wear under engine start-up conditions. These are indicated in Figure 56 above.

The maximum fin tip speed observed on the Trent 900 stage 3 HPC seal fins was 325m/s. However, the stresses generated within the fin test pieces as a result of the centrifugal forces generated during rig testing, limits the current maximum tip speed capability to 240m/s.

For direct comparison, the test conditions shown in Figure 43 were conducted using both uncoated and TBT406 tipped test piece fins. All experimentation was carried out using the Alstom Abradability Facility in Rapperswil, Switzerland. A specially designed fin carrying disc was used in order to provide a representative 360° cutting profile, as shown in Figure 57.

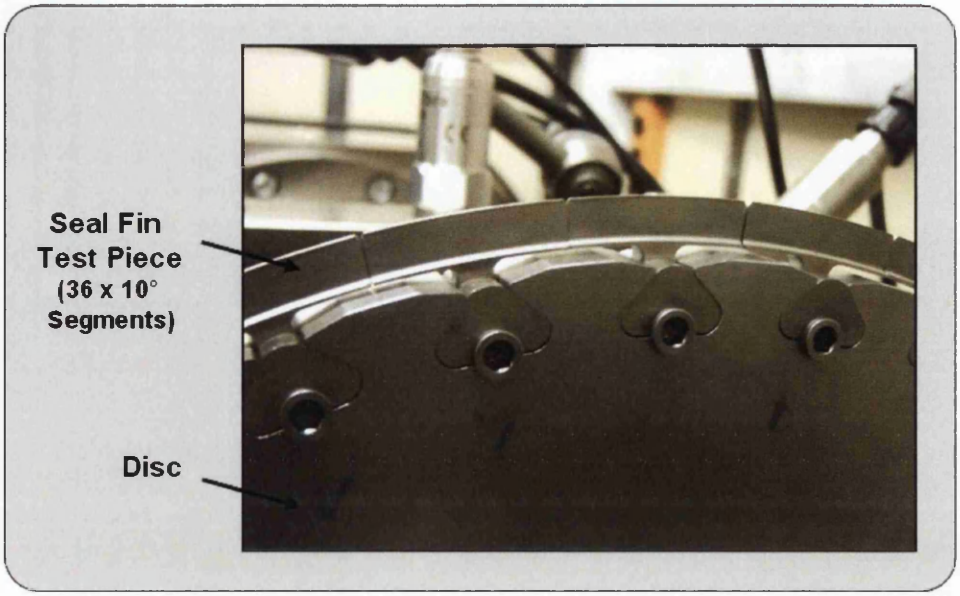

Figure 57. Seal fin test pieces mounted on disc at Alstom Abradability Facility

A total of 36 seal fin test pieces, each having a 10° radius were loaded into the rig disc in order to create a continuous 360° seal fin representative of that which exists in an engine. The seal fin test pieces were designed to have the same tip profile as the seal fins on the Trent 900 HP stage 3 compressor disc. They were machined from an Inco 718 compressor disc, which had undergone the correct forging and heat treatment processes. Figure 58 shows tipped and untipped seal fin test pieces used in the abradability investigation.

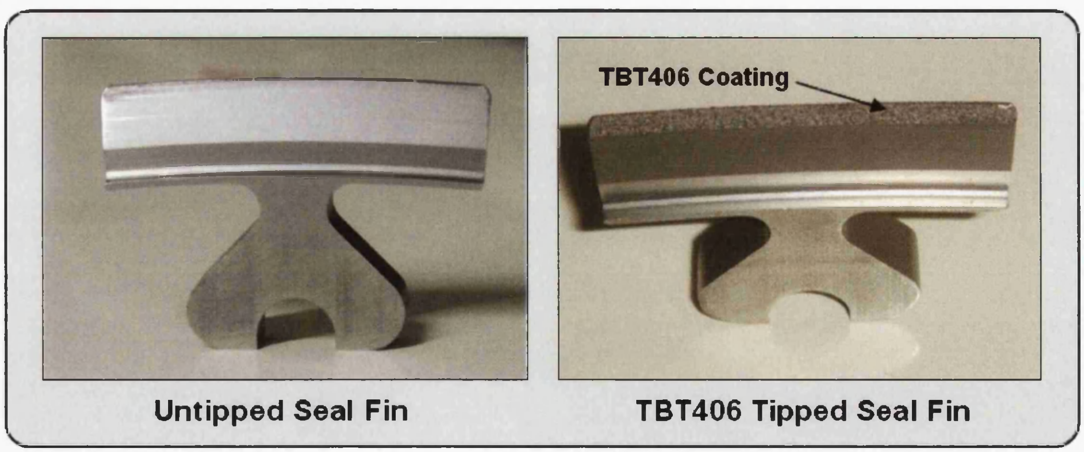

Figure 58. Untipped and TBT406 coating Inco 718 seal fin test pieces

Trent 900 stage 3 shrouds were sectioned to create feltmetal test pieces, used for abradability testing with the aid of a specially designed shroud fixture. Figure 59 shows the feltmetal shroud mounted within the fixture on the Alstom abradability rig.

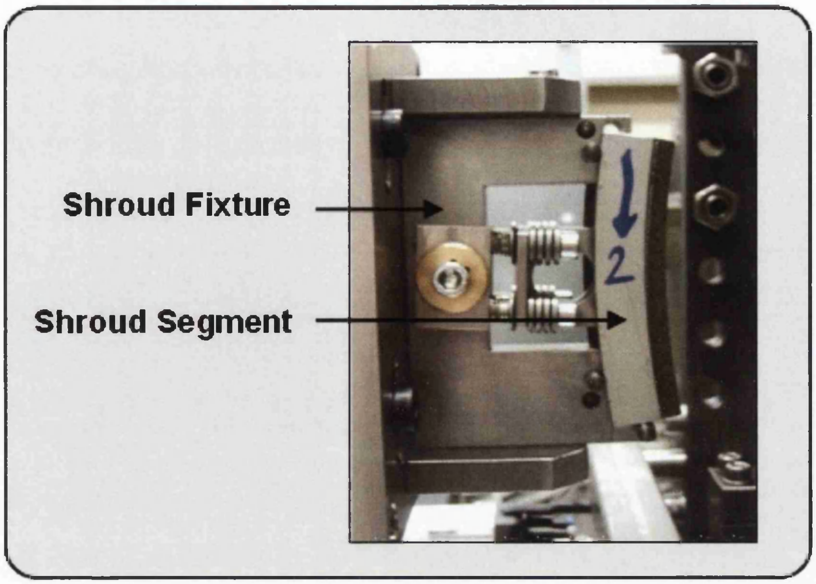

Figure 59. Trent 900 HP stage 3 shroud mounted in fixture at Alstom Abradability Facility

In an effort to gain a quantitative understanding of the temperature increase at a seal fin tip, as the result of contact with the Hastelloy X feltmetal, high-speed pyrometers were used to generate temperature data for all abradability conditions investigated. These were positioned immediately before and after the rub track length to analyse the temperature increase, due to the frictional characteristics between the seal fin and abradable materials.

Following each abradability test, the height and weight change of six seal fin test pieces were measured, together with the weight change of the feltmetal shroud. Fins and shrouds were also visually inspected for any signs of excessive frictional heating and/or material melting and transfer.

5.23 Seal Fin Wear Study – Results

Considerable differences exist between the conditions simulated on an abradability test rig and those observed in the HPC of a modern gas turbine engine. Initial tests focused on generating seal fin melting and transfer, resulting from excessive frictional heating.

Seal fin abradability testing was initially carried out on untipped Inco 718 seal fin test pieces at the test conditions shown in Figure 56. Table 5 shows the average fin

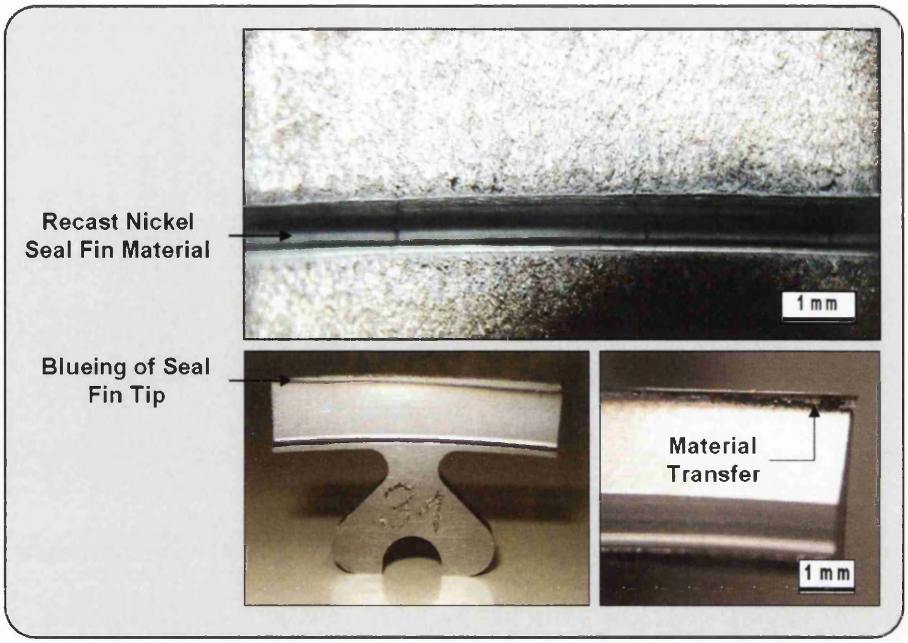

Figure 60. Seal fin test pieces showing blueing and material transfer and feltmetal rub track with recast nickel layer

Pyrometer readings taken from the seal fin tip immediately after the rub track indicated maximum temperatures of approximately 1130°C. During testing a considerably large degree of sparking was observed.

In an effort to understand the effects of multiple rub events, a re-rub test was carried out using Test 4 abradability conditions. Test 4b was completed using the same seal fin and shroud test pieces. A further 1mm incursion was carried out within the same rub track.

The results of Test 4b shown in Table 6 indicate a large increase in the fin height as a result of material transfer. Visual inspection of the seal fin test pieces confirmed the formation of a nickel transfer layer as a result of excessive frictional heating. Consistent with Test 4, seal fins displayed further blueing towards the cutting tip following Test 4b as shown in Figure 61.

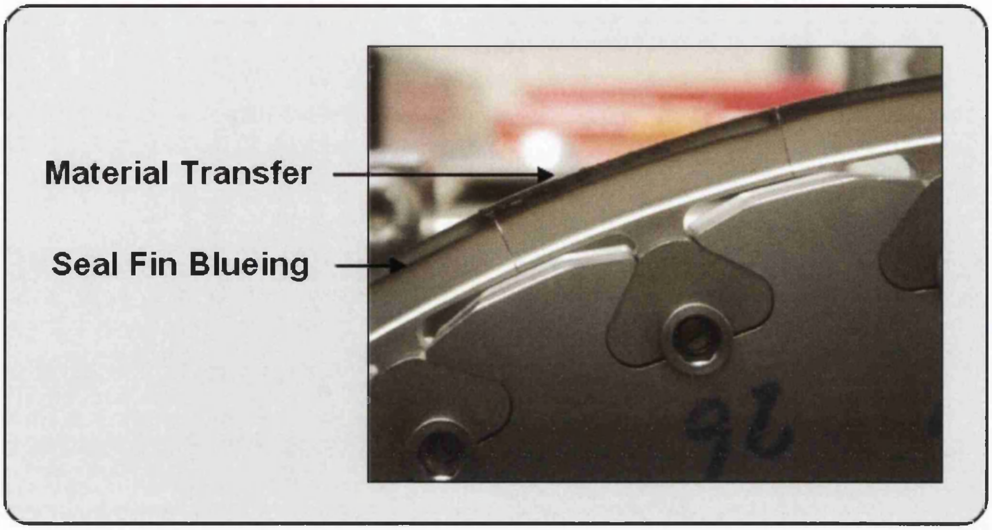

Figure 61. Seal fin test pieces displaying material transfer and blueing following Test 4b

A software error meant that pyrometer data was not recorded during Test 4b, however, observations from the seal fin and shroud indicate that frictional heating resulted in temperatures at least as high as those measured during Test 4.

Although Test 4 was the only abradability condition, resulting in significant material melting and transfer, indications of high frictional heating were also observed during Test 3. Figure 62 shows the rub tracks for Test 2 and Test 3.

Figure 62. Rub tracks from abradability Test 2 and Test 3.

The rub track produced in Test 3 displayed blueing towards the fin exit end of the shroud test piece. In comparison, the rub track produced in Test 2 displays no such blueing. The pyrometer measurements for Test 3 indicate a peak seal fin tip temperature of approximately 770°C.

height and weight change (from a sample of 6 fins per test) and the shroud weight change for each abradability test.

Table 5. Fin and shroud weight change results from untipped fin testing

Test No.	Fin Tip Speed (m/s)	Incursion Rate (μm/s)	Average Δ Fin Height (mm) ±0.002	Average Δ Fin Weight (mg) ±0.1	Δ Shroud Weight (mg) ±0.1
1	210	50	-0.002	5	-76
2	210	150	-0.002	1.67	-116
3	210	250	-0.002	2.17	-59
4	210	500	0.04	-10	Not Measured*
4b	210	500	0.443	0.054	-0.202
5	210	10	0.01	1.5	-108
6	210	50	-0.005	-2.83	-90
7	100	50	0.002	1.5	-66
8	50	1000	-0.03	-1.5	-80
9	50	250	0.003	0.5	-37
10	100	250	0	0.17	-43
11	50	500	0.008	-0.5	-8
12	100	500	0.013	-0.17	-15
13	50	1	-0.002	0.17	-52

*Operator forgot to take measurement prior to test.

The abradability results in Table 14 indicate the conditions used in Test 4, which generated a significant change in seal fin weight. Although there is no significant change in fin height, as a result of a combination of seal fin wear and melting/transfer, a loss in weight of 10mg was consistently observed. Due to an operator error, the shroud weight prior to testing was not measured.

Visual inspection of the seal fins from Test 4 revealed evidence of excessive frictional heating, resulting in material melting and transfer. Seal fin blueing was observed, in addition to intermittent material build-up on areas of the seal fin tips. A recast nickel layer with characteristic residual stress cracking was also observed within the rub track. Figure 60 shows seal fins and the felt metal rub track following Test 4.

In order to investigate the performance of tipped Inco 718 seal fins, a single set of 36 seal fin test pieces were coated with TBT406 abrasive coating and tested under the conditions shown in Figure 63.

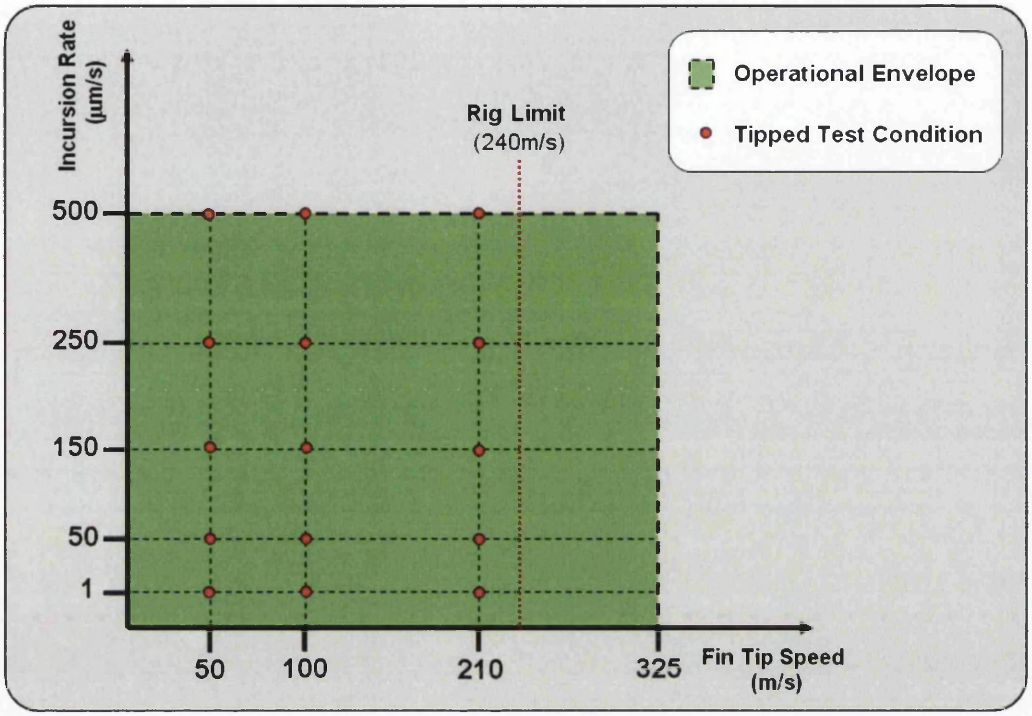

Figure 63. Test conditions investigated using TBT406 tipped seal fin test pieces

Table 6 shows the average fin height and weight change (from samples of 6 fins per test) and the shroud weight change for all abradability tests carried out using TBT406 tipped seal fins.

Table 6. Fin and shroud weight change results for tipped fin testing

Test No.	Fin Tip Speed (m/s)	Incursion Rate (μm/s)	Average Δ Fin Height (mm) ±0.002	Average Δ Fin Weight (mg) ±0.1	Δ Shroud Weight (mg) ±0.1
14	210	500	0.002	0.004	0.073
15	210	250	0.013	0.001	0.092
16	210	150	0.002	0.001	0.09
17	210	50	0.002	-0.002	0.109
18	210	1	0.007	0.004	0.093
19	50	500	-0.002	-0.001	0.029
20	50	250	0.002	-0.001	0.039
21	50	150	0.003	0	0.035
22	50	50	0	0.001	0.054
23	50	1	0	-0.002	0.103
24	100	500	0	-0.003	0.047
25	100	250	-0.002	0.002	0.044

26	100	150	-0.002	-0.003	0.035
27	100	50	-0.002	-0.002	0.075
28	100	1	-0.002	0.002	0.09

The single set of TBT406 tipped seal fins were used successfully for all 15 abradability tests. No significant fin wear was measured in terms of weight or height change. All rub temperatures were below the capability of the pyrometers used (less than 300°C). Visual inspection of the seal fins following the abradability tests concluded that there was no significant change to the appearance of the TBT406 coating or the seal fin material. Figure 64 shows a tipped seal fin prior to testing and following the 15 abradability tests shown in Table 6.

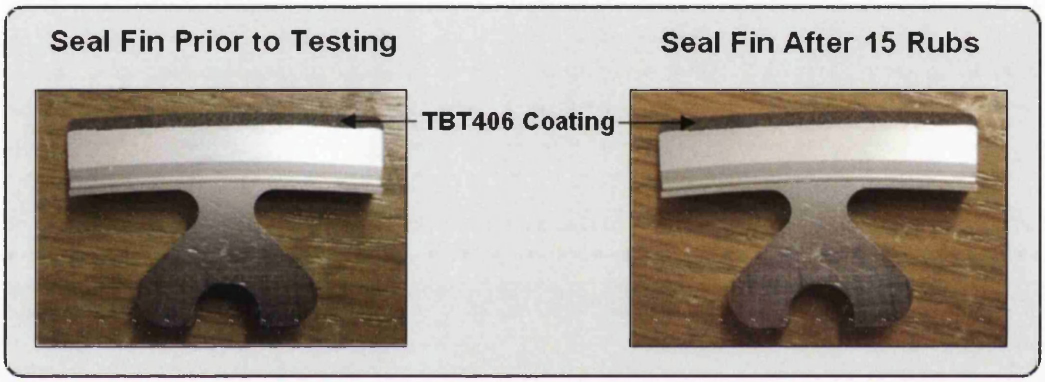

Figure 64. TBT406 tipped seal fin test piece before and after abradability testing

5.24 Seal Fin Wear Study – Discussion

Alstom abradability testing was carried out on representative Inco 718 seal fin test pieces under engine conditions in an attempt to understand the mechanisms associated with seal fin wear resulting from excessive frictional heating.

Material transfer and pick-up on seal fin tips was successfully generated during abradability testing under a 210m/s fin tip speed and a 500µm/s incursion rate. Pyrometer measurements indicated a maximum tip temperature immediately after the rub track of approximately 1130°C. The Inco 718 seal fin material has a melting point of 1260°C, however, significant material softening occurs at temperatures below this, which appears to drive the material transfer mechanism.

Discolouration and blueing of the seal fin tip suggests that heating was highly localised around the contact surface. However, it is important to consider the relatively short duration of the 500μm/s, during which the rub lasts only 2 seconds. In service, the rub duration under such high incursion speeds may also be relatively short, however extended lower speed rubs may combine to extend heating effects.

A layer of recast nickel was observed within the rub track created. This material is probably a mixture of seal fin and Hastelloy X feltmetal, which has become molten within a highly localised area about the contact between seal fin and feltmetal.

A repeat rub under the 210m/s fin tip speed and 500μm/s incursion rate conditions was carried out to investigate the effect of multiple rub incidences. The repeat rub was carried out on the same rub track. Excessive frictional heating again resulted in material melting and transfer. The secondary rub was more aggressive, as a result of the presence of the hard recast layer, which was less abradable than the low density Hastelloy X feltmetal material.

Although no other abradability conditions produced sufficient frictional heating to generate material transfer, significant heating was measured during testing at a 210m/s fin tip speed and a 250μm/s incursion rate. A maximum seal fin tip temperature of 770°C was recorded immediately after the rub track.

Blueing towards the exit of the rub track was also observed, which suggests that temperature accumulates over the duration of the rub. It can also be assumed that, during the remaining rotation, the seal fins cool as they lose heat to the ambient air within the test facility room, assisted by the high velocity air passing over their surfaces.

During service, rubbing can potentially occur over 360° of a seal fin rotation due to the effects of thermal expansion and centrifugal loading acting on the compressor disc. The abradability results indicate that increasing the rub track length would have a significant influence on the amount of frictional heating observed during rubbing. It is therefore fair to assume that as rub track length increases the onset of seal fin wear would occur at lower incursion rates.

Testing over a range of rub track lengths would allow the temperature increases and losses over a complete seal fin rotation to be calculated using the ratio of heating time (during rubbing) and cooling time (non-rubbing rotation). This data could then be used to extrapolate to any length of rub track for direct comparison with engine run components.

Repeat abradability testing was also carried out on Inco 718 seal fin test pieces tipped with TBT406 abrasive coating. A single set of 36 seal fin test pieces was successfully used for all 15 test conditions with no measurable seal fin wear or degradation of the TBT406 coating. No temperature data was recorded for any of the tipped seal fin tests as the rub temperatures were all below the 300°C lower capability of the optical pyrometers.

5.25 Seal Fin Wear Study – Conclusions

Seal fin abradability testing has been carried out at the Alstom Abradability Facility in an attempt to generate seal fin wear and material transfer as a result of excessive frictional heating during rubbing. A range of engine representative abradability conditions were selected to identify the most aggressive conditions associated with these failure mechanisms. Although rig capability was limited to fin tip speeds of 240m/s, it was possible to generate abradability data for a wide range of engine representative conditions.

Tests were repeated with seal fins tipped with TBT406 abrasive coating to evaluate the performance of the coating in relation to seal fin wear and rub temperatures.

Excessive frictional heating was found to be most prominent under abradability conditions with high incursion rates and high fin tip speeds. Material transfer and pick-up on seal fin tips was generated during testing at 210m/s fin tip speeds and 500μm/s incursion rate. Seal fin tip temperatures immediately after the rub track were measured at 1130°C. Frictional heating under such short test durations (2 second rub duration) was highly localised around the seal fin tip, which displayed blueing.

Excessive rub temperatures were also measured during a 210m/s fin tip speed and 250μm/s incursion rate test condition. Pyrometer measurements indicated a seal fin temperature immediately after the rub track of 770°C. In this case blueing was observed towards the exit of the rub track, indicating an increasing contact temperature as a function of rub duration.

In order to understand the phenomenon, it would be advantageous to carry out further abradability testing on longer rub track lengths. Temperature data from immediately before and after the rub track could then be used to extrapolate to engine representative geometries.

Seal fins tipped with TBT406 abrasive coatings performed excellently under all abradability conditions and all rub temperatures were below the 300°C temperature capability of the optical pyrometers. No degradation or wear of seal fins or coating material was observed.

Following the positive outcome of these abradability trials further testing is now scheduled to evaluate the fatigue penalties associated with applying TBT406 coating to the seal fins of HPC discs.

5.3 New Abradable Material Development

As part of the Seal Coat European Funded Research Programme (discussed in section 4.3) a new generation of abradable coatings has been developed. System requirements defined by Rolls-Royce have been used to design a number of nickel-based abradable powders, using the proprietary cladding technology developed by Neomet.

This cladding technique produces composite powder materials via a reducing process, in which a metal (usually nickel) is uniformly coated onto metallic or non-metallic core particles. Nickel is reduced onto the core particles in a batch operation in reduction autoclaves. Core particles are agitated to ensure suspension, while nickel is reduced from solution to uniformly coat the core surfaces.

The abradable coatings developed by this method have been tested in order to evaluate their performance against a number of key design criteria. An overview of the 3-Phase Testing and Evaluation Process used to validate the new coating systems is shown in Figure 65.

Phase 1

Erosion/Abradability Balance And Ageing Characterisation
Ageing for 1008hrs @ 650°C

As-sprayed and aged test pieces

Abradability Testing (Neomet)
Using Neomet Standard parameter sets+take-off condition.
Criteria: Pick-up<M320
Blade wear<M314

Erosion Testing (Neomet)
GE-E5 Class A Erosion test
Criteria: >1 Erosion value

Additional Tests (Neomet)
Sieve Pan Analysis/Laser Diffraction Size distribution

Reference Measurements (R-R)
Coating R15Y Hardness
Imaging: Macro, Micro, SE, BSE, Powder

Phase 2

Coating Characterisation

Thermal Shock Testing (R-R)
Cyclic heat quench lab test. 15 Cycles, reference images @ 0,5,10 and 15 cycles.
Criteria: Compared to Metco 320

Corrosion Testing (R-R)
Sea fog and humidity tests.
Baselined against Metco 314
Criteria: No Corrosion

Abradability (Sulzer Innotec)
Sulzer Innotec engine conditions Re-slam, Take-off, and Climb.
Baselined against Metco 320 and Metco 314

Additional Wear Tests
Alstom detailed topography map
Wear track tribology analysis, including pluck-out assessment and wear track roughness measure

Phase 3

Material Data Acquisition

Mechanical Properties
Helmholtz resonator test (MTU)
Tensile button test (Neomet)

Thermal Testing (R-R)
TMA: Thermal expansion
Specific heat capacity
Thermal Conductivity

Figure 65. 3-Phase Testing and Evaluation Process used to evaluate new coating systems developed during the Seal Coat Programme

The criteria for each evaluation technique (shown in red) were designed to ensure that new coatings provide a minimum level of functionality and improvement on the current state of the art systems. Baseline systems of Metco 320 and Metco 314 were selected to provide minimum properties.

The Phase 1 testing focuses upon evaluating the abradability/erosion property balance, which is a fundamental characteristic of any abradable material. It is essential that the abradable has the ability to abrade preferentially to the engine rotatives, while maintaining sufficient erosion resistance to withstand the aggressive properties of the compressor gas stream. The testing in Phase 2 aims to characterise the performance of the new abradable systems under representative aero engine conditions. Abradability testing is therefore carried out at elevated temperatures and complimented by environmental testing such as thermal shock and corrosion assessments.

Phase 3 activities focus on generating materials property data for the new coating systems. The data will provide a fundamental understanding of the coating materials and enable validation of the Seal Coat abradability model discussed in section 4.3.

All of the new coating systems evaluated as part of the Seal Coat Programme displayed the required erosion, corrosion and thermal shock resistance. This is a positive result, as each of these assessments evaluated the coating against a known failure mechanism associated with predecessor coatings. However, the abradability results generated within the Testing and Evaluation Process were less conclusive.

5.31 New Abradable Material Development – Introduction

The functionality of any abradable material is dependent upon its ability to wear preferentially to engine rotatives (e.g. compressor blade tips) (Zheng and Daubler 2002). In an attempt to evaluate the abradability performance of the new coating materials developed as part of the Seal Coat Programme, abradability testing was carried out during Phase 1 and 2 of the coating Testing and Evaluation Process, described above. The abradability work described in this section preceded the Corporate Rig Strategy and the Alstom abradability Rig Validation Programme, which were therefore not used in this study.

Phase 1 abradability testing was carried out using the Canadian National Research Centre (CNRC) Abradability Facility based in Ottawa, as shown in Figure 66.

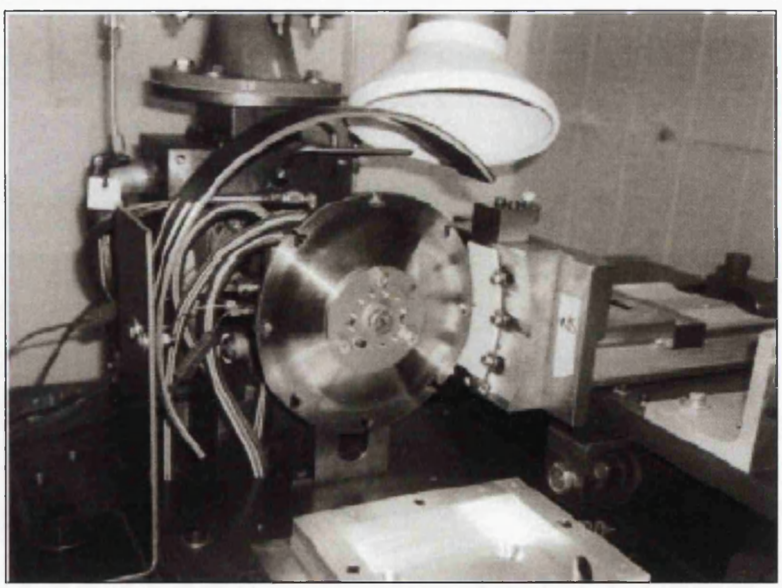

Figure 66. CNRC Abradability Facility in Ottawa, Canada

The aim of Phase 1 testing was to evaluate abradability performance at room temperature. These tests provided an initial understanding of the abradability of the new coating systems compared to their respective erosion resistance, compared to the baseline materials of Metco 320 and Metco 314 (Section 3.7).

Phase 2 abradability testing was then carried out to build on the understanding generated from room temperature assessment with high-temperature rub data using the Sulzer Innotec facility in Switzerland (see section 2.6) (Ernst and Wilson 2005). The Sulzer Innotec facility also uses a full size Pratt and Whitney disc, which is closer to the geometry of a real aero engine than that of the room temperature CNRC facility.

5.32 New Abradable Material Development – Experimental Design

Abradability performance is dictated by a number of key rub parameters including blade tip speed and incursion rate (Schmid 1997). It is also important to take into account variations in rig and engine geometry. In an attempt to standardise the effects of blade tip speed and incursion rate a fixed cut depth per pass (a') parameter was used:

$$\frac{IR}{RPS \times B} = a' \qquad \text{Equation 2}$$

where IR is the incursion rate of the test, RPS is the revolutions per second of the disc and B is the number of blades. In service most of the cutting is done by a single blade and Abradability testing is almost always carried out using a single bladed disc.

Values of a' were calculated for a typical high-pressure compressor stage of a large civil engine. Calculations were completed for three operational conditions; mid-climb, take-off and surge. The calculated a' values were read across to both the CNRC and Sulzer Innotec abradability facilities by varying blade tip speed and incursion rates. Table 7 shows the calculated a' values and respective blade tip speed and incursion rates for CNRC and Sulzer Innotec abradability facilities.

Table 7. Incursion rate and blade tip speed for Phase 1 and 2 abradability testing of Seal Coat abradables

	CNRC Facility			Sulzer Innotec Facility		
Condition	**Tip Speed** (ms^{-1})	**Incursion Rate** (μms^{-1})	**a'** (μm)	**Tip Speed** (ms^{-1})	**Incursion Rate** (μms^{-1})	**a'** (μm)
Mid-climb	305	2.5	0.006	370	2	0.011
Take-off	305	138	0.325	400	136	0.662
Surge	153	760	3.574	400	760	3.701

All abradability tests were carried out using a single bladed disc and a constant rub depth of 1mm.

In order to evaluate the abradability performance of the new coating systems, compared to the baseline materials over the life cycle of their operation, Phase 1 and 2 abradability evaluations were carried out on 'as-received' and aged coating materials. Ageing involved heating the test pieces at 650°C for 1008 hours and to generate representative baseline data; Metco 314 test pieces were also aged in the same way.

Phase 1 testing investigated the abradability performance of the new abradable systems shown in Table 8 against the baseline materials of Metco 320, Metco 314 and SM2042.

Table 8. New abradable coatings and baseline systems investigated in Phase 1 testing

Composition	**Reference Code**	**Manufacturing Route**	**Hardness** (R15 Y)	**GE Erosion No.** (s/mil)
90NiCrAl / 10BN+10% Polyester	W1089-76 (76)	Plasma (F4)	6	2.30
90NiCrAl / 10BN+10% Polyester	W1089-76 (79)	Plasma (F4)	21	3.00
90NiCrAl / 10BN+10% Polyester	W1089-76 (83)	Plasma (F4)	23	3.00
90NiCrAl / 10BN	W1089-46	Flame (6P-II)	19	3.89
Metco 320, Al-Si+hBN	W1095-43	Plasma (F4)	56	4.49
Metco 314, NiCrAl+Bentonite	W1082-64	Flame (6P-II)	40	6.06
CoNiCrAlY + Polyester/hBN (SM2042)	2042	Plasma (F4)	41	2.07

Phase 2 testing evaluated the high-temperature abradability characteristics of the new abradable systems shown in Table 9 against the baseline materials of Metco 320 and Metco 314.

Table 9. New abradable coatings and baseline systems investigated in Phase 2 testing

Composition	**Manufacturing Route**	**Hardness** (R15 Y) ±1	**GE Erosion No.** (s/mil)
90NiCrAl / 10BN	Flame (6P-II)	19	2.70
90NiCrAl / 10BN+12.5% Polyester	Plasma (9MB)	22	3.33
90NiCrAl / 10BN+10% Polyester	Plasma (F4)	11	2.19
Metco 320, Al-Si+hBN	Plasma (F4)	56	4.49
Metco 314, NiCrAl+Bentonite	Flame (6P-II)	40	6.06

5.33 New Abradable Material Development – Results

Figure 67 shows the Phase 1 abradability results in terms of blade wear (+) and blade tip pick-up (-) for the as-received coating systems. Bars are colour coded to signify the three test conditions, climb, take-off and surge.

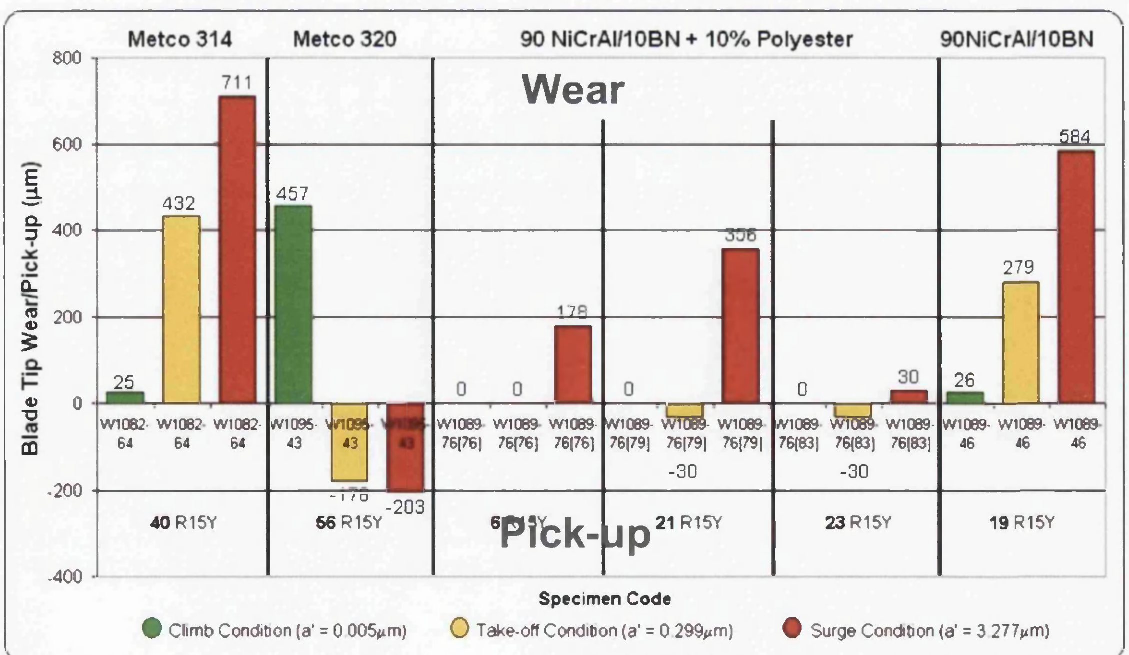

Figure 67. Abradability results for Phase 1 assessment of as-received coating systems

Abradability testing was also carried out on aged specimens, following the aging of coatings at 650°C for 1008 hours. The abradability performance in terms of total blade tip wear/pick-up is shown in Figure 68, together with the respective hardness values for the aged coating materials.

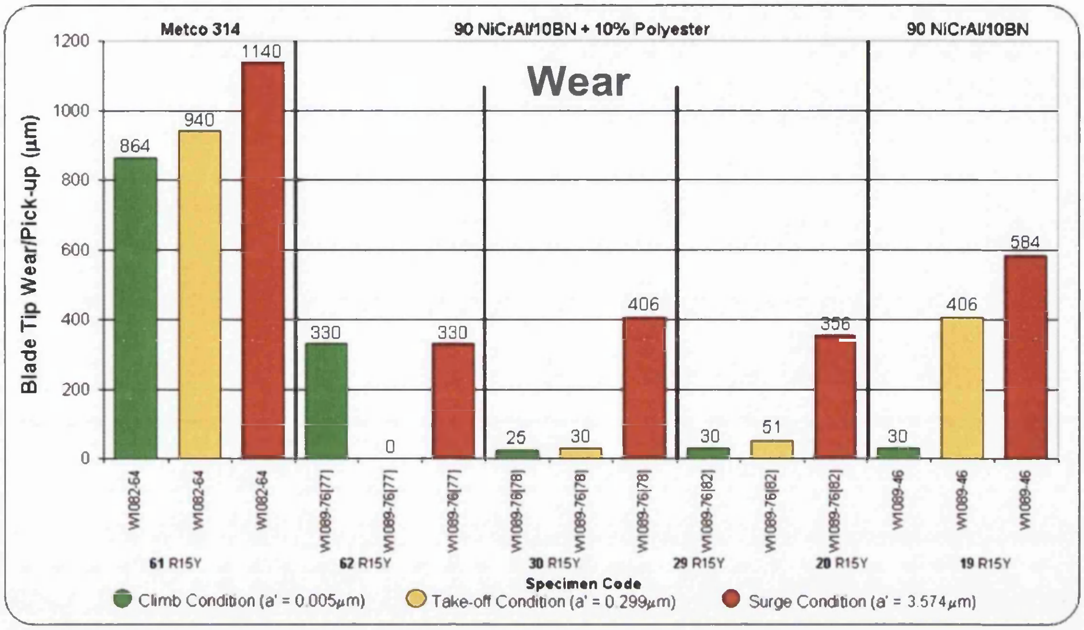

Figure 68. Abradability results for Phase 1 assessment of aged coating systems

Phase 2, high-temperature abradability testing was completed at the Sulzer Innotec Abradability Facility. Testing was again carried out on the new coating systems in both the as-received and aged conditions and against the baseline coating materials. All testing was carried out at 500°C.

Initial Phase 2 abradability testing focused on the performance of the aged coating materials. The abradability results, in terms of total blade tip wear/pick-up, for the aged coating materials tested at the Sulzer Innotec Abradability Facility are shown in Figure 69.

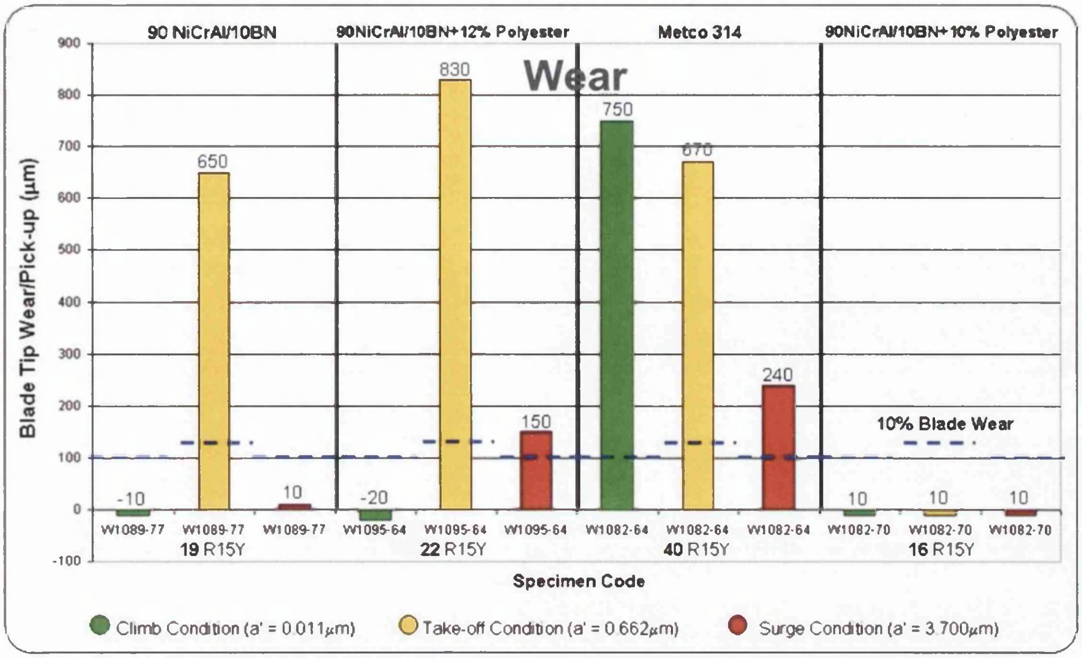

Figure 69. Abradability results for Phase 2 assessment of aged coating systems

The results shown in Figure 69 suggest that the most aggressive abradability condition in terms of blade wear, occurs at Take-off. However, it is important to take into account test duration. The high incursion rate of the surge condition means that the abradability test lasts only one second, whilst the 2µms-1 incursion rate of the climb condition test takes 500 seconds.

Figure 70 shows the results of the Phase 2 abradability evaluation of aged coating systems per second of testing.

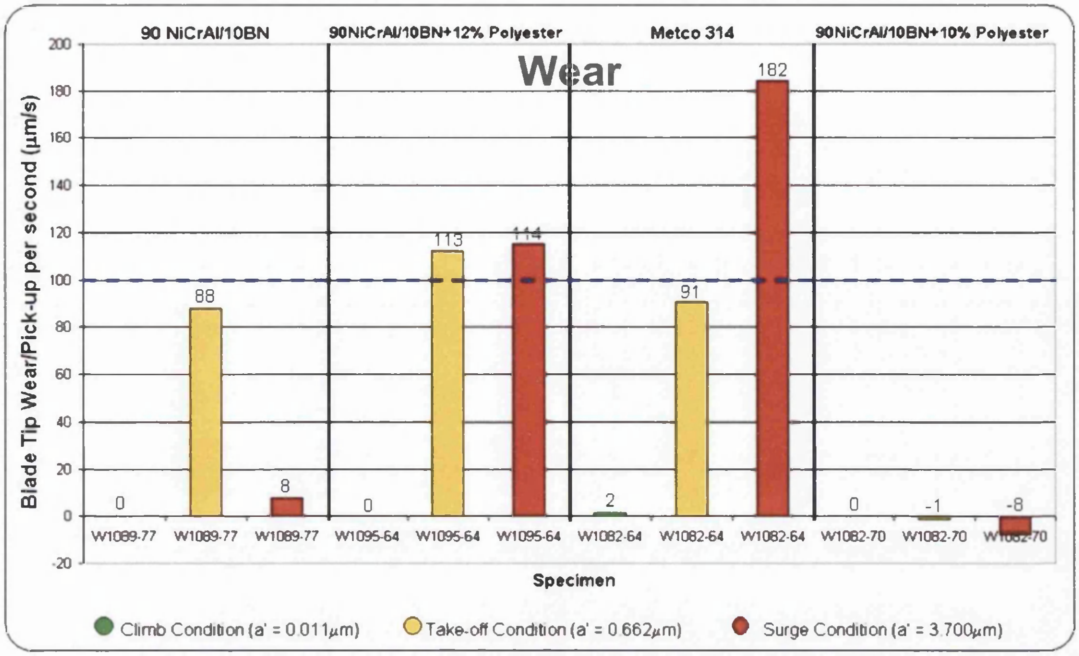

Figure 70. Abradability results for Phase 2 assessment of aged coating systems per second of testing

High-temperature abradability testing was also carried out at the Sulzer Innotec facility on 'as-received' coatings. In order to assess the variability of the abradability performance this test matrix was expanded to include repeat test conditions. Figure 71 shows the coating materials and test conditions used, with the respective blade tip wear/pick-up measurements.

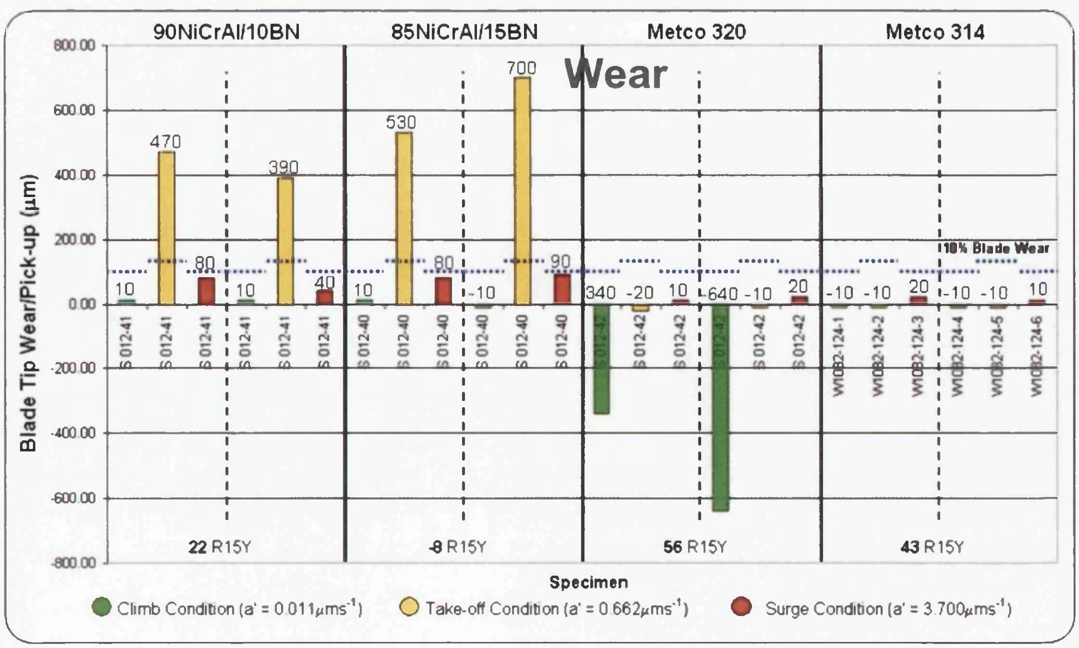

Figure 71. Abradability results for Phase 2 assessment of 'as-received' coating systems

The time dependency of results from the as-received Phase 2 abradability testing is shown in Figure 72, which illustrates the results per second of testing.

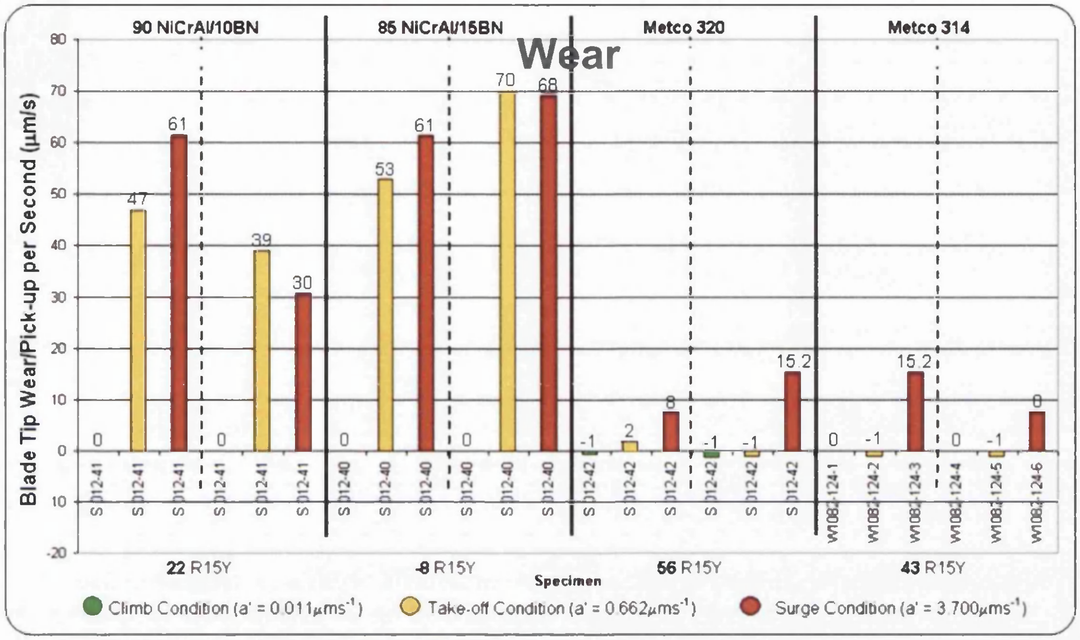

Figure 72. Abradability results for Phase 2 assessment of as-received coating systems per second of testing

5.34 New Abradable Material Development – Discussion

As part of the Testing and Evaluation process of new abradable coating systems developed within the Seal Coat Programme, a 2 Phase abradability investigation was used to evaluate the abradability performance at ambient and elevated temperatures. Blade wear and blade tip pick-up were measured following each test as a measure of abradability performance. Baseline testing was also carried out using existing coating systems for direct comparison.

Blade wear is usually associated with harder or more aggressive abradable coating materials. Some materials, including Metco 314, are known to age harden, which may lead to an increase in blade wear over time in service.

Pick-up of abradable material on the blade tip is a phenomenon associated with 'hot' rubbing conditions caused by high frictional heating. This is usually a mechanism associated with aluminium or lower melting point alloy based abradables (Ghasripoor and Schmid 1998).

The Phase 1 abradability assessment was carried out at room temperature using the CNRC abradability facility. The predefined pass/fail criteria for the new coatings systems was to show less blade tip wear than Metco 314 and less blade tip pick-up than Metco 320.

Figures 67 and 68 confirm that all new coating systems assessed on the CNRC abradability facility produce less blade tip wear than Metco 314 and less abradable pick-up than Metco 320. The new systems indicated improvements over the current state-of-the art coatings in all three abradability conditions in both the 'as-received' and 'aged' conditions.

The Sulzer Innotec abradability facility was used to assess the abradability performance of the new coating systems at high temperature. Abradability performance of the new coating materials was again compared to that Metco 320 and Metco 314. The predefined pass/fail criteria, in terms of abradability performance for all test conditions, was defined demonstrating less than 10% blade wear as a function of the total incursion depth and no significant abradable pick-up.

Figure 69 indicates that both the flame sprayed and plasma sprayed systems containing 12% polyester demonstrated large amounts of blade wear during Take-off condition rubs ($400ms^{-1}$, $136\mu ms^{-1}$). This was also replicated with the Metco 314 baseline material. The plasma sprayed system containing 10% polyester indicated no significant blade wear or pick-up following each of the test conditions. Microstructural analysis showed no significant variations between the microstructures of the two plasma systems assessed in the aged condition, as shown in Figure 73.

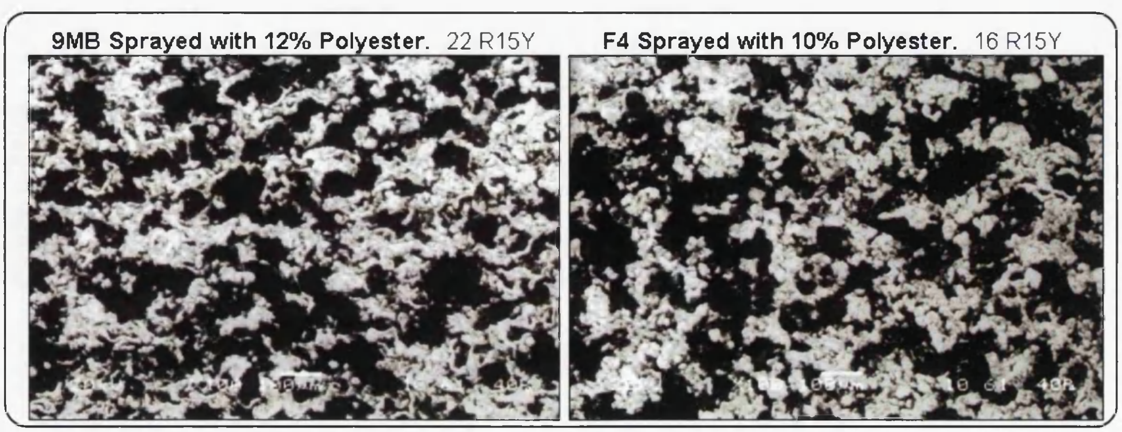

Figure 73. Microstructures of new plasma systems following ageing at 600°C for 1008hours

Inspection of the rub track surfaces of both the 9M and F4 plasma coatings, revealed an extremely irregular surface finish, with large scale coating spallation or 'macro-rupture', which is not indicated by the plot of blade wear/pick-up. The macro-rupture mechanism became increasingly prominent during the higher incursion rate rub conditions, particularly on the F4 plasma sprayed coating system, as shown in Figure 74.

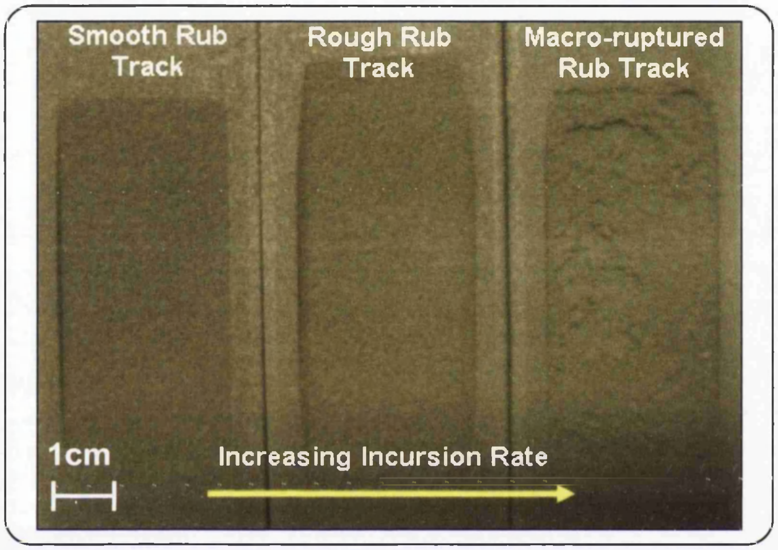

Figure 74. The onset of macro-rupture mechanism at high incursion rate rub condition

The macro-rupture of the coating surface at high-incursion rates reduces the amount of blade wear by absorbing the rub energy. However, the resultant surface condition of the rub track is extremely poor, and would have a detrimental effect on the flow of the gas stream within the compressor. Defects on the surface of the coating may also lead to additional spallation and/or erosion of the coating during service.

Following the investigation of aged coating materials, the abradability performance of as-received coating materials was carried out using the three test conditions. The results of the high-temperature abradability testing completed on the as-received coating materials are shown in Figure 71. Each test condition was replicated in order to assess repeatability and to reduce the influence of cyclic phenomena, for example abradable pick-up on blade tip.

From these results it appears that, for both 90NiCrAl+10BN and 85NiCrAl+15BN compositions of the new coating systems, blade wear is most prominent during the Take-off test condition. Figure 72, shows the results for each condition per second of testing, providing a simplistic overview of the time dependency of each test condition. It is clear that for the new coating systems the rate of blade wear is most significant during higher incursion rate tests (take-off and surge conditions).

As with the aged test piece testing, macro-rupture of the abradable coatings appears to reduce blade wear as incursion rate increases. This is evident on the rub tracks of both 90NiCrAl+10BN and 95NiCrAl+15BN new coating systems and to a lesser extent with the Metco 314 material. The Aluminium based Metco 320 coatings did not display any significant macro-rupture following each of the three test conditions. However, there was extensive grooving following low incursion rate testing, which is driven by high frictional heating. The wear tracks of all coatings tested at high-temperature in the as-received condition are shown in Figure 75.

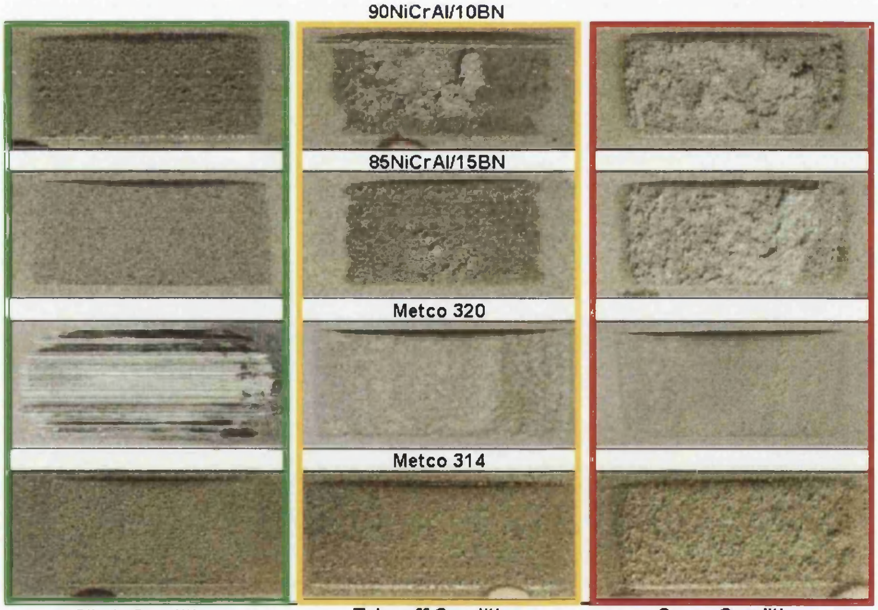

Figure 75. The wear tracks of all coatings tested at high-temperature (600°C) in the as-received conditions at the Sulzer Innotec Facility

The mechanisms which drive the grooving at low incursion rate rubs on the aluminium-based Metco 320 and the macro-rupture of the nickel-based systems are quite different. However, both mechanisms do appear to be associated high-temperature rubbing. In an attempt to quantify the rub temperature generated during each test, thermal paints were applied to the blades prior to testing.

Thermal paints are time and temperature dependant i.e. they change colour with time at temperature. Calibration charts can then be used to estimate the paint temperature for a given period of time. Figure 76 shows the painted blades for each of the coating materials evaluated following testing.

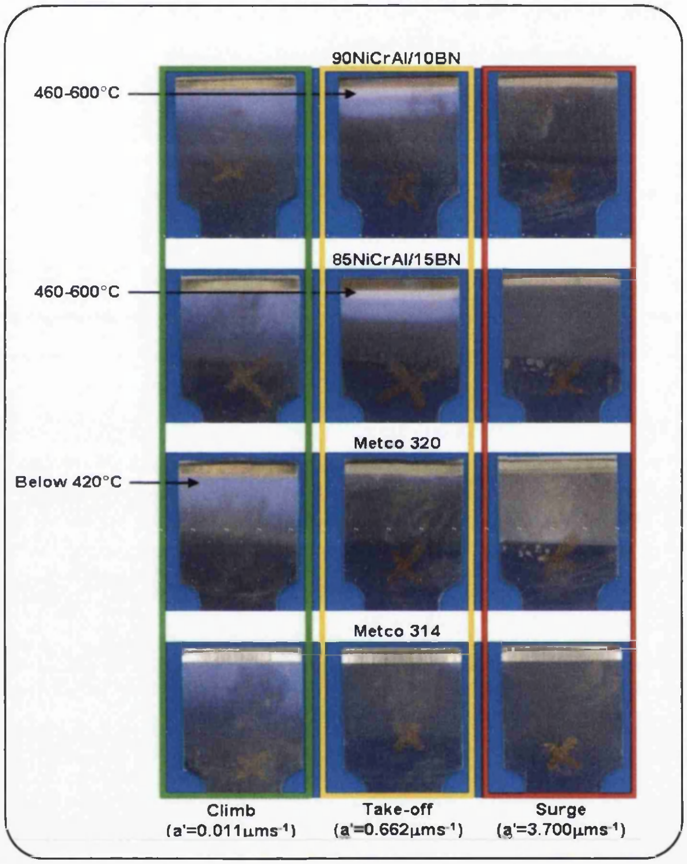

Figure 76. Painted blades used during high-temperature abradability testing of as-received coating materials

The thermal paint results shown in Figure 76 indicate that both pick-up and blade wear mechanisms are associated with increased rub temperatures. The macro-rupture mechanism, which was particularly evident on the new coating systems during the surge condition, appears to generate the lowest blade temperatures.

Video of the Sulzer Innotec abradability testing revealed excessive sparking during both the take-off and surge condition tests for the new coating systems. Both the 90NiCrAl+10BN and 85NiCrAl+15BN materials generated a large amount of bright white sparking during rubbing. The intensity of sparking suggests that it may have been caused by combusting titanium blade material. This was not observed on either of the baseline materials under any of the three test conditions.

5.35 New Abradable Material Development – Conclusions

Room temperature abradability testing of the new coating materials generated within the Seal Coat programme was carried out at the CNRC Abradability Facility in Ottawa, Canada. The new abradable materials showed improved abradability performance in terms of pick-up and blade wear, when compared to baseline materials of Metco 320 and Metco 314 in both the as-received and aged conditions. This has been attributed to the combination in properties of soft nickel, abradable materials.

High-temperature abradability testing was completed at the Sulzer Innotec Abradability facility in Switzerland. Testing was carried out on as-received and aged coating materials in order to assess the abradability performance following time in service. The 90NiCrAl flame sprayed coating and the 90NiCrAl+12%polyester plasma sprayed system both displayed significant blade wear following the take-off test condition. However, the 90NiCrAl/10BN+10% polyester coating did not generate blade wear under any of the test conditions. It is believed that macro-rupture of the coating surface absorbed the rub energy, thus reducing the propensity for blade wear.

High-temperature testing of 90NiCrAl+10BN and 85NiCrAl+15BN compositions of the flame sprayed new coating systems in the as-received condition showed blade wear generation during the take-off condition. Blade wear also occurred during the surge condition, although this appears to have been limited by the onset of macro-rupture.

Thermal paint applied to the blades prior to abradability testing shows that tests generating pick-up or blade wear were also susceptible to frictional heating.

The Macro-rupture mechanism, identified for the new coating systems during high-incursion rate rubs, does not appear to damage blades or cause excessive frictional heating. However, the resultant rub track surface is extremely uneven and would be unsuitable for use within the gas stream of a compressor.

Extensive bright white sparking was observed during testing of as-received 90NiCrAl+10BN and 85NiCrAl+15BN during the take-off and surge test conditions.

From the results of this investigation it is unclear why the new coating systems suffer extensive macro-rupture during high-incursion rate rubs. There appears to be an inherent macro-scale weakness within the coating system, which is unable to withstand the rub conditions associated with high incursion rates. Further investigation of the abradability performance of these new generations of soft nickel abradables is necessary in order to understand the drivers associated with this mechanism. A more comprehensive abradability study will also enable the definition of boundary conditions, at which point macro-rupture becomes prevalent, providing an understanding of this mechanism and an opportunity for it to be eliminated from future abradable systems.

5.4 Abradability Investigation

The functionality of an abradable material requires the system to abrade preferentially to compressor rotatives in order to provide an effective gas seal (Zheng and Daubler 2002). The complexity of abradability mechanics has been highlighted by the work discussed in Section 3.6. The importance of understanding abradability mechanics and the current lack of a fundamental understanding of this area highlights the need for a comprehensive experimental study, utilising the latest abradability facility capability.

5.41 Abradability Investigation – Introduction

In order to design an optimised abradable system it is essential to identify the key coating properties, which influence abradability performance and to understand the service conditions responsible for various wear characteristics (Zheng 2002). During the flight cycle of an aero engine the abradability conditions within the compressor are highly dynamic (Ghasripoor *et al* 1997). Low-speed incursion rates are driven by the thermal expansion of the engine casing and compressor disc. High-speed incursion rate rubs are generated during engine acceleration events, like take-off or aggressive military manoeuvres. Over a single engine cycle the combination of these events creates a complex abradability map, with discrete abradability mechanisms associated with specific blade tip incursion rate combinations (Schmid 1997). Figure 77 shows a closure plot (clearance vs. time) for a typical civil engine stage during engine running-in handling.

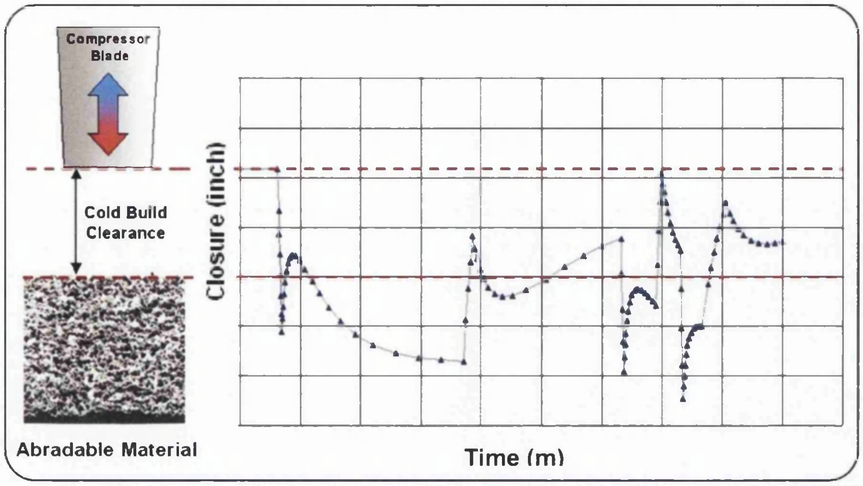

Figure 77. Closure plot for civil engine during engine running-in handling

Service experience shows that abradability performance, in relation to blade wear/pick-up, is heavily dependent on the relative incursion rates and blade tip speeds. However, it is important to recognise that the abrading conditions generated within a gas turbine compressor are far removed from traditional cutting mechanics associated with more conventional machining operations (Schmid 1997). The high blade tip speed and relatively small incursion rates generate unique and highly complex abrading characteristics, which are also dependent upon blade material, geometry and abradable composition. To understand the abradability results generated in this investigation it is first necessary to appreciate the influence of incursion rate and blade tip speeds on the abradability rig, in order to compare these to engine conditions.

Within an engine incursion rates are a result of thermal and centrifugal loading on the disc and blade assemblies (Ghasripoor *et al* 1997). This phenomenon is simulated on an abradability test facility by radial movement of a test piece towards a rotating blade. These two scenarios are illustrated in Figure 78.

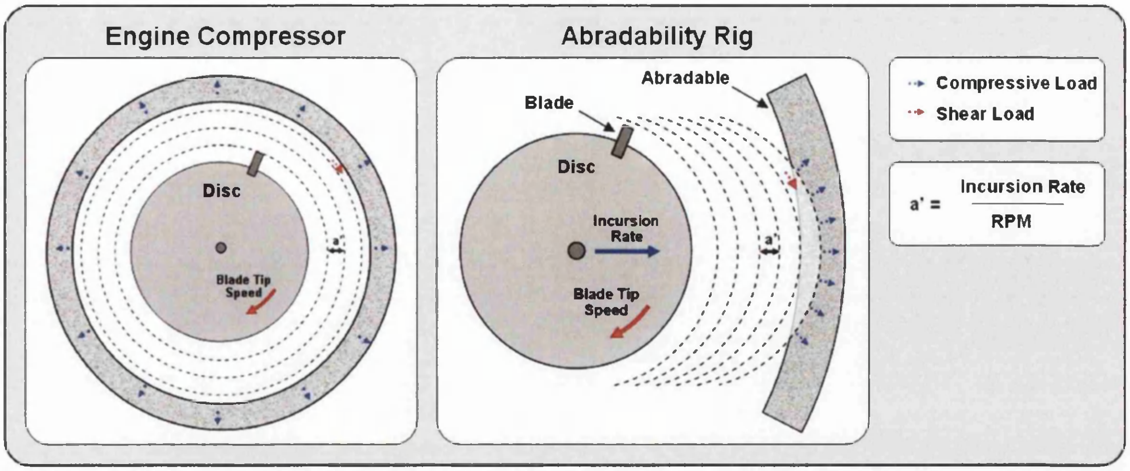

Figure 78. Comparison between engine compressor and abradability facility conditions

As shown in Figure 78, clearly there are differences between the rub characteristics of an abradability test rig when compared to those observed in an engine. Most important of these is the growth rate and total length of the rub track, which can be much greater in an engine as the blade tips grow to match the diameter of the abradable coating surface. It is important to be aware of such inconsistencies when analysing abradability rig data, particularly with regard to the temperature generated during a rub, which has been shown to be a function of the rub track length, as discussed in Section 5.2.

In addition to the requirements for optimum engine efficiency and performance, reliability and safety considerations are important factors when designing an abradable system (Chupp 2002). Excessive temperatures generated by frictional heating during various rub conditions can lead to melting and material transfer of blade and/or abradable material. This can result in an increase in the clearance gap between blade tip and compressor rotor path with an associated decrease in engine performance (Bindon 1989).

Titanium rotatives provide a particular challenge due to the risk of titanium fire. If excessive heating is generated at the tip of a Ti compressor blade under the correct pressure conditions ignition can occur, which can result in extremely intense combustion of the Ti material (Uihlein and Schlegal 1997). Significant damage can result in impact damage to blades down stream and/or an imbalance of the rotor. Although rare the aggressive nature of a Ti fire event inevitably results in an engine shut-down.

As discussed in Section 3.5 abradability theories are available, which provide an explanation for the mechanical process associated with a blade rubbing an abradable surface. The Schmid (1997) abradability model provides a principle understanding of the abradability mechanics associated with a perfectly elastic abradable material under the action of an incurring rotative. Mechanical analysis of abradable materials, such as the work carried out using the Freestanding Coating Process discussed in Section 4.2, does however suggest that thermally sprayed materials do not act in a purely ductile manner. In addition to extremely low ultimate tensile strength, stress-strain curves for abradable materials, generated with the Freestanding coating methodology, indicate that even at extremely low loads there is evidence of plastic deformation.

Service experience also shows that under various conditions, abradability mechanics can generate large amounts of frictional heating and excessive forces on the surface of the abradable. Clearly, efficient elastic abradability is not always the dominant wear mechanism.

Although understanding of abradability mechanics at a fundamental level is limited, literature is available, which attempts to quantify abradability performance with numerical models. The majority of work uses standard frictional heating equations to provide a numerical understanding of the heating behaviour following contact between a rotating component and static abradable surface (Ling and Simkins 1967). Although useful as a ranking tool, these models assume that frictional behaviour is consistent at engine representative tip speeds which, due to the changing abradability mechanisms, are incapable of providing absolute rub temperature data.

To date the most representative model for abradability in thermally sprayed abradables, has been developed as part of the Seal Coat EU funded programme, as discussed in Section 4.4 (Faraoun *et al* 2005). The Seal Coat Abradability model does not currently take into account boundary conditions of dominant abradability mechanisms or model material removal. Results generated from the model have yet to be validated against experimental load and temperature data.

It is therefore necessary to define the dominant abradability mechanism at a given rub condition in order to model the contact temperatures and loads generated. Historically it has been difficult to identify the boundaries between various abradability conditions, due to the limited experimental data of rub temperatures and loads under controlled conditions.

The aim of this Abradability Investigation was to understand the abradability mechanics during engine representative conditions for three abradable systems, typical of the current suite of abradable materials in operation. The study involves a detailed investigation of abradability carried out on the Alstom Abradability Facility, generating detailed load and temperature data. This is in addition to blade wear and abradable loss measurements for a range of service conditions. The experimental procedure represents the largest single study of abradability mechanics carried out by Rolls-Royce, providing comprehensive abradability maps of representative abradable systems under engine service conditions. The objectives of this study are as follows:

i) To identify the mechanics of abradability associated with specific operating conditions for a given abradable material and to determine boundary conditions between various abradability regimes.

ii) To correlate abradability mechanisms with load and temperature data from associated rubbing conditions and highlight key performance drivers.

iii) To generate numerical interpretation of abradability performance from first principle material response and rig data.

5.42 Abradability Investigation – Experimental Design

An investigation of blade tip speed and incursion rates has been conducted for a range of civil engines in order to design a representative abradability test matrix. Blade tip speed can be calculated directly from the shaft RPM and the diameter of the disc + blade. Incursion rates, which are the result of a thermo-mechanical combination of centrifugal loading of discs and blades and thermal expansion of the rotatives and engine casing, are however more complicated. It is possible to calculate the incursion rate for a given blade tip speed by combining SC03 stress models with Whole Engine Models (WEM) to provide the resultant blade tip/rotor path incursion rate. Limited probe data, which has been correlated with modelling results for a range of civil engines for running-in and handling, is also available as shown in Figure 79.

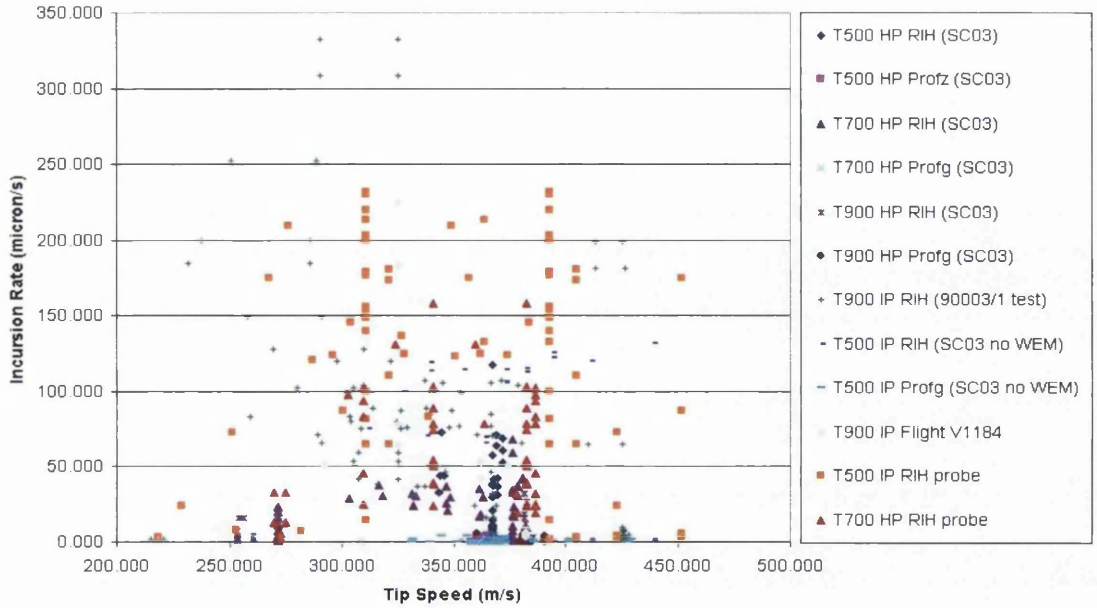

Figure 79. Blade tip speeds and incursion rates of large civil engines during running-in and handling

In order to utilise this data in a representative manner on an abradability rig, it is necessary to standardise the data in terms of the incursion depth-per-blade pass. This is achieved by assuming that during service a single compressor blade is responsible for all abradability. It is then possible to calculate the cut depth per pass (a'), as shown in Figure 80.

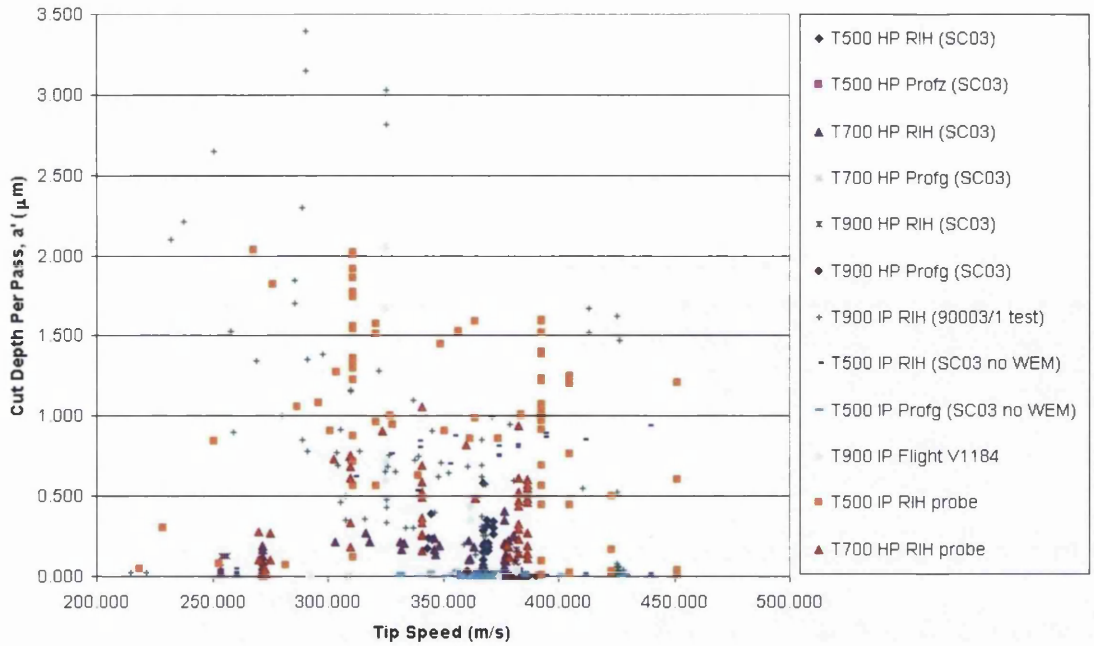

Figure 80. Blade tip speeds and a' values for large civil engines during running-in handling

The data presented in Figure 56 has been used to generate test matrices for abradability testing of three abradable coating systems representative of the current abradable used in service. In line with the Corporate Rig Strategy, the Abradability Investigation was carried out at the highly-instrumented Alstom Abradability Facility.

From the a' and blade tip speed measurements shown in Figure 80 a test matrix has been generated, which focuses on the abradability conditions associated with normal operational service. Additional tests are also shown which will be used to understand the abradability mechanics associated with rubbing conditions outside the normal operational envelope, such as those associated with a surge event. The test matrix is shown in Table 10.

Table 10. Test Matrix for Abradability Testing at Alstom Highly Instrumented Abradability Facility

Incursion Rate (μm/s)	**Blade Tip Speed** (m/s)				
	200	250	300	350	400
1	X	X	X	X	X
50		X	X	X	X
100	X	X	X	X	X
250		X	X	X	X
500	X	X	X	X	X
750		X	X	X	X
1000	X		X		X

The higher incursion rates investigated on the Alstom abradability facility are a result of the small rig disc diameter. This matrix will be completed for three coating types, representing distinct abradable material families currently used within the IP and HP compressors:

Metco 320	Al-Si + hBN	Aluminium Abradable (58 R15Y)
Metco 314	NiCrAlY + Bentonite	Hard Nickel Abradable (50 R15Y)
Durabrade 2614	NiCrAlY + Bentonite + hBN	Soft Nickel Abradable (35 R15Y)

Durabrade 2614 represents the latest generation of 'titanium friendly' nickel abradables which, due to their high volumes of porosity and dislocator, have relatively low hardness values (Sulzer Metco 2006). Although this coating system is not yet in service, it has been highlighted as a potential abradable for a number of new civil and military applications based upon the results of this assessment, in which the Durabrade test pieces had an R15Y hardness of 35.

For all abradability test conditions a measure of blade wear/material pick-up was taken from the blade, and a volume of material removed from the coating as a function of mass change. In addition, temperature and load measurements were gathered during testing in order to gain a fundamental understanding of the abradability characteristics associated with a given condition. Figure 81 shows the arrangement of pyrometers and load cells, which are calibrated to take readings at every 40th blade pass.

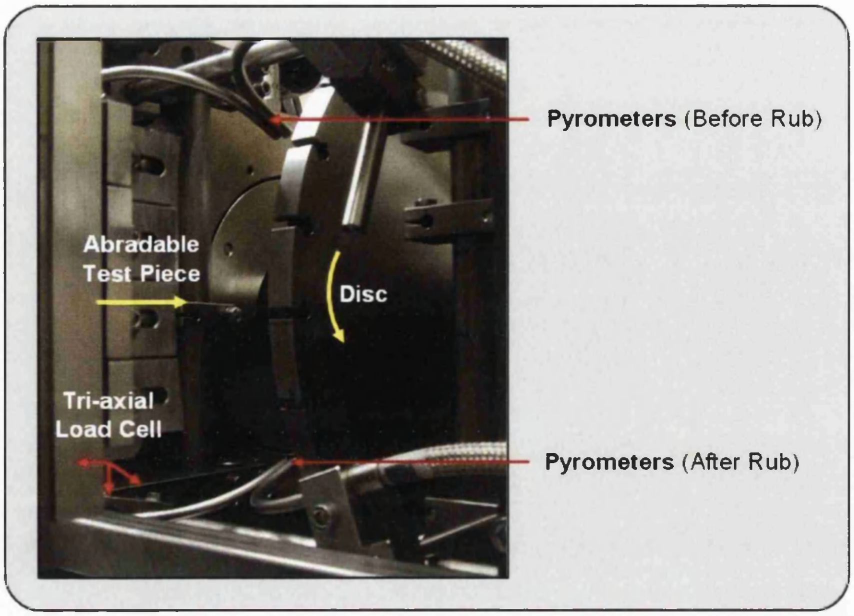

Figure 81. Arrangement of Alstom Abradability Facility Instrumentation

Pyrometers positioned above and below the test piece measure the temperature of the blade tip immediately before and after every 40th rub. This arrangement provides information concerning the heating rate during rubbing and the cooling rate during the remaining rotation time, allowing extrapolation to larger rub lengths and component geometries. The load cells on the test piece provide force measurement during rub testing in the radial, axial and tangential directions, which can then be correlated with the temperature measurement.

To make the conditions of the abradability testing as representative as possible, all testing was carried out using Ti 6/4 blades with a blade tip thickness of 1.5mm and a blade tip width of 15mm, as shown in Figure 82.

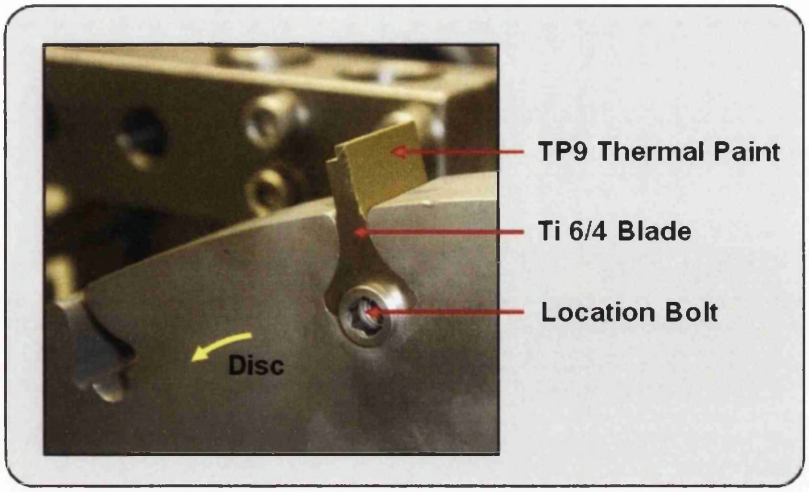

Figure 82. Ti 6/4 blade with Rolls-Royce TP9 thermal paint mounted in Alstom Abradability Facility disc

All blade test pieces used were painted with Rolls-Royce thermal paint (TP-9) in order to gather additional information on the temperature gradient away from the blade tip and the accumulative heat generation at the tip.

5.43 Abradability Investigation – Results

Tables 11-13 summarise the abradability test results for Metco 320, Metco 314, soft Durabrade and hard Durabrade respectively. Blade wear is shown as a negative change in blade height whilst blade and substrate weight loss is shown as a negative change in weight.

Table 11. Abradability test results including blade height change, blade and abradable weight change and rub load and temperature data for Metco 320

Test No.	Blade Tip Speed (m/s)	Incursion Rate (mm/s)	Cut per Blade (mm)	Δ Blade Height (mm)	Δ Blade Weight (mg)	Δ Substrate Weight (mg)	Max Rub Temp (°C)	Max Radial Load (N)
462	200	1	0.01	0.48	-9	-2210	740	82
463	200	100	0.57	-0.16	-8	-930	536	370
464	200	500	2.86	0.02	1	-760	505	780
465	200	1000	5.72	0.03	0	-610	520	986
466	200	2000	11.44	0.02	0	-730	476	530
457	250	1	0.00	0.63	17	-2450	740	85
458	250	50	0.23	0.12	1	-1130	627	180
459	250	100	0.46	0.06	1	-1760	570	200
460	250	200	0.91	0.03	1	-920	505	180
461	250	500	2.29	0.01	1	-930	490	540
483	300	1	0.00	0.46	-2	-1830	740	-
482	300	50	0.19	0.04	0	-1080	553	315
481	300	100	0.38	0.02	1	-1050	490	420
480	300	200	0.76	0.01	0	-950	490	900
519	300	350	1.33	-0.01	-2	-1070	490	436
479	300	500	1.91	0.00	0	-980	520	221
478	300	1000	3.81	0.00	-1	-1070	490	441
477	300	2000	7.62	-0.01	-2	-930	490	655
527	360	1	0.00	-0.90	-74	-470	853	-
508	360	50	0.16	0.15	3	-1270	505	80
507	360	100	0.32	0.04	0	-1050	490	116
506	360	200	0.64	0.00	-1	-1140	505	105
505	360	500	1.59	0.00	-3	-1120	520	257
514	419	1	0.00	-0.17	-29	-200	766	69
513	419	50	0.14	0.04	1	-1700	490	134
512	419	100	0.27	0.01	4	-1360	490	239
511	419	200	0.55	0.00	1	-1440	490	264
510	419	500	1.36	0.00	-4	-1340	505	590
509	419	1000	2.73	0.01	0	-1350	490	241

Table 12. Abradability test results including blade height change, blade and abradable weight change and rub load and temperature data for Metco 314

Test No.	Blade Tip Speed (m/s)	Incursion Rate (mm/s)	Cut per Blade (mm)	Δ Blade Height (mm)	Δ Blade Weight (mg)	Δ Substrate Weight (mg)	Max Rub Temp (°C)	Max Radial Load (N)
472	200	1	0.01	-0.16	-16	-1960	956	67
473	200	100	0.57	-0.79	-88	-160	995	116
474	200	500	2.86	-0.87	-74	-10	1080	540
475	200	1000	5.72	-0.68	-65	-10	1127	722
476	200	2000	11.44	-0.46	-42	-20	1036	1490
467	250	1	0.00	0.01	0	-2580	-	-
456	250	50	0.23	-0.94	-98	-250	1353	196
468	250	50	0.23	-0.85	-89	-270	1178	140
469	250	100	0.46	-0.92	-97	-180	1178	83
470	250	200	0.91	-0.89	-81	-90	1204	144
471	250	500	2.29	-0.80	-75	-90	1178	424
517	300	1	0.00	0.00	-3	-3140	490	-
518	300	50	0.19	-0.74	-81	-570	1036	111
501	300	100	0.38	-0.88	-95	-270	1127	122
500	300	200	0.76	-0.90	-97	-220	1127	80
499	300	350	1.33	-0.90	-99	-200	1080	108
498	300	500	1.91	-0.90	-91	-150	1080	141
485	300	1000	3.81	-1.01	-92	-70	1036	314
484	300	2000	7.62	-0.59	-60	-70	1080	745
504	360	1	0.00	0.00	-2	-260	-	77
503	360	50	0.16	-0.74	-76	-840	920	110
502	360	100	0.32	-0.83	-91	-310	1127	84
487	360	200	0.64	-0.98	-106	-240	1178	84
486	360	500	1.59	-0.95	-98	-460	1127	133
525	419	1	0.00	0.01	0	-3850	476	80
523	419	50	0.14	-0.61	-57	-1650	920	112
522	419	100	0.27	-1.07	-109	-490	956	77
521	419	200	0.55	-0.97	-104	-310	1178	124
516	419	500	1.36	-1.02	-110	-340	1036	90
515	419	1000	2.73	501.4	-49	-1590	853	115

Table 13. Abradability test results including blade height change, blade and abradable weight change and rub load and temperature data for Durabrade

Test No.	Blade Tip Speed (m/s)	Incursion Rate (mm/s)	Cut per Blade (mm)	Δ Blade Height (mm)	Δ Blade Weight (mg)	Δ Substrate Weight (mg)	Max Rub Temperature (°C)	Max Radial Load (N)
538	200	1	0.01	-0.01	-0.7	-2440	436	-
539	200	200	1.14	-0.49	-55.8	-1080	920	56
540	200	500	2.86	-0.33	-42.5	-1240	956	56
541	200	1000	5.72	-0.41	-42.9	-1210	956	120
542	200	2000	11.44	-0.30	-45.4	-900	886	188
545	300	1	0.00	0.00	0	-2430	-	-
546	300	200	0.76	-0.51	-47	-810	956	50
547	300	500	1.91	-0.38	-46	-1450	956	68
548	300	1000	3.81	-0.20	-28	-1940	920	72
549	300	2000	7.62	-0.03	-7	-960	715	80
535	419	1	0.00	0.01	-0.5	-3380	-	51
536	419	200	0.55	-0.83	-91.1	-450	995	-
537	419	500	1.36	-0.50	-57.5	-1470	995	181
543	419	1000	2.73	-0.29	-26	-2680	853	182
544	419	2000	5.46	-0.16	-19	-2910	536	83

The results shown in Tables 8-10 indicte a wide range of abradability performance between the various coating systems and test conditions. Further analysis of this data reveals a number of abradability performance trends.

Figure 83 indicates a plot of the blade height change for the Metco 320 abradability testing. The data is generated by increasing incursion rate for a given blade tip speed.

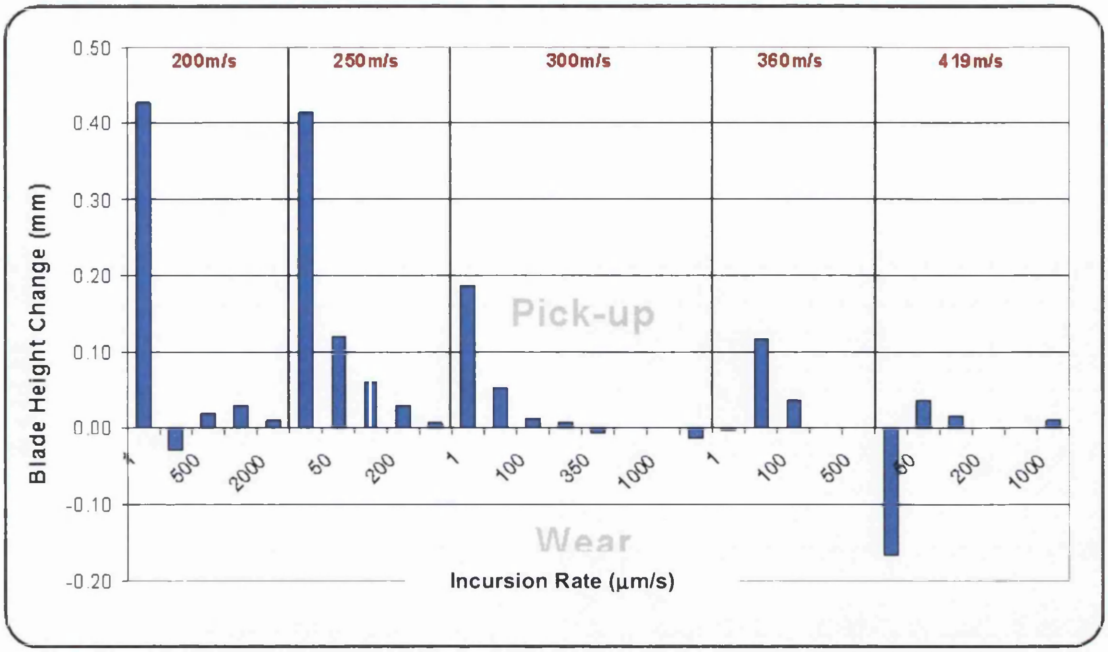

Figure 83. Blade height change data for Metco 320 abradability testing

During low incursion rate, low blade tip speed rub conditions, Metco 320 experiences excessive pick-up and an increase in blade height, as shown in Figure 59. These tests also generated high blade tip temperatures of 740-853°C. This phenomenon was not observed at higher (>360m/s) blade tip speeds. In fact at 419m/s blade tip speed and 1µm/s incursion rate a blade wear of 0.17mm was recorded.

Thermal paints were applied to blade tips at Rolls-Royce to provide additional rub temperature information. Figure 84 shows the thermal gradient from the tip of a low incursion rate Metco 320 abradability test.

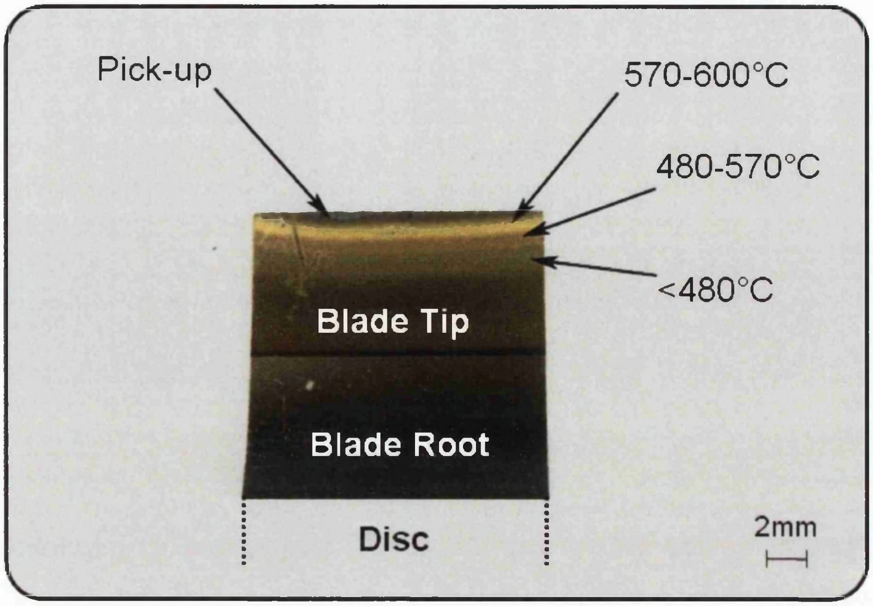

Figure 84. Thermally painted blade following Metco 320 low incursion rate abradability testing

Figure 84 shows that the high rub temperatures generated at the blade tip are highly localised, whilst the temperature away from the blade tip is significantly lower. This could potentially generate high thermal stresses within the blade, leading to tip cracking or creep.

Figure 85 shows the blade height change data for the abradability tests carried out on Metco 314 abradable coatings.

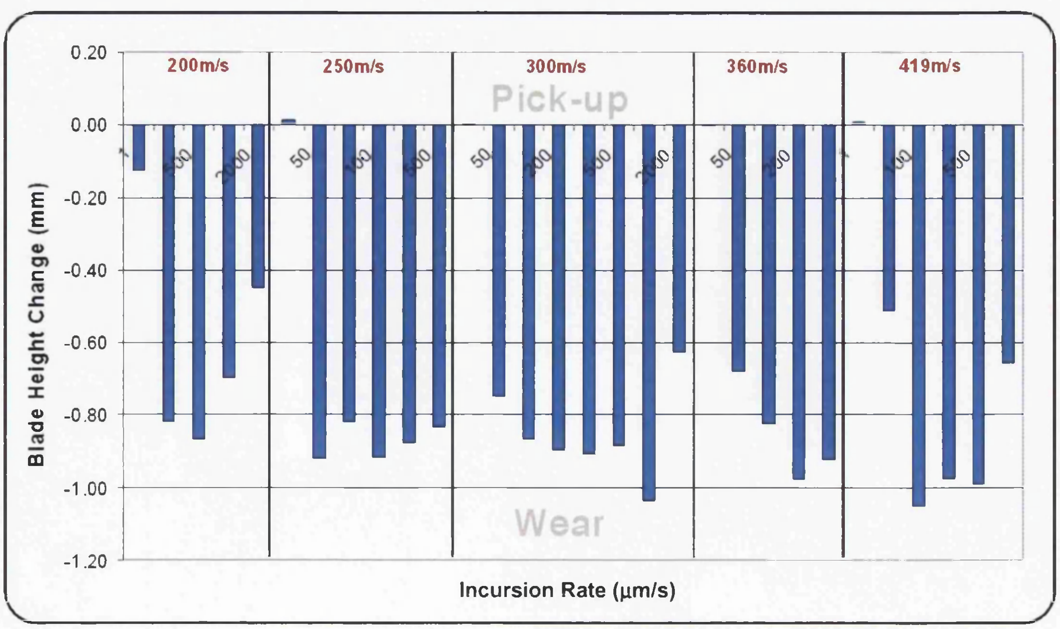

Figure 85. Blade height change data for Metco 314 abradability testing

From the blade height change data shown in Figure 85 it is clear that the hard nickel abradable matrix of Metco 314 produces excessive blade wear under most abradability conditions. Table 9 also shows that the rub temperature associated with these tests was approximately 1000°C. However, Metco 314 does show good abradability performance under 1μm/s incursion rate rubs, where there was little or no measurable blade wear. The rub temperatures under this condition were measured at approximately 450°C.

Figure 86 shows the blade height change data generated during abradability testing of the Durabrade coating material.

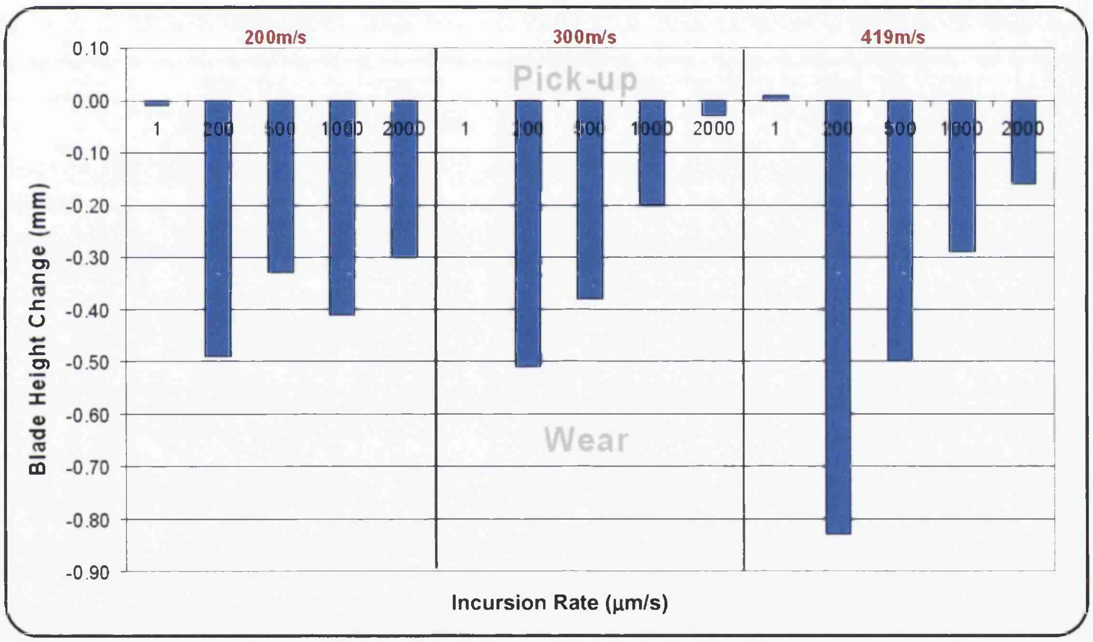

Figure 86. Blade height change data for Durabrade abradability testing

From the blade height change data shown in Figure 86 it becomes apparent that, as a nickel matrix alternative abradable, Durabrade produces less blade wear compared to Metco 314. Blade tip temperature is also seen to increase with blade wear. Throughout consistent Metco 314 testing during 1mm/s incursion rate rub conditions, there was minimal blade height change.

In addition to the abradability data shown in Figure 83-86, abradability rub track characteristics often provided useful information relating to the abradability mechanisms associated with a coating material. Figure 87 shows the rub tracks for the Metco 320 abradability tests.

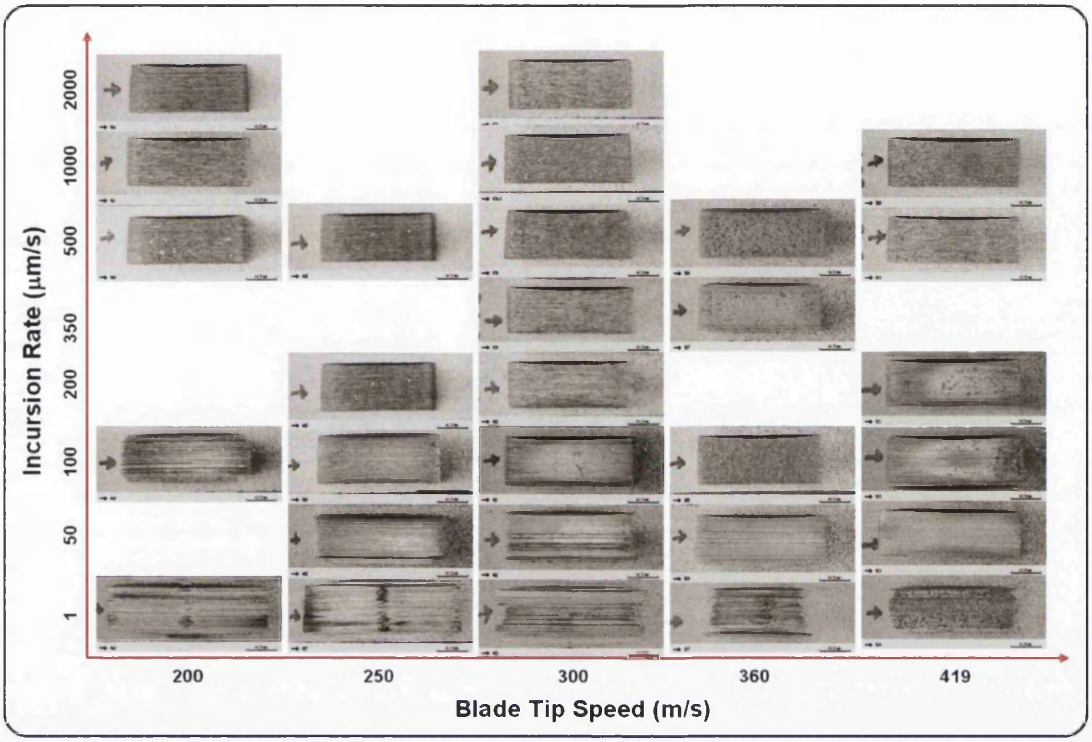

Figure 87. Metco 320 abradability test piece rub tracks as a function of blade tip speed and incursion rate

From the rub tracks shown in Figure 87 there is evidence of gramophone grooving (as discussed in section 3.8) particularly following low incursion rate, low blade tip speed rubs. This mechanism operates up to incursion rates of 100µm/s, above which the rub tracks indicate effective abradability with no significant heating or loading effects, consistent with the measured temperature and load readings shown in Table 8.

Figure 88 shows the rub tracks for the abradability testing of Metco 314.

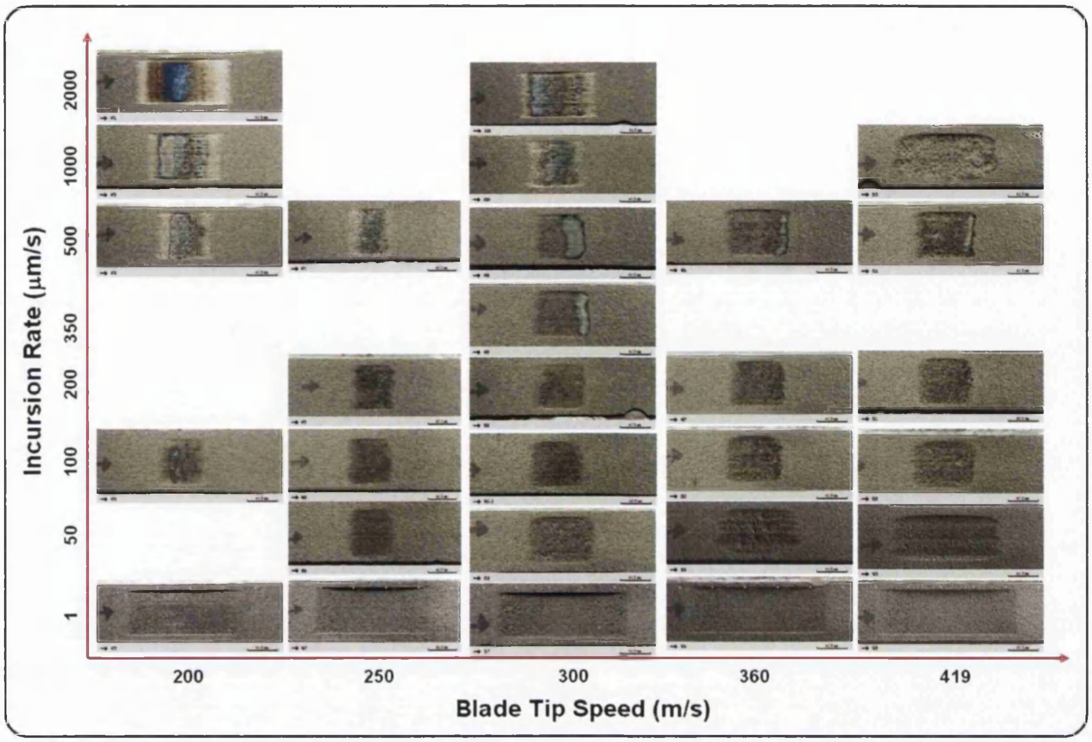

Figure 88. Metco 314 abradability test piece rub tracks as a function of blade tip speed and incursion rate

The Metco 314 rub tracks in Figure 88 indicate that, during high incursion rate rub conditions, significant heating was generated, resulting in blueing of the rub tracks. During high incursion rate and high blade tip speed rubs there is also evidence of macro rupture. From the rub tracks shown in Figure 60 it appears that, at 1μm/s, incursion rate rubs Metco 314 abrades in an effective manner with no evidence of significant heat generation or loading. Although the measured readings for maximum temperature shown in Table 12 are higher than corresponding values for Metco 320 these are still considerably below the melting point of the nickel matrix material.

Figure 89 shows the rub tracks for the abradability testing of Durabrade 2614 abradable coating material.

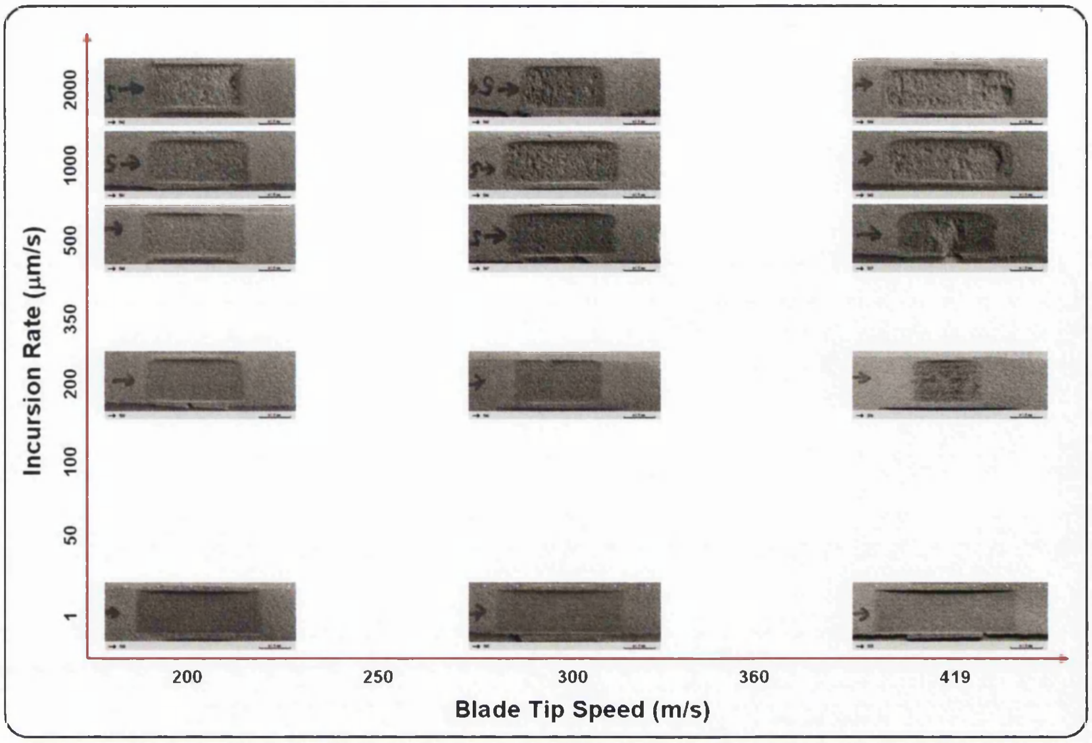

Figure 89. Durabrade abradability test piece rub tracks as a function of blade tip speed and incursion rate

The Durabrade rub tracks shown in Figure 61 highlight the material's propensity to suffer from large scale macro rupture at high incursion rate, high blade tip speed rub conditions. Under lower incursion rate and blade tip speed abradability the rub tracks for this coating material show no evidence of excessive heating or loading.

5.44 Abradability Investigation – Discussion

This investigation has generated a large quantity of abradability performance data over a range of operating conditions for the three distinct families of abradable coatings currently used within the IP and HP compressors. In order to understand these results it is necessary to consider each coating material independently.

Metco 320 Abradability Performance

During service, Metco 320 abradable coatings have been observed to suffer from gramophone grooving as a result of pick-up on blade tip (Hopkins 2003). These conditions are associated with low incursion rate rubs such as those observed during the climb phase of a typical flight cycle.

Consistent with service experience under low incursion rate rubs, excessive rub temperatures of between 740 and 853°C were measured. These are significantly higher than the melting point of the aluminium-silicon matrix material of 612°C. As a result the coating melts under the action of the incurring blade and is transferred to the blade tip. Following transfer the abradable materials will solidify and the brittle recast material can then be released (or partially released) by the rotating blade. Observations during testing confirmed the cyclic nature of this phenomenon. Blade tip sparking was observed to vary with a regular cyclic nature during low incursion rate testing. For this reason it is not possible to rely on the positive blade height change measurements as an accurate measure of the rub temperature or absolute amount of pick-up.

It can been recognised from the temperature and blade height change data for Metco 320, that at high blade tip speeds the 1μm/s incursion rate pick-up did not occur. This result indicates that the pick-up mechanism associated with aluminium based abradables is not purely a function of the cut depth per blade pass (a'), but is also dependent on blade tip speed.

In Section 5.14, the concept of rubbing time (t_{rub}) was defined in Equation 3 as:

$$\frac{w}{v} = t_{rub}$$

Equation 3

where w is the blade width and v the blade tip speed. For Metco 320, pick-up is the result of high frictional heating under low incursion rate and therefore low a' rub conditions, which appear to increase with increasing values of t_{rub}. It is therefore possible to surmise the following relationship for rub temperature T:

$$\frac{T_{rub}}{a'} \propto T$$

Equation 4

As T approaches the melting point of the abradable matrix material, pick-up and transfer will occur. Correspondingly, as the abradable coating becomes molten, the sliding friction drops and the rub temperature falls to below the solidus of the material, creating a recast aluminium layer on the blade tip. As the blade continues to incur contact, frictional heating will be regained and the cyclic transfer process will continue.

Figure 90 shows an overview of the pick-up measurements for the Metco 320 abradability tests within the operational envelope of the IP and HP compressors.

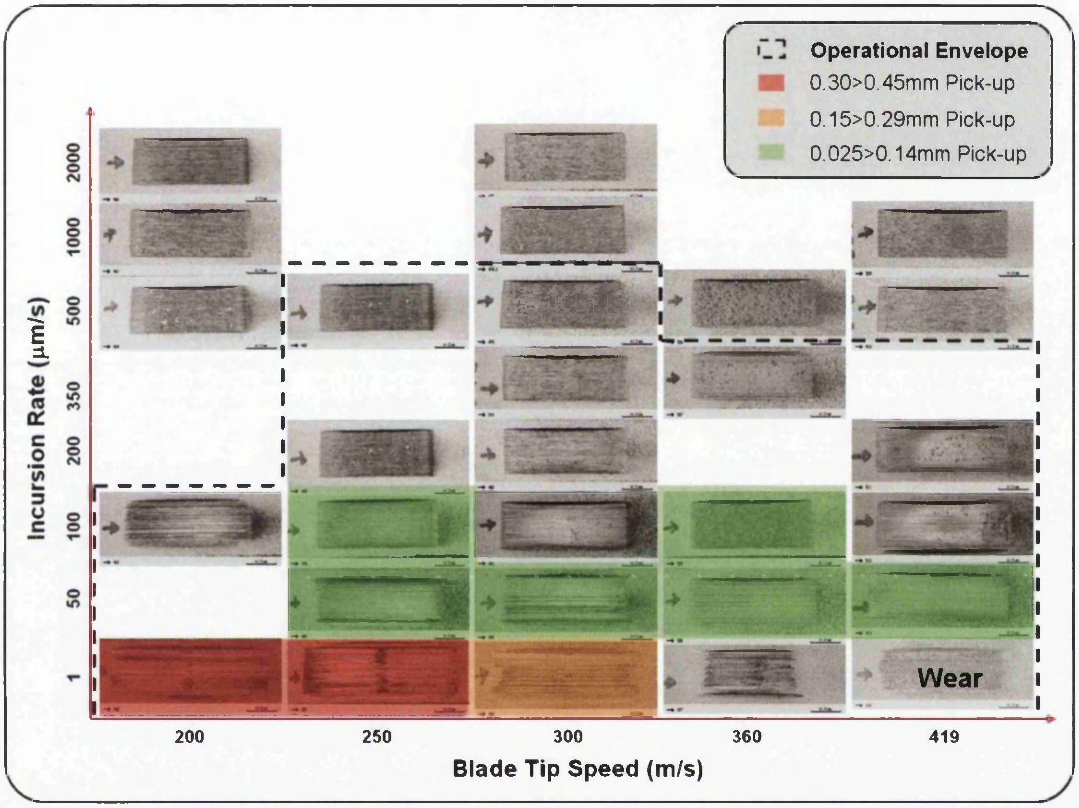

Figure 90. Metco 320 pick-up measurements and engine operational envelope

From Figure 87 it is clear that Metco 320 pick-up under low incursion rate rub conditions falls within the operational envelope of the engine. From these results it is fair to assume that pick-up will occur during normal operation throughout the flight cycle.

It is extremely difficult to eliminate low incursion rate rubs from the operational conditions of an abradable system, due to the highly dynamic nature of the closure plot shown in Figure 77. As a thermally driven mechanism it is clear that, to prevent pick-up, it is necessary to lower the sliding friction of the abradable/blade interface or to use an abradable matrix material with a melting point above the maximum rub temperature T.

Metco 314 Abradability Performance

The abradability performance of the nickel based abradable Metco 314 revealed very different characteristics to those of Metco 320. As a hard nickel system, Metco 314 is used in the hotter HP compressor stages as a nickel blade abradable (Sulzer Metco 2006). Metco 314 is not used against titanium blades due to the risk of titanium fire, resulting from high blade tip wear.

Consistent with service experience, the abradability results for Metco 314 abradable coating showed excessive blade wear over a wide range of operational conditions. Inversely to the pick-up measurements generated during Metco 320 testing, blade wear was seen to be most prevalent during higher incursion rate rubs. Similar to the pick-up observed during Metco 320 testing, blade wear during Metco 314 tests was associated with high rub temperature. Many tests generated blade tip temperatures in excess of 1000°C. These temperatures are also indicated by rub track blueing, as indicated in Figure 88. High radial loads were also recorded during the high incursion rate testing of Metco 314.

The low blade wear and associated low temperatures and loads for the Metco 314 abradable coating system during 1μm/s incursion rate rubs suggests that, under these conditions, the system operates within the Schmid abradability model (Schmid 1997). The coating is abraded efficiently and as a result there is minimal frictional heating and/or wear of the blade material.

However, at higher than 1μm/s incursion rate rubs the abradability mechanics of the Metco 314 system change dramatically. Large rub temperatures and radial loads are generated as a result of ineffective abradability, which ultimately leads to high levels of blade wear. There appears to be a step change in mechanism, which occurs between 1 and 50μm/s incursion rate. This change leads to an order of magnitude increase in the amount of blade wear. These effects are most prevalent during high blade speed rubs, with the exception of the 419m/s rub at 2000μm/s incursion rate condition, where large scale macro rupture occurred.

Figure 91 indicates the amount of blade wear measured for the Metco 314 abradability tests and the operational envelope of the IP and HP compressors.

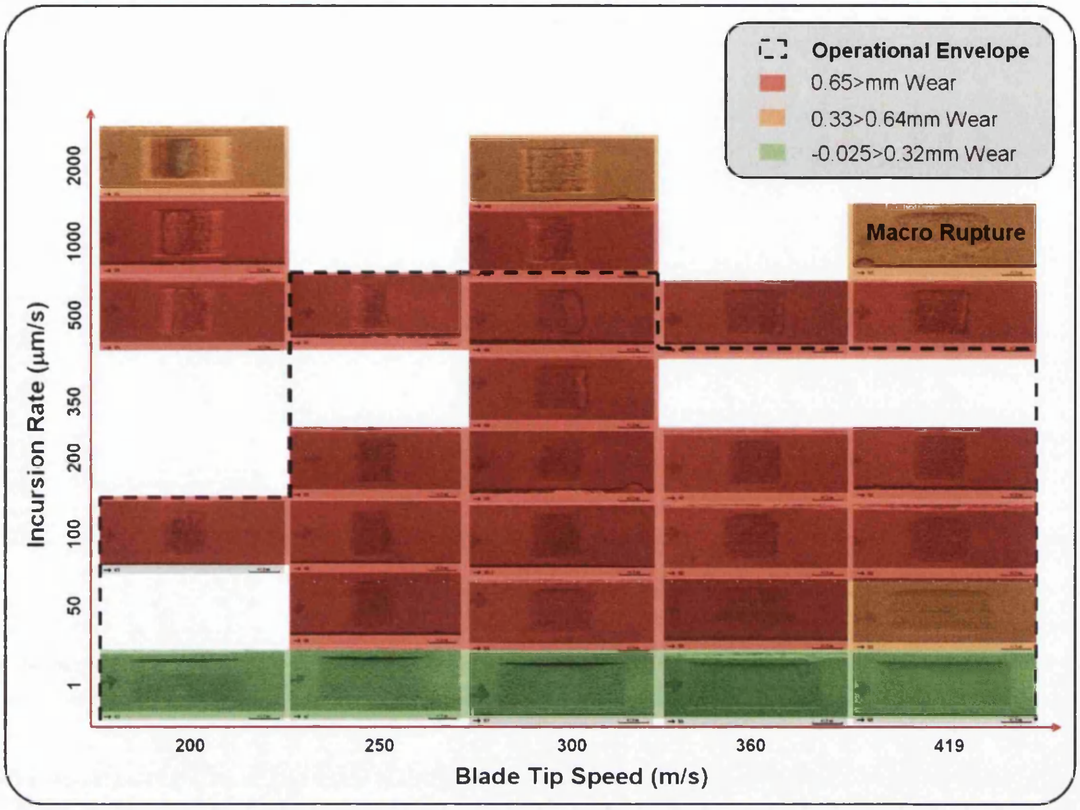

Figure 91. Metco 314 blade wear measurements and engine operational envelope

It is clear from the blade wear measurement shown in Figure 91 that there is a step change in the abradability mechanism of Metco 314, which occurs between 1 and 50 µm/s incursion rate rub conditions. This boundary condition appears to be consistent for all blade tip speeds and therefore, predominately driven by the value of a', as shown in Figure 92.

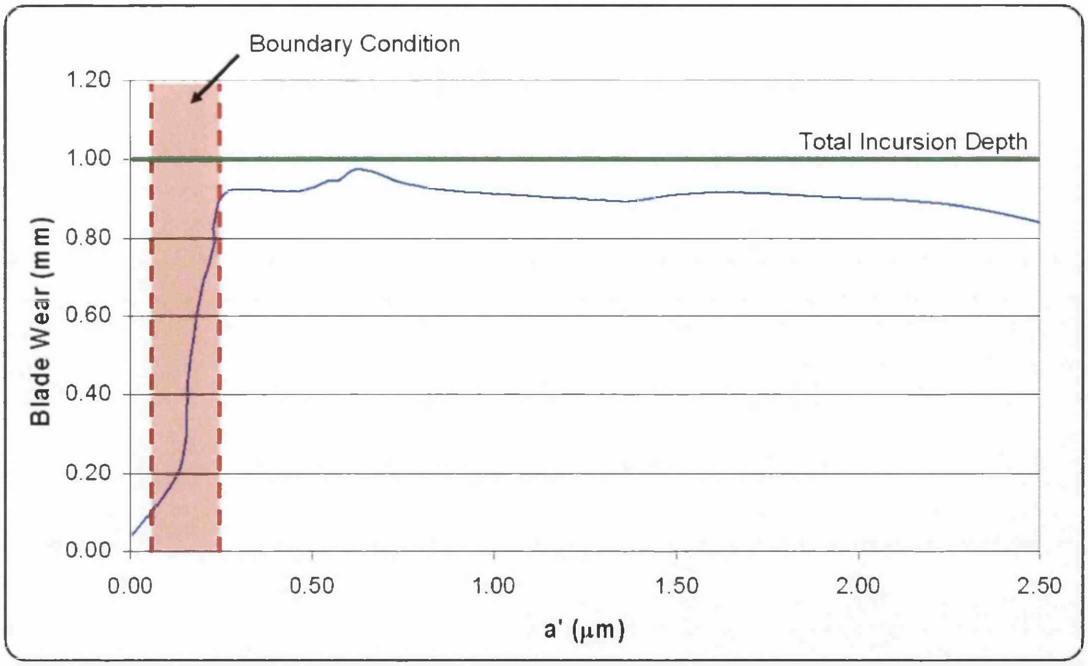

Figure 92. Blade wear increase as a result of Metco 314 a' boundary condition

During the abradability tests, a' varies from approximately 0.001μm during the 1μm/s incursion rate tests to approximately 0.1μm during the 50μm/s tests. The Metco 314 powder particles are approximately 100-150μm in diameter and it is therefore unlikely that the boundary conditions associated with the change in a' is directly related to the powder particle size of the coating material. As the powder particles and resultant coating structure are much coarser than the values of a' involved, the properties of the coating can be considered constant for all abradability test conditions used.

For nickel systems including Metco 314, it appears that the Schmid (1997) model of abradability is only effective during low incursion rates. Under these conditions, moderate compressive loads within the coating allow elastic release of abradable material behind the blade tip. At higher incursion rates, compressive loads may increase beyond the elastic limit of the coating material. As a result the combustion sprayed porous abradable will densify, increasing the coating hardness and generating high blade wear.

The Metco 314 abradability results indicate that hard nickel systems are ineffective when used with titanium blade materials, under moderate and high incursion rate rub conditions, including those associated with the take-off phase of a typical flight cycle.

Durabrade 2614 Abradability Performance

The soft nickel based Durabrade 2614 abradable coating represents the latest commercially abradable coating system (Sulzer Metco 2006). The material is designed to provide the high-temperature capability of a hard nickel system with the 'titanium-friendly' blade performance of an aluminium coating.

The blade height change measurements generated from the abradability testing of Durabrade 2614 identify a significant reduction in blade wear compared to the results of the Metco 314 tests. However, the rub tracks illustrated in Figure 61 show that at high blade tip speed, high incursion rate rub conditions, macro rupture has occurred. The resultant rub tracks are rough with large areas of coating spallation. Figure 93 indicates the amount of blade wear measured for the Durabrade 2614 abradability tests and the operational envelope of the IP and HP compressors.

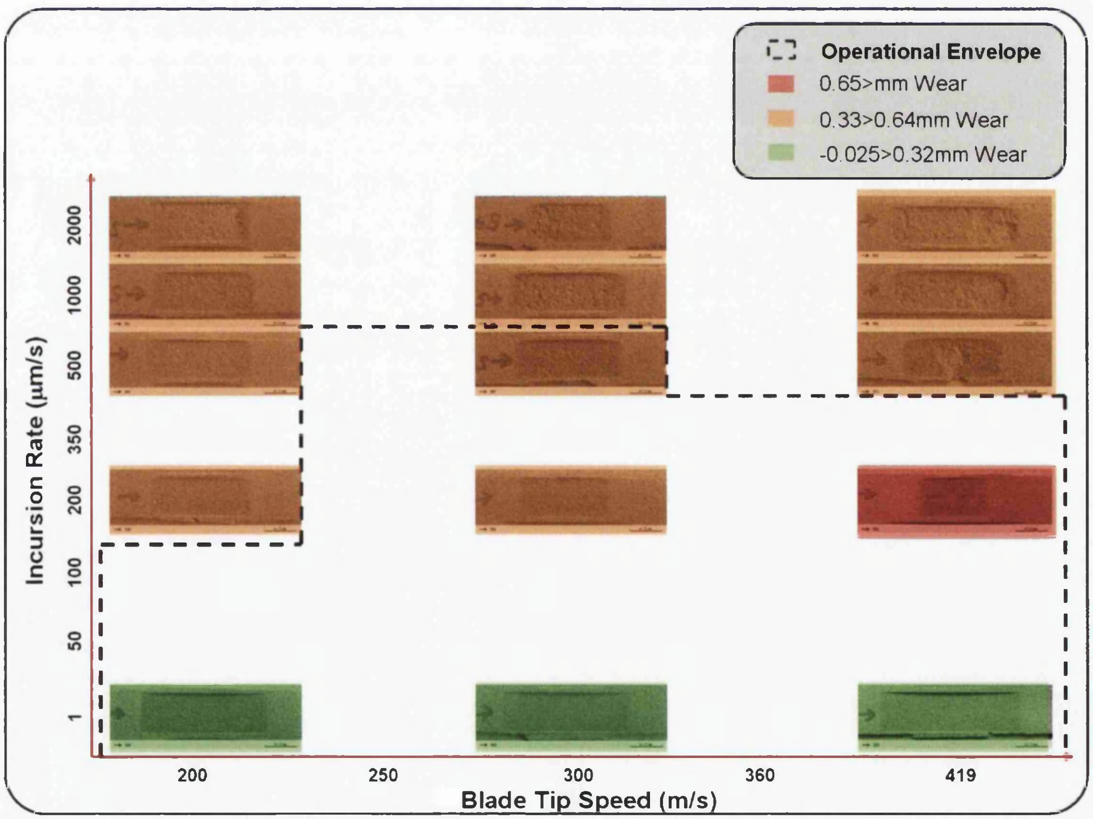

Figure 93. Durabrade 2614 blade wear measurements and engine operational envelope

As discussed in Section 5.3, macro rupture of an abradable coating reduces the amount of blade wear by absorbing the rub energy. However, the resultant surface condition of the rub track is extremely poor, and would have a detrimental effect the flow of the gas stream within the compressor. The defects on the surface of the coating may also lead to additional spallation and/or erosion of the coating during service. Macro rupture appears to be associated with the high-energy rub conditions where a combination of high incursion rate and high blade tip speeds generate extremely high strain rate fractures to form within the coating material.

The Durabrade 2614 suffers from greater macro rupture at lower incursion rate and blade tip speed conditions than the harder nickel based abradable Metco 314 test pieces. The significant compositional difference between the two nickel systems is the additions of a secondary hBN dislocator phase, which lowers the hardness of Durabrade.

It appears that the increased dislocator content of Durabrade 2614, which is designed to reduce blade wear, has a detrimental effect upon the mechanical integrity of the coating material.

5.45 Abradability Investigation – Conclusions

The investigation has examined the abradability characteristics of three distinct abradable coating types under a range of engine representative, abradability conditions. The systems investigated represent the three discrete families of abradable currently available:

Metco 320	Al-Si + hBN	Aluminium Abradable (58 R15Y)
Metco 314	NiCrAlY + Bentonite	Hard Nickel Abradable (50 R15Y)
Durabrade 2614	NiCrAlY + Bentonite + hBN	Soft Nickel Abradable (35 R15Y)

All testing was carried out at the Alstom Abradability Facility in Rapperswil, Switzerland. This facility was selected due to its unique level of instrumentation, which enables both load and temperature data to be captured during abradability testing.

In addition to blade wear and substrate weight loss measurements, optical pyrometers and high-speed load cells provided temperature and load data during testing. Consideration of the thermal and mechanical aspects for a given coating system has provided a fundamental understanding of the highly complex abradability characteristics.

In order to understand the abradability performance of the three abradable coating types it was necessary to consider each system individually.

Metco 320 Abradability Conclusions

The Metco 320 abradability tests generated abradable transfer and blade tip pick-up during low incursion rate, low blade tip rub conditions, consistent with service experience. Results show that pick-up is a function of both incursion rate and blade tip speed, as expressed by the following equation:

$$\frac{w/v}{a'} \propto T \qquad \text{Equation 5}$$

Pick-up is a thermally driven mechanism (Hopkins 2003). To prevent pick-up occurring during low incursion rate, low blade tip speed rubs, it is necessary to decrease the sliding friction of the abradable/blade interface or to use an abradable matrix material with a melting point in excess of the maximum rub temperature T.

Increasing the volume content of the dislocator phase may lower the frictional behaviour of the coating. However, higher volumes of dislocator material will also lower the thermal fatigue and/or erosion resistance of the coating material. Additions of high melting point metals, for example copper, could be used to raise the melting point of the abradable matrix.

In order to understand the effectiveness of a Cu-Al based abradable a full test and evaluation programme needs to be carried out. This should include further abradability trials particularly focusing upon low incursion rate rub conditions, together with erosion and Freestanding Coating testing.

Metco 314 Abradability Conclusions

The Metco 314 abradability results indicate that hard nickel systems are ineffective when used in conjunction with titanium blade materials, under moderate and high incursion rate rub conditions, including those associated with the take-off phase of a typical flight cycle. Blade wear is believed to be associated with densification of the porous, combustion sprayed, abradable coating.

In order to improve the abradability performance of nickel based abradables like Metco 314 it is therefore necessary to produce a fully dense abradable, using plasma spray equipment. However, it would be necessary to balance the density of the coating with abradability performance at lower incursion rates and it may be possible to produce a fully dense, but soft coating, using additions of a soft dislocator such as the hBN as used in Durabrade 2614.

Durabrade 2614 Abradability Conclusions

Durabrade 2614 represents the latest concept in abradable coating technology. Additions of a secondary dislocator phase enable a high-temperature nickel abradable to be produced with low R15Y hardness values. The system is designed to provide 'titanium friendly' abradability performance with extended temperature capability.

Abradability results indicate that Durabrade 2614 significantly reduces blade wear over a range of operational conditions. However, rub track assessment revealed evidence of macro rupture during high blade tip speed, high incursion rate, rub conditions.

The Durabrade 2614 abradability results suggest there is a compromise between the abradability performance and the mechanical integrity of nickel based abradable systems. These results do not support the use of Durabrade with titanium blades within the operational conditions of the IP and HP compressor.

Abradability Conclusions Overview

The abradability investigation has demonstrated how the abradability performance of all the commercially available abradable families varies over the range of incursion rate and blade tip speeds observed during normal IP and HP compressor operation. From these results the following important relationships and abradability mechanisms have been identified:

- Al-Si based abradables do not provide sufficient temperature capability for low incursion rate rub conditions, where rub temperatures can exceed 700°C. These conditions generate abradable pick-up on the blade tip.

- A Cu-Al matrix abradable would have improved temperature capability and therefore prevent the onset of pick-up at low incursion rate rub conditions.

- Combustion sprayed hard nickel abradable systems like Metco 314 produce high blade wear at incursion rates above a recognised boundary condition between 1-50μm/s. Above these conditions, densification of the coating surface raises the material hardness, leading to accelerated blade wear.

- Soft combustion-sprayed nickel abradable Durabrade 2614 coatings are designed for use with titanium blades over a range of operating temperatures. Compared to Metco 314, blade wear is significantly reduced by Durabrade 2614. However, low mechanical integrity, resulting from the secondary hBN dislocator phase, produced extensive macro rupture at >200μm/s incursion rate rubs.

- Producing a fully dense plasma sprayed system with additions of a secondary dislocator phase may enable high incursion rate rubs. In this way in may be possible to combine the mechanical integrity of Metco 314 with the abradability performance of a soft nickel system like Durabrade 2614. An assessment of the mechanical integrity of such coating systems using the Freestanding Coating Process should be used to calculate a coating integrity/abradability performance balance.

- The rub temperatures, generated over a wide range of abradability conditions associated with normal operation, are much greater than the environmental temperature of the IP and HP compressors. Thermal paints have identified that these frictional heating effects are highly localised at the blade tip, where thermal stresses generated at the blade tip may result in blade tip cracking or aerofoil creep failure.

- Further analysis, including stress modelling of the thermal stresses generated during normal operational rub conditions, should be carried out in an effort to determine a safe rub temperature envelope.

5.5 Technology Review of Metallic Foams

Metallic foam materials are finding an increasing number of applications in a wide variety of industries (Ashby *et al* 2000). The range of unique properties associated with these ultra-lightweight metallic materials, incuding high-energy absorption, have led to the development and full scale production of various foamed materials (Davies and Zhen 1983). As a relatively premature technology, these materials are currently at varying stages of material and manufacturing readiness.

There is the potential for metallic foams to be used as compressor clearance control materials, particularly where surge margin reduction case treatments are applied. These include hector slots or circumferential grooving. Case treatments have proved to be problematic for traditional thermal-sprayed abradable coatings, which are susceptible to cracking and spallation due to the exposed coating edges.

Metallic foams, including the materials shown in Figure 94, possess a number of desirable properties, which make them attractive as an alternative to traditional thermally sprayed abradables.

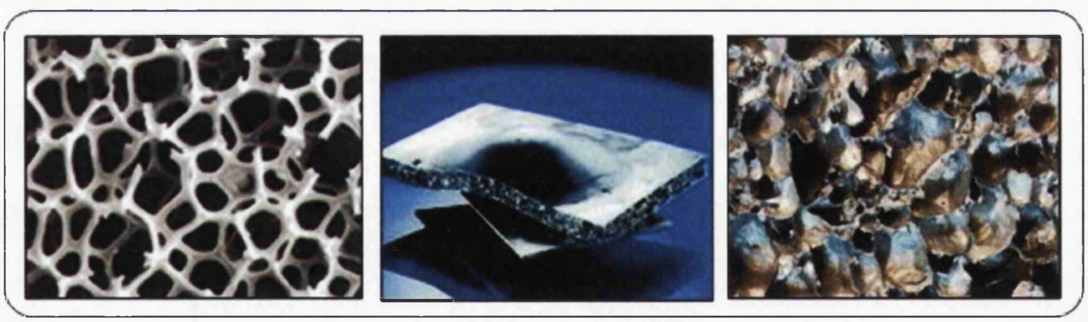

Figure 94. Example of a range of available metallic foam structures

As extremely low density cellular materials, metallic foams have exceptional strength to weight properties. High levels of porosity could also allow foam materials to collapse, as opposed to abrade, under the action of an incurring compressor blade. On densifying metallic foam would provide a functional clearance control without producing problematic debris.

5.51 Technology Review of Metallic Foams - Introduction

The basic material system requirements of metallic foams for clearance control are documented in a Clearance Control Requirements Report (Sellars and Hopkins

2004). This document, together with specific engine operational data (incursion rate and blade tip speed data), will be used to evaluate each metallic foam material against a set of five prioritised criteria, as shown in Table 14.

Table 14. Criteria for the evaluation of metallic foam materials for compressor sealing

1	**Material**	Temperature capability, stability at temperature
2	**Manufacturing Readiness**	Process control and stability, component size and capacity
3	**Abradability Performance**	Ability to wear/cut/collapse preferentially to blade material
4	**Pore Size**	Provides structural integrity across posts of circumferential grooves
5	**Gas Permeability**	Provides sufficient sealing either with/without additional filler material

When considering metallic foams for any new application, it is important to evaluate both the manufacturing capability and the theoretical properties achievable from a given material structure (Banhart *et al* 1999). At present many of the materials and processes are laboratory based, with no or limited manufacturing output. As with any process, relative costs and process control must be evaluated in any upscale in production.

A Technology Review of metallic foam materials has been carried out to evaluate the manufacturing methods, capability and material properties associated with foamed structures currently available. Potential attachment methods have also been evaluated with a view to attaching the foamed materials to compressor rotor path casings.

In order to evaluate possible analysis techniques, supplied foam materials were sectioned using a number of methods to determine an appropriate machining technique for further analysis. Rockwell hardness indentation was studied as a simplistic evaluation of deformation characteristics for metallic foams under compressive loads with the aid of 3-dimensional CT equipment.

5.52 Technology Review of Metallic Foams – System Requirements

The basic engineering requirements for a metallic foam material for compressor clearance control have been documented as a design guide (Sellars and Hopkins 2004). These requirements were communicated to a number of metallic foam manufacturers with a request for test pieces and process specifications for evaluation. The materials submitted were then assessed in abradability screening trials in order to evaluate the abradability characteristics of their structures. As a review of 'off-the-shelf' materials these preliminary trials will provide assurance that metallic foams are capable of generating functional abradable structures.

Manufacturing techniques were also evaluated against a set of material property and geometry requirements. If successful, the development of a metallic foam abradable could lead to the widespread use of such a system on a range of engines and compressor stages. However, the initial applications targeted by this specific study are for specific military applications. The basic material properties for these applications for IP compressor stages containing circumferential groves are summarised in Table 15.

Table 15. Material requirements of metallic foam materials for compressor clearance control

	Minimum Requirements	**Optimum Requirements**
Temperature	Operation without significant degradation up to 440°C	Operation without significant degradation up to 650°C
Deformation	• A high cyclic compressive load will be applied in the direction of arrow 'B' • Anticipated deformation by 2-3mm in the direction of arrow 'B' • Fingers will be expected to deform without buckling	
Mechanical Integrity	• Material must have sufficient mechanical integrity to withstand a certain degree of vibration and some mechanical loading	
Corrosion	• Material should be resistant to atmospheric corrosion (moist salty atmosphere)	
Thermal Fatigue	• No signs of cracking following Thermal Shock testing	
Gas Permeability	• All surfaces, apart from the ends of the fingers (arrow 'B'), will be sealed to prevent gas permeation	
Surface Texture	• Define surface roughness	

Although the specific geometry of the initial components may vary, the basic profile of a compressor rotor path casing containing circumferential groves is shown in Figure 95.

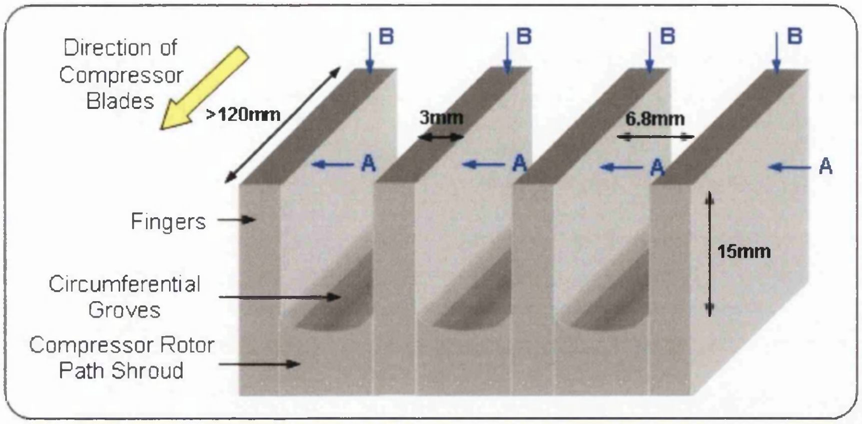

Figure 95. Basic circumferentially grooved compressor rotor path

The flow of the gas stream within the compressor will result in a loading on each of the circumferential fingers, as identified in Figure 95 by arrows 'A'. There will also be a compressive loading during the action of the incurring compressor blades, which is signified by the arrows 'B'. The specified component length is 120mm although in reality this circumferential component could be a 360° ring, which slots into the rotor path shroud.

Due to the complexity of the circumferential grooved rotor path, foam manufacturers were asked to supply simple flat plate test pieces for the initial abradability screening trials. The method of manufacture for such a grooved component is heavily dependent upon the foam manufacturing process. In some cases it is possible to create the specified net-shape component, during the foaming process (Ashby *et al* 2000). Alternative foaming techniques would require additional manufacturing processes for such a complex geometry.

5.53 Technology Review of Metallic Foams – Manufacturing Techniques

Currently, nine distinct manufacturing techniques are available for the manufacture of metallic foam materials (Banhart *et al* 1999). Within each of these, laboratories and industrial manufacturers have developed individual variations in order to achieve specific material properties or requirements. These processes can be divided into the following four technology groups (Ashby *et al* 2000):

i) Foams formed from the vapour phase

ii) Foams electrodeposited in aqueous solution

iii) Foams which form as a result of liquid-state processing

iv) Foams created in a solid state

Each manufacturing process can generate open and/or closed cell porous, metal structures from a subset of metallic materials with a range of densities and cell sizes. Critically for the end user, many of these manufacturing processes currently offer limited output quantity and/or quality control. In addition, many large-scale process facilities have been designed around a specific, and often specialist, product. Even small material modification in terms of material properties or geometry of components can often require extensive manufacturing investment and associated lead-times. Figure 96 shows the range of cell size and relative density of the different metal foam manufacturing methods available (Ashby *et al* 2000). The geometry of the circumferential grooves specified means that realistically, in order to provide the required sealing capability, the pore size of the metallic foam will need to be less than 1mm.

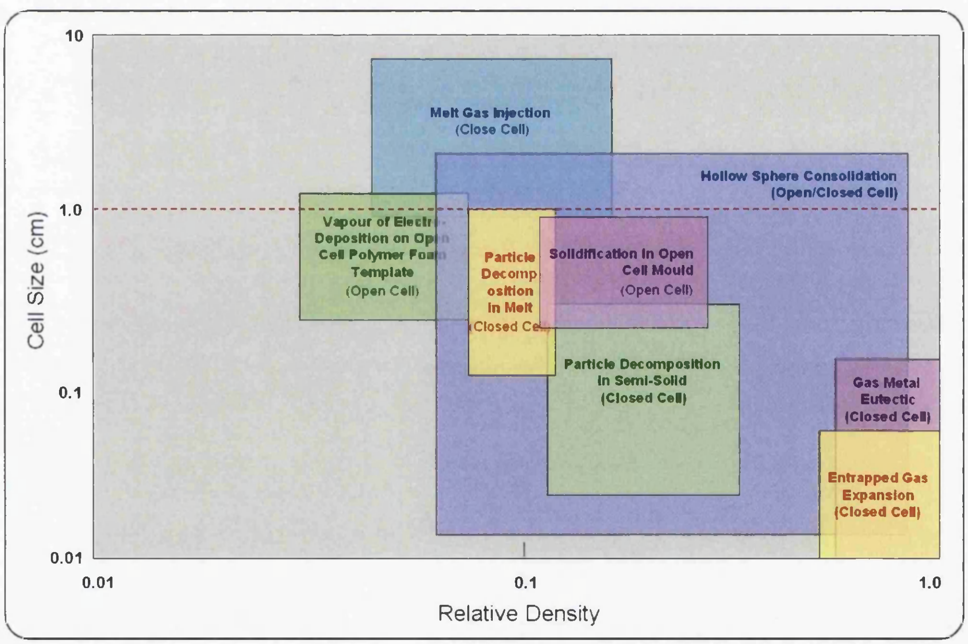

Figure 96. Cell size and relative density associated with metallic foam manufacturing methods

Most of the metallic foam manufacturing techniques currently available have been developed at research facilities and technical institutes around the world and later upscaled by industrial partners for specific applications. There are therefore no commercially available metallic foam materials, which offer all the material requirements defined and specified above. However, there are a number of manufacturing processes which, with the necessary investment and development, could potentially produce foamed materials offering the required range of properties.

5.54 Technology Review of Metallic Foams – Attachment Methodology

A literature review has been undertaken in order to determine potential joining techniques for an abradable liner, fabricated from a foamed metal attached to a compressor case. The options evaluated include mechanical fastening, adhesive bonding, brazing and welding. Most of the reviewed literature has reported work associated with aluminium foams for use in non-aerospace applications. Work on other foamed materials, including stainless steel or nickel foams, has not been developed to the same extent.

Mechanical Fixtures

It should be possible to produce a foamed metallic structure on a substrate, which could be subsequently attached to the compressor case. However, this type of manufacture has only been proven with aluminium foams. These have the advantage that fittings could be made in a variety of geometries that would satisfy the design intent and remain relatively cheap to 'tool-up' and produce. Finding suitable glues with the correct long-term high-temperature capabilities will prove difficult as no published literature on the S-bond adhesive could be found. These would need to be determined during the next phase of the work.

Welding Techniques

Ultrasonic welding would require significant tooling, together with considerable development activities, before it could be used routinely. The method would include joining the liner to an attachment feature which would in turn be joined to the compressor case to allow the liner to be replaced. A comprehensive business case study, dependent upon the numbers of liners manufactured, would need to be carried out in order to justify its use.

Laser welding of the liner to an attachment feature would be difficult, due to the collapse of the foam that most researchers report, and would require the development of filler wire containing a foaming agent compatible with the liner foam material. Although electron beam would not produce the same collapse, a filler wire would still be required before a capable process could be developed. The beam welding option is not currently recognised as being sufficiently well developed or easy to adapt to the present requirements.

Brazing Processes

Brazing capabilities have been demonstrated in stainless steel foams and, provided a suitable interlayer could be chosen, this process could be adaptable to nickel or other metal foams and therefore become attractive for development. Metal Powder Joining is another promising technology that could be adapted for use with metal foams and its ability to bond where there is a varying gap would make it particularly suitable for joining foamed liners to an attachment feature.

5.55 Technology Review of Metallic Foams – Analysis Techniques

The abradability characteristics of a metallic foam material will be dictated by a range of parameters that include density, cell size, wall thickness etc. It is therefore necessary to be able to analyse the structural features of these materials without deforming their appearance.

A range of metallic foam materials was sectioned using a range of techniques in order to assess the amount of structural damage sustained. Figure 97 illustrates a hollow, metal sphere, metallic foam structure, sectioned using four alternative cutting methods.

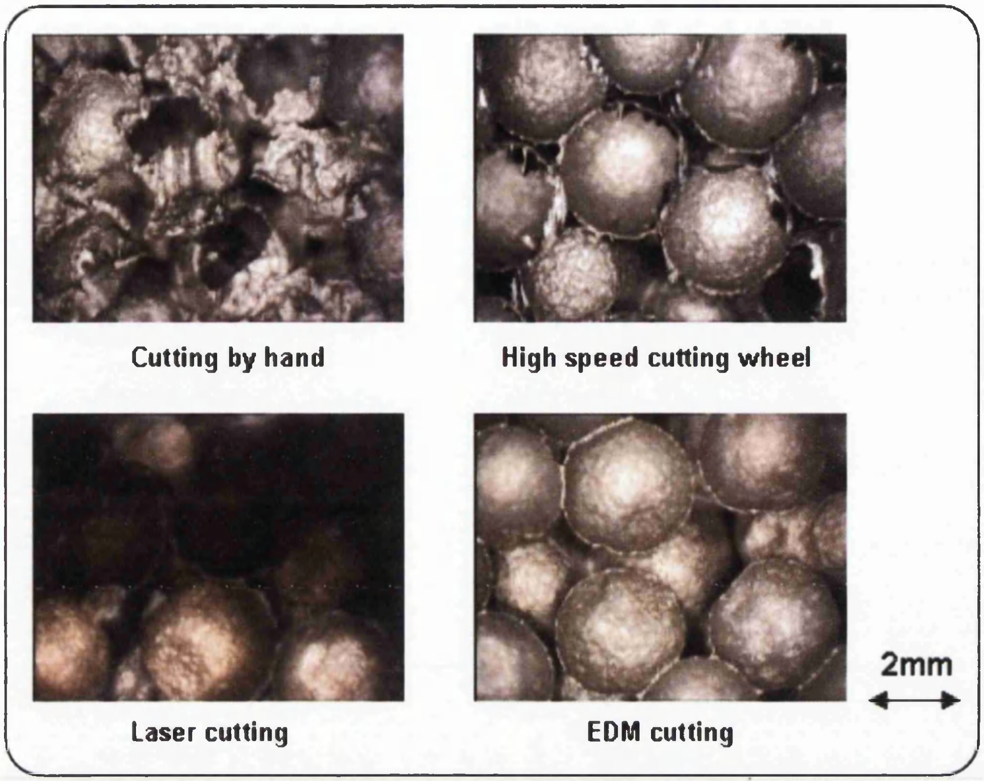

Figure 97. Metallic foam structures following sectioning, using a range of cutting techniques.

The structures shown in Figure 97 display varying degrees of smearing and/or melting, as a result of the sectioning processes. EDM cutting resulted in minimal structural deformation with no significant material smearing or melting observed.

Ideally, under the action of an incurring blade tip a metallic foam compressor seal would deform plastically, producing an effective gas seal without creating debris. The deformation mechanisms of a number of metallic foam materials were studied in a simple laboratory experiment, in which specimens were locally compressed, using a Rockwell hardness indenter. Figure 98 shows the structure of the stainless steel, hollow metal spheres following deformation.

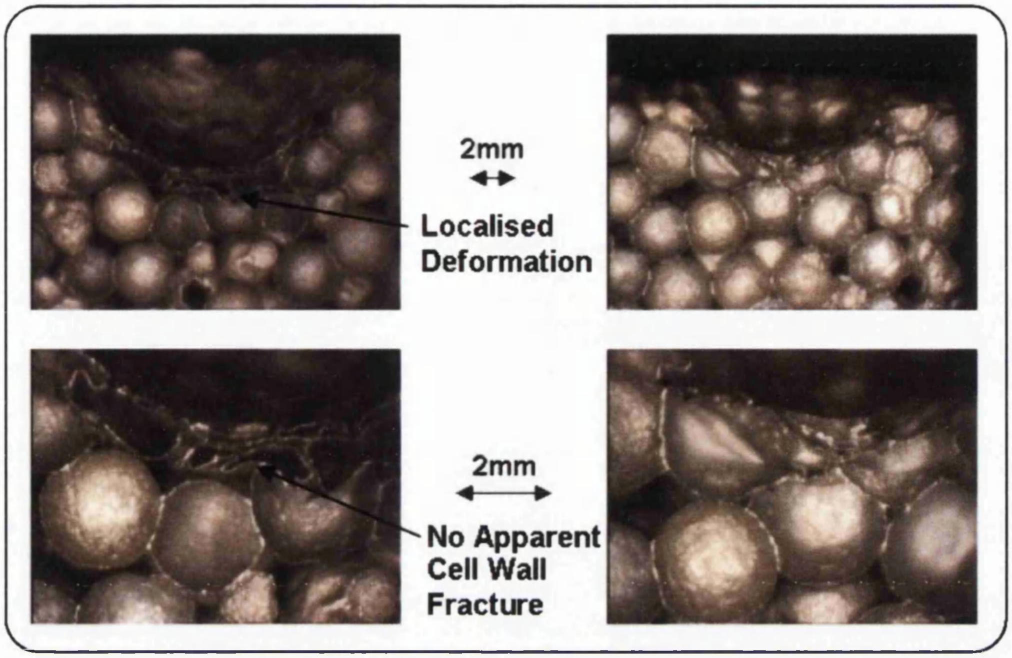

Figure 98. Rockwell hardness indentation evaluation of compressive deformation

Deformation within the hollow metal sphere structure is highly localised about the area of compaction. The hollow spheres immediately adjacent to the indentation have plastically deformed in order to absorb the majority of the load applied. There is no evidence of cell wall fracture or material loss.

A similar investigation was also carried out on open cell, nickel structure foams, which had been manufactured using the metal deposit onto cellular precursor method. Unlike the hollow metal spheres, the ligaments of these nickel structures were unable to plastically deform under the compressive loads of the hardness indenter, resulting in material fracture.

In addition to test piece sectioning it is extremely useful to have the ability to examine the internal structure of a metallic foam material, without the possibility of damage during machining operations. CT scanning equipment produces a 3-dimensional image of the structure of a body by compiling x-ray images, taken at a series of depths throughout the thickness of a body. Figure 99 provides a CT image of a hollow metal sphere specimen.

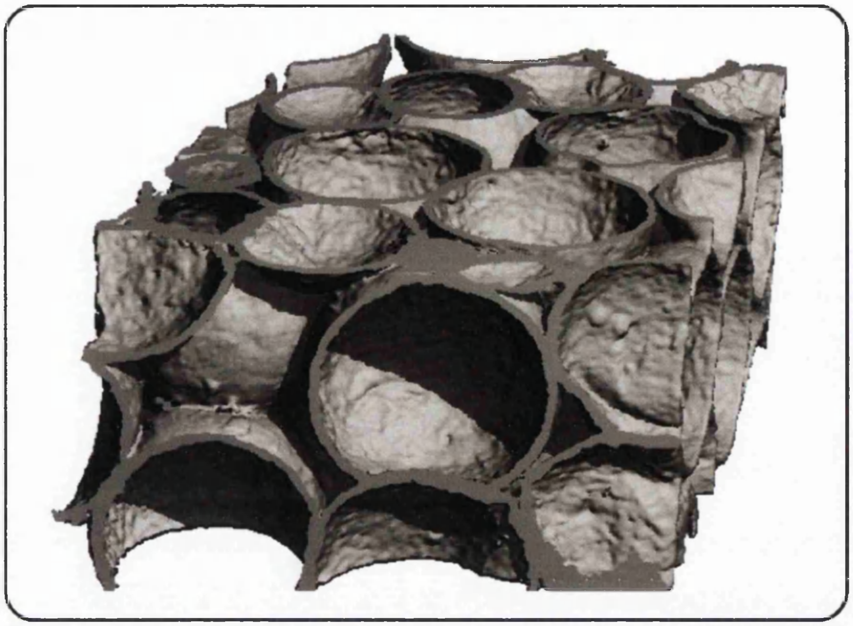

Figure 99. 3-dimensional CT image of hollow metal sphere structure

CT equipment was also used to analyse deformation characteristics following Rockwell indentation, as shown in Figure 99. The CT image provides an excellent visual interpretation of material deformation, also allowing pore size and cell wall thickness to be calculated.

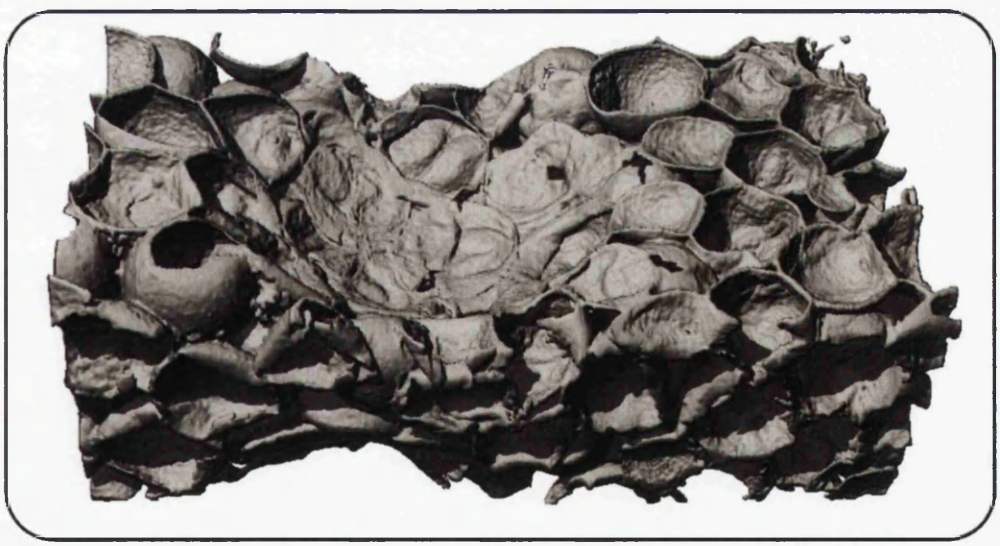

Figure 100. CT image of hollow metal sphere structure following Rockwell hardness compaction assessment

Where necessary this type of CT analysis will be used to analyse the rub track morphology of abradability test pieces in order to understand the abradability mechanisms associated with various foam structures and abradability conditions.

5.56 Technology Review of Metallic Foams – Conclusions

From the initial technology of metallic foam materials, their manufacturing methodology and potential attachment methods, it is clear that there is no current 'off the shelf' solution to satisfy the system requirements of a compressor sealing material. However, a number of potential process routes are evident and material properties exist, which could be tailored in order to achieve the material property and operating requirements of metallic foams.

As part of the ACET Programme Rolls-Royce, with consultation from metallic foam specialists at Nottingham University, will be discussing with the Fraunhofer Institute the potential material development of a small number of candidate systems. The Institute has extensive experience of metallic foams and their manufacture, in addition to numerous links to industrial partners, with the capacity for full scale and volume production.

Metallic foams form an extremely new technology area, therefore substantiation of manufacturing readiness must form a critical part of a development/approval process (Branhart *et al* 1999). Many of the material structures reported in literature are in very early stages of development or have specific and/or specialist end-users.

A number of joining techniques are available for the attachment of metallic foam materials to rotor path shroud components. The options evaluated include mechanical fastening, adhesive bonding, brazing and welding.

Most reviewed literature has reported work associated with aluminium foams for use in non-aerospace applications. However, work on other foamed material, for example stainless steel or nickel foams, has not been developed to the same extent. Hence development activities will of necessity have to be more comprehensive to exploit the full potential of these materials. A more detailed study of possible attachment methodology will now be carried out, focusing upon selected candidate systems.

The Fraunhofer Institutes, IFAM and IWU in Germany have been developing a number of different foam and porous metal manufacturing routes for over ten years. Of these processes the hollow metal spheres, produced via coating polymer balls with metal powder in suspension and then sintering, together with open cell aluminium structures produced with the addition of a foaming agent into the melt, are the most mature in terms of manufacturing capacity and material property data (Andersen *et al* 2000). Processes like direct printing and fibre metallurgy are also within the Fraunhofer portfolio but as yet do not offer comparable levels for manufacturing control and/or capability. As a world leader in metallic foam technology, and with strategic relationships with manufacturing facilities, Fraunhofer have the capability to provide a wide range of materials and processing expertise. It is anticipated that Fraunhofer will provide metallic foam material and property data on a contract basis under a specific non-disclosure agreement, in order to protect IPR generated during the ACET Programme.

Clearly there are still a number of gaps in current understanding, with respect to clearance control performance of metallic foam materials. It is therefore not possible to move forward with a single candidate system. Development strategy will therefore focus upon stainless steel metal hollow spheres, with a fallback alternative materials type, which will be defined following the completion of abradability screening trials.

5.6 Abradables Blueprint of Understanding

Together with ongoing research programmes the definition of performance drivers discussed in this section has enabled an understanding of abradable coating materials and their characteristics. It is therefore essential to capture this knowledge in an effective format for future abradable development.

The Abradables Blueprint of Understanding Document (Sellars and Hopkins 2005) summarises the requirements of compressor abradables, based on experimental findings and service experience, gathered from current state-of-the-art systems. The document is updated regularly to provide an accurate design guide or 'blueprint' for the future development of robust abradable coating materials.

Ultimately, the performance and stability of the abradable system is dictated by the coating structure and variability within the manufacturing process, also over the service life of a coating due to environmental effects. In addition to highlighting the advantages, limitations and possible improvements of current abradables, key design considerations for establishing functional and robust abradable systems for the future during manufacture and service are defined within the Abradables Blueprint of Understanding (Sellars and Hopkins 2005).

6 Implementation of Technology

Previous sections have discussed the generation of property data and the influence of key properties and characteristics upon the performance of an abradable system. It seems pertinent to consider the control of process variables, which influence the properties of coating materials and ensure their performance over their subsequent service life.

Thermal spraying is a highly dynamic process which, due to the large number of process parameters, is often difficult to control in a robust manner (Pfender 1999). Variability within a final coating structure, and therefore properties, can often be the result of a number of powder, equipment and process inconsistencies.

In an effort to produce abradable coating materials with optimised structural and property characteristics and minimum variability it is essential to determine the relationships between material properties and process parameters (Herman and Sampath 1994).

6.1 Metco 320 Spray Process Optimisation

A number of in-service failures of Metco 320 compressor rotor path abradable coatings have highlighted the need to reduce variability within the manufacturing process. Investigations concluded that failures were largely due to the poor thermal fatigue resistance of coatings, resulting in cracking and ultimately coating loss. The potential exists for this type of failure to have enormous effects on the performance and efficiency of an engine, due to the increased clearance gap size between compressor blade tip and rotor path (Bendon 1989). This thermally induced failure is caused by a mismatch in the coefficients of thermal expansion of the abradable coating and the shroud (substrate) material as discussed in Section 3.2.

It is apparent that some Metco 320 coatings show a higher propensity than others to crack, due to the aforementioned thermal stresses. However, reasons why this unfavourable coating variability occurs remain unclear.

The plasma spray process used to manufacture Metco 320 abradable coatings is extremely complex and the resulting coating properties are highly sensitive to the spray parameters used (Pfender 1999). In an attempt to reduce the in-service coating variability, it is essential to gain a fundamental understanding of the relationships between spray parameters and coating properties and to supply this information to new manufacture and overhaul facilities for the spraying of Metco 320 abradable coatings.

6.1.1 Metco 320 Spray Process Optimisation - Introduction

Around the world there are numerous new manufacture and overhaul spray facilities producing Metco 320 abradable coatings. The guidelines for spray parameters and manufacturing procedures for spraying Metco 320 are provided through the Sulzer Metco Service Bulletin. Although this document is designed to assist spray facilities in the manufacturing of Metco 320 coatings, it only provides recommended spray parameters. This means that spray facilities often use different parameters in order to achieve a coating to Rolls-Royce CME 5033 quality specification (Rolls-Royce 1994). Unfortunately the current CME standard allows a considerable amount of microstructural and mechanical coating variation.

To investigate relationships between the spray parameters used in the manufacture of Metco 320 and the structure and properties of the coating material, a Design of Experiment (DOE) has been carried out using a suite of mechanical, thermal and microstructural test methods. These were selected to focus upon specific structure characteristics and material properties, which are believed to influence the integrity of Metco 320 abradable coatings, with particular emphasis upon the thermal shock resistance of the material. The investigation considered the spray parameters of two plasma spray guns currently used by manufacturing facilities and overhaul bases to manufacture Metco 320 abradable coatings.

6.1.2 Metco 320 Spray Process Optimisation – Experimental Design

A DOE factorial design was used to evaluate the spray parameters of two plasma spray guns currently used by manufacturing facilities and overhaul bases for Metco 320 compressor abradable coating. Through consultation with Sulzer Metco and plasma spraying experts at Rolls-Royce, key parameters were selected, which are believed to be influential in the production of abradable coatings for both the Sulzer Metco 9M and the F4 plasma gun types. Upper and lower limits were then selected, all of which were within Rolls-Royce specifications. This type of investigation is designed to highlight the key spray parameters and their individual and combined influence on coating integrity. Although similar, there are a number of key differences between the guns, which means it is essential to divide the study and to look at gun specific parameter sets.

Tables 16 and 17 indicate the spray parameters, which were varied during the experiment, together with the relevant upper and lower limits for 9M and F4 gun types respectively.

Table 16. 9M Spray parameters varied with respective limits

Parameter	**Lower Limit**	**Upper Limit**
Powder feed rate (lb/h)	6	8
Primary gas flow (SCFH)	190.8	233.2
Secondary gas flow (SCFH)	10	20
Spray distance (ins)	4	6
Current (Amps)	400	600
Injector angle	Port 1	Port 2
Carrier gas (l/min)	6	10
Injection spray rate	Single	Dual

Table 17. F4 Spray parameters varied with respective limits

Parameter	**Lower Limit**	**Upper Limit**
Powder feed rate (lb/h)	6	8
Primary gas flow (SLPM)	63	77
Secondary gas flow (SLPM)	5	15
Spray distance (ins)	4	6
Current (Amps)	400	600
Nozzle size (mm)	6	8
Injector angle (°)	15	90
Carrier gas (l/min)	6	10
Injection spray rate	Single	Dual

All other spray parameters were kept constant and within Service Bulletin and Rolls-Royce specifications throughout the spraying programme. Log sheets were supplied to Sulzer Metco along with the specimen substrates to ensure that any variations in spray procedure or significant irregularities were recorded

MiniTab software was used for each gun parameter set to construct a spray matrix in order to investigate the influence of each parameter on the integrity of Metco 320. Each matrix contained 2 dulicates of 16 parameters.

Test piece spraying was carried out at the Sulzer Metco research facility in Westbury, New York. For the mechanical, thermal and microstructural analysis three specimens were sprayed using each parameter set; two specimens measuring 76mm x 25mm x 3mm and one specimen 40mm x 10mm x 1.2mm. Specimens were sprayed using a rotating stage in order to mimic the spraying of rotor path shroud components. All specimens were sprayed using a single batch of Metco 320 powder, (batch number 330651) to a thickness of at least 1.5mm.

To understand relationships between spraying parameters, microstructural characteristics and the mechanical properties of the abradable material, a number of analysis techniques have been used as described below:

Hardness Testing

All of the test pieces produced in the spray DOE were hardness tested using a Rockwell (R15Y) superficial hardness tester, providing results which measured coating strength. Hardness is also the principal control method for manufacture. Metco 320 coatings should be sprayed within a hardness range of 45-70 R15Y according to Rolls-Royce (1994) quality documents and the Sulzer Metco service bulletin.

Thermal Shock Testing

The Thermal Shock Test method discussed in Section 4.1 was used to evaluate the thermal fatigue resistance of the DOE test pieces. A thermal shock test piece measuring 12mm x 24mm x 3.5mm was sectioned from each specimen set and the coating slab milled to a uniform thickness of 1mm.

Microscope images at x12 magnification were taken of all thermal shock test pieces, following 15 thermal shock cycles. Figure 101 provides the image of an F4 specimen, taken in order to evaluate the amount of thermally induced cracking.

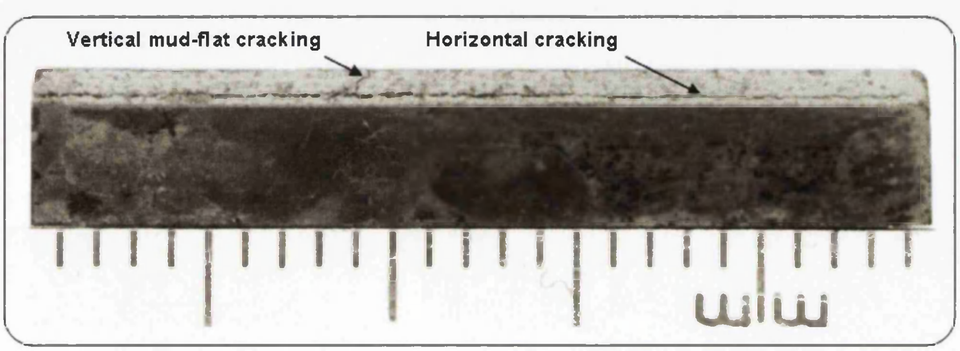

Figure 101. Metco 320 thermal shock test piece sprayed using F4 plasma system

Due to the objective nature of this test and the large number of test pieces within the study, the evaluation of thermal fatigue cracking provided a simple ranking of the coatings.

Microstructural Analysis

Image analysis software was used to analyse various microstructural features from the DOE test pieces. Digital Backscattered Electron (BSE) images were used to accurately quantify the various coating constituents. From each specimen set 3 images were captured at 100X magnification. In an attempt to identify possible weakening characteristics within the structure the amount and size distribution of the dislocator phase hexagonal boron nitride (hBN) was evaluated.

The hBN is a soft synthetic platelet material with properties similar to those of graphite. hBN is included to increase the abradability of Metco 320. During spaying, the hBN particles degrade and fragment to varying degrees, depending upon the intensity and velocity of the plasma. This phenomenon could be a primary factor in the variability of the coating properties.

Image analysis was used to quantify both the total amount of hBN and the size distribution of the hBN particles within the microstructure of each specimen set. All image analysis was carried out by Rolls-Royce, using the Image Pro software package.

6.13 Metco 320 Spray Process Optimisation – Results

The spray DOE matrices for the 9M and F4 plasma sprayed test pieces are shown in Tables 18 and 19 respectively.

Table 18. DOE spray matrix for Metco 320 test pieces spayed with 9M plasma sprayed system

Specimen No.	Powder Feed Rate	Primary Gas Flow	Secondary Gas Flow	Spray Distance	Current	Injection Angle	Carrier Gas	Injection Spray Rate
1	8	190.8	10	6	600	Port 1	10	single
2	8	190.8	20	4	600	Port 1	6	dual
3	8	233.2	10	4	600	Port 2	6	single
4	8	190.8	20	6	400	Port 2	6	single
5	6	233.2	20	4	400	Port 2	6	dual
6	8	233.2	20	4	400	Port 1	10	single
7	8	190.8	10	4	400	Port 2	10	dual
9	8	190.8	20	4	600	Port 1	6	dual
10	6	190.8	20	4	600	Port 2	10	single
11	8	233.2	10	6	400	Port 1	6	dual
12	6	190.8	10	6	600	Port 2	6	dual
13	6	233.2	10	6	400	Port 2	10	single
14	6	190.8	10	4	400	Port 1	6	single
15	8	190.8	20	6	400	Port 2	6	single
16	8	190.8	10	6	600	Port 1	10	single
17	8	233.2	10	6	400	Port 1	6	dual
18	6	190.8	20	4	600	Port 2	10	single
19	6	190.8	10	4	400	Port 1	6	single
20	6	233.2	20	6	600	Port 1	6	single
21	6	190.8	20	6	400	Port 1	10	dual
22	8	233.2	20	6	600	Port 2	10	dual
23	6	233.2	10	4	600	Port 1	10	dual
24	8	233.2	20	4	400	Port 1	10	single
25	6	233.2	20	4	400	Port 2	6	dual
26	8	233.2	10	4	600	Port 2	6	single
27	6	190.8	10	6	600	Port 2	6	dual
28	8	190.8	10	4	400	Port 2	10	dual
29	6	233.2	10	6	400	Port 2	10	single
30	6	190.8	20	6	400	Port 1	10	dual
31	8	233.2	20	6	600	Port 2	10	dual
32	6	233.2	10	4	600	Port 1	10	dual

Table 19. DOE spray matrix for Metco 320 test pieces spayed with F4 plasma sprayed system

Specimen No.	Powder Feed Rate	Primary Gas Flow	Secondary Gas Flow	Spray Distance	Current	Nozzle Size	Injection Angle	Carrier Gas	Injection Spray Rate
33	8	63	15	6	400	6	90	6	single
34	6	77	15	4	400	6	90	10	dual
35	8	77	5	6	400	6	15	10	single
36	6	63	15	4	600	8	90	6	single
37	6	63	15	4	600	8	90	6	single
38	8	63	15	6	400	6	90	6	single
39	8	77	5	4	400	8	90	6	dual
40	6	77	5	6	600	6	90	6	dual
41	6	63	5	6	400	8	90	10	single
42	6	63	15	6	600	6	15	10	dual
43	8	63	5	4	600	6	90	10	single
44	8	77	5	4	400	8	90	6	dual
45	8	77	5	6	400	6	15	10	single
46	6	77	5	6	600	6	90	6	dual
47	6	77	5	4	600	8	15	10	single
48	8	63	5	6	600	8	15	6	dual
49	6	77	15	6	400	8	15	6	single
50	8	77	15	6	600	8	90	10	dual
51	6	63	15	6	600	6	15	10	dual
52	6	77	15	4	400	6	90	10	dual
53	8	63	5	4	600	6	90	10	single
54	8	63	5	6	600	8	15	6	dual
55	8	77	15	6	600	8	90	10	dual
56	6	77	5	4	600	8	15	10	single
57	6	63	5	6	400	8	90	10	single
58	8	63	15	4	400	8	15	10	dual
59	6	77	15	6	400	8	15	6	single
60	8	77	15	4	600	6	15	6	single
61	8	63	15	4	400	8	15	10	dual
62	6	63	5	4	400	6	15	6	dual
63	6	63	5	4	400	6	15	6	dual
64	8	77	15	4	600	6	15	6	single

Hardness Testing

The results of the Rockwell hardness tests for the 9M and F4 specimens are shown in Figure 102. 70% of the 9M specimens attained the 45-70 R15Y Rolls-Royce hardness range, whereby only 53% of the F4 specimens achieved this specification limit. Specimens 4, 15, 39, 41, 50 and 55 could not be hardness tested due to insufficient coating thickness caused by nozzle build-up and/or blockage during spraying.

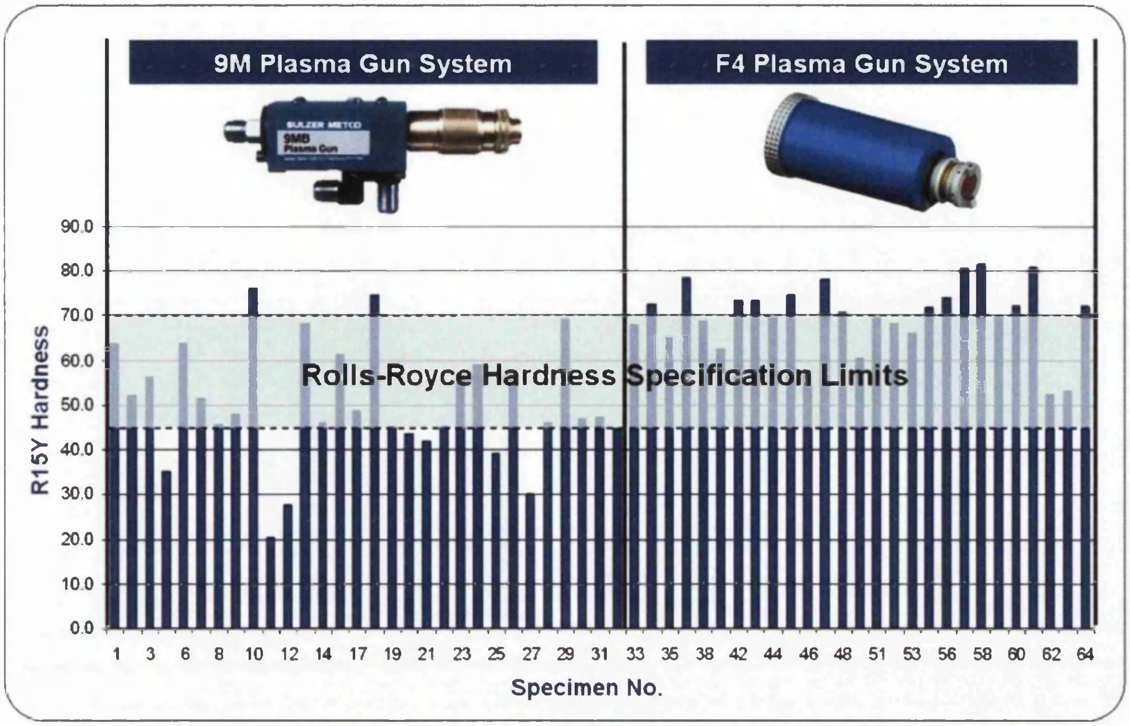

Figure 102. R15Y hardness measurements for 9M and F4 test pieces

There is clearly degree of variability, particularly within the 9M specimens, as a result of changing spray parameters. However, the 9M specimens had a larger hardness range of 58 R15 Y points compared to the less variable 29.2 R15 Y points of the F4 gun. These results suggest that, although the 9M is more likely to produce a coating within specification limits over a range of spray parameters, if controlled correctly the F4 plasma system provides a potentially more robust structure.

Thermal Shock Testing

Following optical analysis of the thermal shock test pieces after 15 thermal cycles there was a clear range of thermal shock resistance over the DOE test pieces. While some revealed no signs of thermal shock cracking, a number of test pieces displayed almost complete delamination and vertical 'mud-flat' cracking from the surface to the bond coat interface.

As shown in Figure 103, test pieces sprayed using the F4 plasma system displayed the worst thermal shock resistance, with both horizontal and vertical cracking. The worst performing 9M test pieces showed significant horizontal cracking although no vertical cracking was identified.

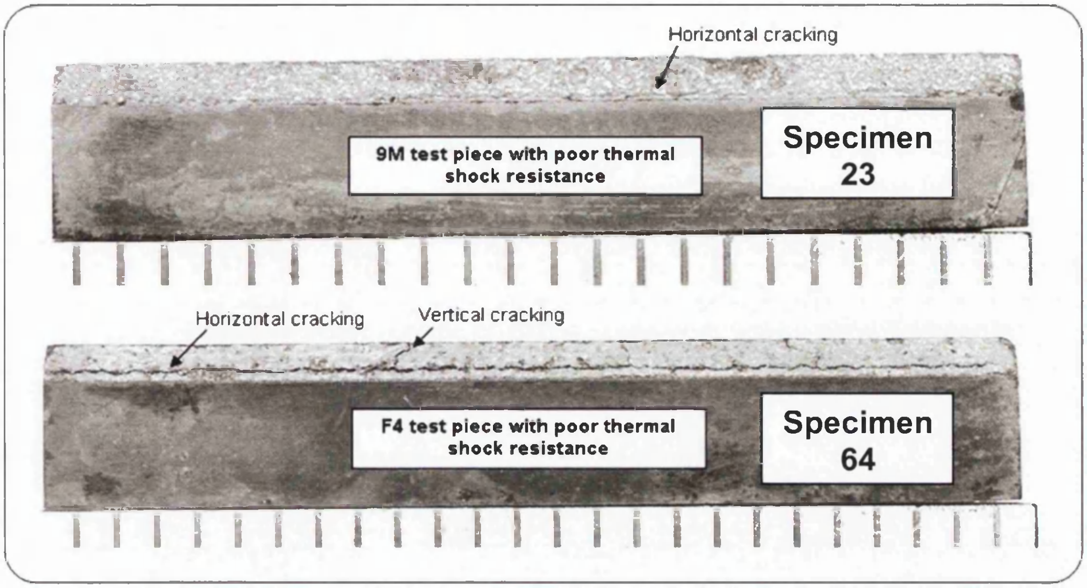

Figure 103. Example of the worst effective F4 and 9M thermal shock test pieces

Thermal shock test pieces sprayed using both the 9M and F4 plasma systems were ranked according to the amount of thermally induced cracking observed.

As a ranking these results have limited use in terms of providing the necessary information for generating a fundamental understanding of spray parameter – coating property relationships. The thermal shock ranking results for the 9M and F4 plasma systems are shown in Table 20. Test piece ranking is arranged in order, relative to the amount of cracking observed, with a ranking of 1 for least cracking.

Table 20. Thermal shock ranking from observations of cracking for both 9M and F4 test pieces

9M Specimens	
Specimen Number	Thermal Shock Ranking
31	1
23	2
30	3
5	4
2	5
12	6
24	7
11	8
7	9
6	10
29	11
13	12
10	13
9	14
1	15
25	16
20	17
17	18
21	19
28	20
26	21
22	22
3	23
18	24
32	25
27	26
19	27
14	28
16	29

F4 Specimens	
Specimen Number	Thermal Shock Ranking
51	1
42	2
45	3
40	4
44	5
61	6
35	7
43	8
63	9
58	10
48	11
33	12
53	13
54	14
57	15
56	16
59	17
52	18
49	19
62	20
46	21
47	22
34	23
38	24
64	24
60	25

Microstructural Analysis

Image analysis was used to calculate the total amount of hBN for the microstructures of all DOE test pieces. In order to evaluate the amount of hBN fragmentation, the number of hBN particles less than 150μm^2 (the hBN_{150} Value) was also quantified. Electron microscope images were converted into black and white for accurate measurement of the various phases within the structure, as illustrated in Figure 104.

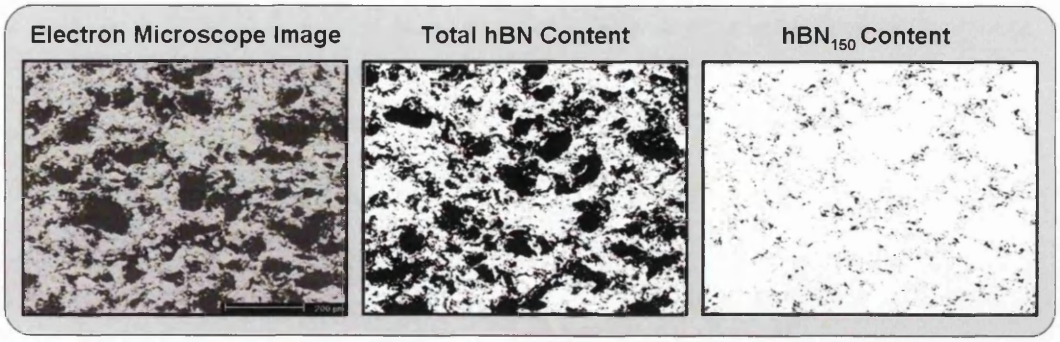

Figure 104. Image analysis of electron microscope image in order to quantify total hBN content and hBN_{150} values

Correlations between the thermal shock ranking results and the hBN measurements from image analysis of the Metco 320 microstructures were investigated. Figure 105 classes the thermal shock of 9M and F4 specimens into the 25% of specimens with the best thermal shock resistance, the mid-range specimens and the lower 25% of those with the worst thermal shock resistance.

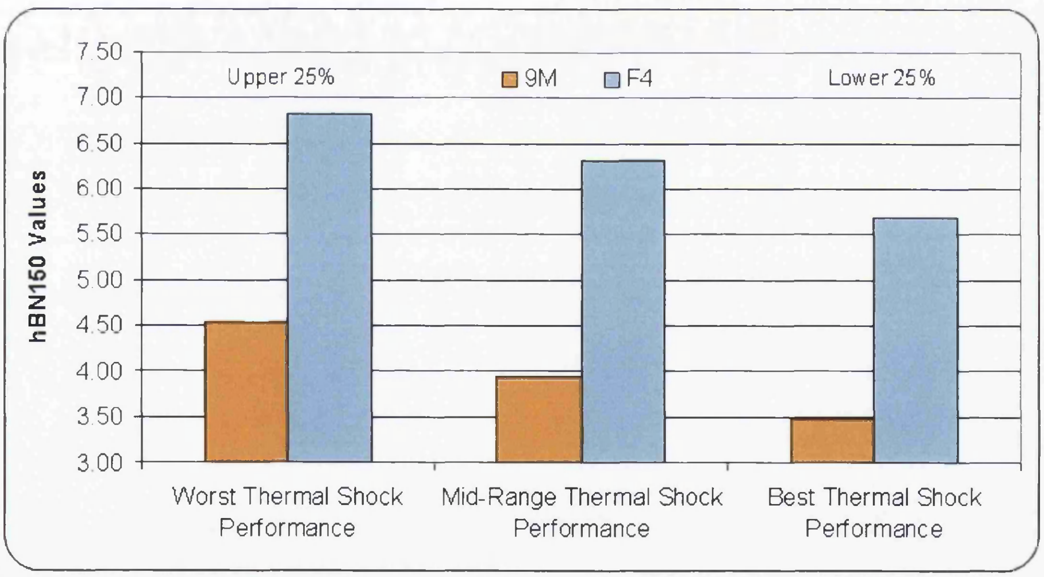

Figure 105. Thermal shock performance of 9M and F4 test pieces against hBN150 values

From Figure 65 it is clear that, as hBN_{150} values increase, there is a trend towards lower thermal shock resistance for both the 9M and F4 systems. It is also apparent that coatings produced using the F4 plasma system contain much more fragmented hBN (a higher hBN_{150} value) particles than the 9M sprayed materials.

6.14 Metco 320 Spray Process Optimisation – Discussion

An investigation of the influence of sprayed parameter variability on the thermal shock resistance of Metco 320 used two spray matrices to evaluate the 9M and F4 plasma sprayed systems. Coating test pieces produced were assessed for coating hardness, microstructural characteristics and thermal shock resistance.

The 9M plasma test pieces 4 and 15, and F4 test pieces 39, 41, 50 and 55 could not be manufactured, due to nozzle build-up and/or blockage during spraying. This was probably due to the combination of high powder feed rates and low energy plasma flames, resulting in a build up of powder at the gun nozzles.

Hardness Testing

The R15Y hardness results measured for all test pieces successfully manufactured are shown in Figure 62, highlighting the degree of property variability that results from the spray parameter changes. From these results it is clear that significant changes occur in the microstructure of Metco 320, which influence the mechanical properties of the coating material as a result of the manufacturing process. Coating property variability was also evident following evaluation of the thermal shock test pieces. Some test pieces showed no signs of cracking after 15 cycles, whereas a number of 9M, and to a great extent F4, test pieces showed extensive cracking.

Thermal Shock Testing

Despite the subjective nature of the thermal shock ranking, a correlation between thermal shock resistance and hBN_{150} values is shown in Figure 65. Thermal shock resistance is significantly reduced as the amount of fine hBN particles within the microstructure increases.

Microstructural Analysis

Large soft hBN particles are designed to improve the abradability performance of Metco 320. However, as the hBN degrades and fragments during thermal spraying, the resultant microstructure contains a percentage of finer hBN particles. These become dispersed throughout the Al-Si matrix, providing low energy pathways for crack propagation.

This is an important key process variable, however, while image analysis provides a useful research technique, it is not a realistic method for process control at manufacture. In order to improve the manufacturing control of Metco 320 coatings, sprayed at new manufacturing and at overhaul facilities, it is necessary to understand the relationship between hBN characteristics and coating hardness.

Figure 106 illustrates the relationship between R15Y hardness and the total amount of hBN within the 9M plasma-sprayed Metco 320 coatings.

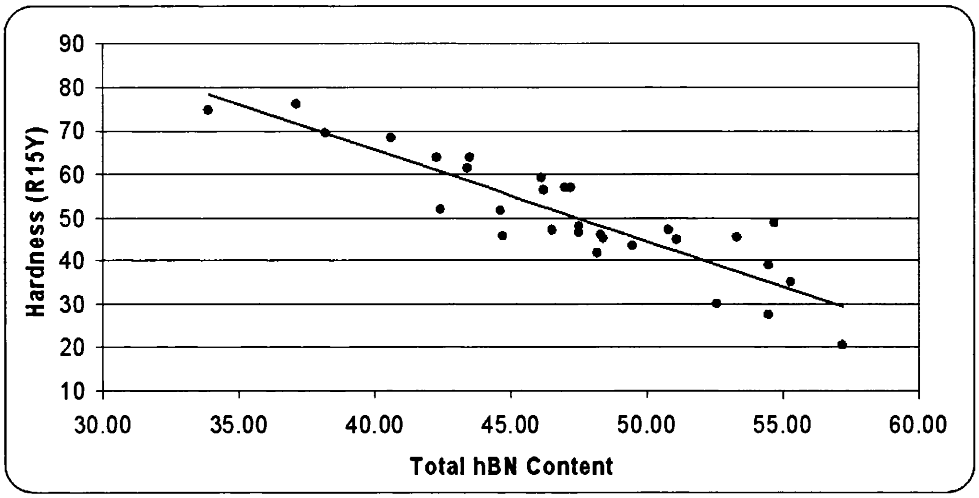

Figure 106. Plot showing relationship between total hBN content and R15Y hardness for coatings produced using 9M plasma system

The relationship between coating hardness and hBN content is a result of the extremely low strength of hBN. A similarly strong correlation was also observed for the F4 test pieces.

Figure 107 shows a plot of coating hardness against hBN150 values for coatings produced using the F4 plasma system.

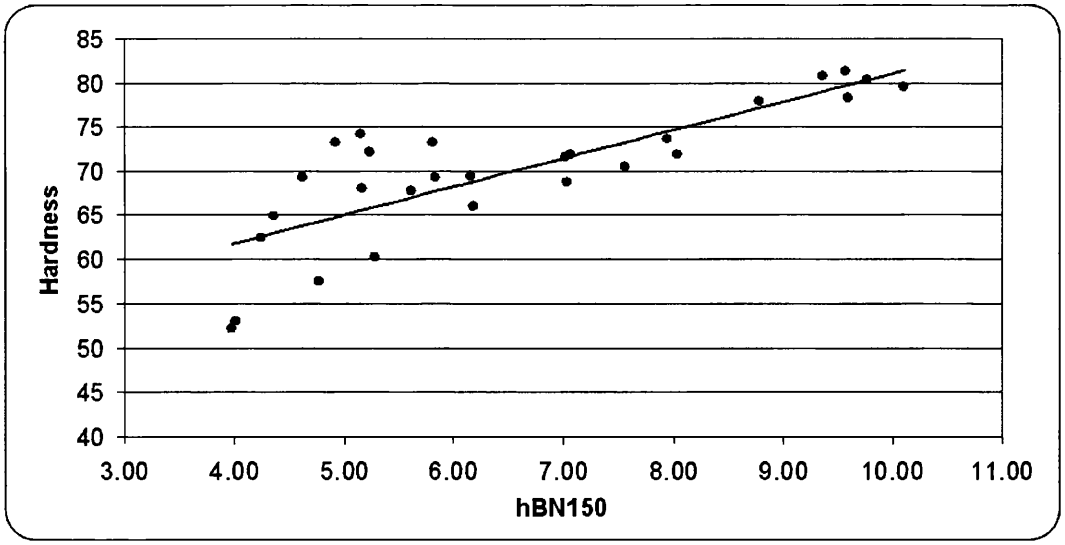

Figure 107. Plot of relationship between hBN_{150} values and R15Y hardness for coatings produced using F4 plasma system

In this case, once again there is a strong correlation between hardness and the hBN_{150} values of Metco 320 coatings. This result is important in understanding the way in which the fundamentals of the plasma spraying process influence the structural integrity of the coating material.

Metco 320 powder is an agglomerate system. Each powder agglomerate contains a particle of Al-Si matrix material, and a particle of hBN dislocator, held together by an organic binder, which in the case of Metco 320 is self cross-linking acrylic latex (Sulzer Metco 2006). The binder is necessary to protect the hBN from degradation at high temperature, which leads to hBN particle fragmentation.

The extreme temperatures of the plasma flame means that a certain amount of binder is burnt out during spraying, leading to some hBN degradation. The degree of binder burnout and subsequent hBN degradation is dependent upon a combination of spray factors, including the temperature of the plasma, the amount of powder within the plasma, and the time the powder spends in the plasma before reaching the substrate material.

The correlation between hBN150 and coating hardness indicated in Figure 107, and also displayed by the 9M test pieces, is a result of the inability of the thermal spray process to effectively contain fine or light particles. As hBN fragments during spraying, some of the finer particles will become deflected by the high-velocity plasma and not captured within the coating during deposition. As a result, as hBN150 values increase, the total amount of hBN within the coating is reduced, as indicated in Figure 108.

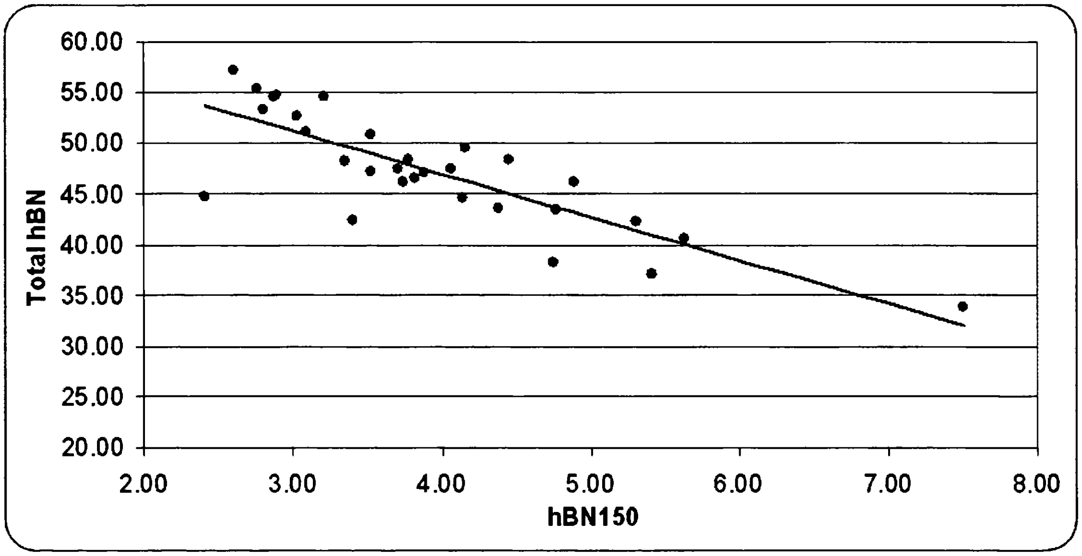

Figure 108. Plot showing the relationship between total hBN and hBN150 values for coating produced using the 9M plasma system

Linear regression was used in generated formulae to describe the relationship between coating hardness and hBN150 values for the 9M and F4 systems. For the 9M plasma gun system it can be recognised that the relationship between hardness and hBN_{150} obeys the following relationship:

$$hBN_{150} = 0.07H + 0.64 \qquad \text{Equation 6}$$

This regressive technique was then applied to the specimens sprayed using the F4 plasma system. The relationship between hardness and hBN150 was shown to obey the following formula:

$$hBN_{150} = 0.20H - 7.78 \qquad \text{Equation 7}$$

Equations 6 and 7 hold true for as sprayed Metco 320, due to the softening effects of binder burnout and silicon precipitation during time at temperature. As binder content will change following time at service temperature, these formulae cannot be applied to engine run coatings.

Spray Parameter Investigation

In order to assess the effects of the spray parameters shown in Tables 1 and 2 on the coating integrity of Metco 320, the data gathered from the microstructural assessment of the fine hBN particles and hardness tests was used with the Minitab software as measures of coating integrity.

The output results (hBN150 values and R15 Y hardness results) were investigated individually for both the 9M and F4 plasma guns. Following identification of the key parameter, a combined model can then be produced, which provides a gun specific parameter set for optimum coating integrity.

Pareto charts were used to identify the key parameters from those investigated, with respect to the R15Y hardness test results. An important term is one in which the average response at the low and high settings are significantly different. The Pareto charts in Figure 109 indicate the 1st and 2nd order spray parameter interactions for the R15 Y hardness results of both the 9M and F4 plasma gun systems.

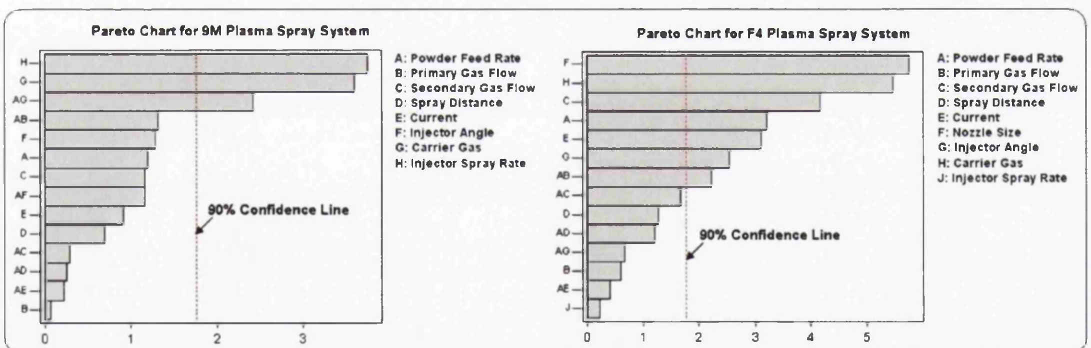

Figure 109. Pareto charts showing 1st and 2nd order parameter interactions, which influence coating hardness

The Pareto charts in Figure 109 indicate that a number of 1st and 2nd order parameter relationships fall below the 90% confidence line, and are therefore not statistically significant. By progressively removing these 1st and 2nd order interactions it is possible to focus upon the parameters, which are statistically significant. Figure 110 shows the modified Pareto charts for the statistically significant 1st and 2nd order parameter interactions for the R25 Y hardness results of both the 9M and F4 plasma gun systems. The 9M gun type appears to have significantly less statistically significant parameters than the F4. Although current actually sits slightly below the 90% confidence line, it was decided to include the parameter in the model, as it is believed to be an important factor, with a strong influence on flame intensity.

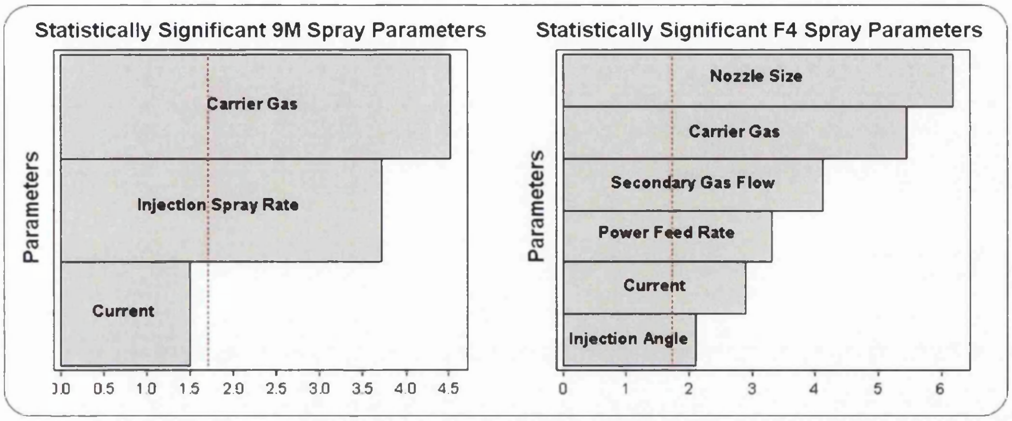

Figure 110. Modified Pareto charts showing statistically significant 9M and F4 spay parameters in relation to coating hardness

These key parameters can be used to fine tune Metco 320 coating hardness in order to achieve the Rolls-Royce quality specification limits of 45-70 R15Y and also to reduce the amount of fine hBN within the coating structure.

6.15 Metco 320 Spray Process Optimisation – Conclusions

From the thermal, mechanical and microstructural assessment of Metco 320 abradable coatings produced in the DOE study, a number of important, spray parameter coating property relationships have been identified. These will provide the foundations for future source control activities of Metco 320 abradable coatings covered by current and new manufacturing facilities.

From the DOE study of Metco 320 coatings sprayed using the 9M and F4 plasma systems, the following relationships have been identified between spray parameters and coating properties:

- The hardness of Metco 320 coatings produced using the 9M plasma gun system are more sensitive to spray parameter variations than coatings produced using the F4 system. This suggests that the F4 system offers a more robust manufacturing method than the 9M system, although the F4 system has been shown to produce harder coatings, which often display poor thermal shock resistance.

- The hardness of Metco 320 coatings is strongly influenced by the total amount of hBN dislocator phase within the coating. The greater the total hBN content the lower the hardness of the coating. As the total amount of hBN increases the amount of fine hBN particles (particles less than 150μm^2) decreases.

- The hBN150 values of as sprayed Metco 320 can be estimated using gun specific formulae, generated using linear regression techniques, from hardness measurement of the coating.

- It is believed that a dispersion of fine hBN throughout the Al-Si matrix material of Metco 320 creates low-energy pathways for crack propagation under the effects of thermal stress. Minimising fine hBN particles (<150μm^2) improves the thermal shock resistance of Metco 320 coatings.

- In addition to the coating hardness and amount of fine hBN particles, there are other factors, which influence the thermal shock resistance of Metco 320 abradable coatings. It is possible that these include splat boundary oxidation and residual stresses within coating materials following spraying.

From the detailed study of the coatings produced it is clear that with both the 9M and F4 plasma systems, both are sensitive to small parameter variations. In order to ensure the integrity of the coating produced using these systems it is therefore essential to carry out a robust source control approval on all new manufacturing facilities.

At present a validation programme is being carried out, which investigates the thermal shock resistance of Metco 320 coatings produced at a number of overhaul facilities around the world. Coating evaluation will be carried out on test pieces sprayed alongside engine components in order to gain representative results. Coating material will be assessed against key criteria, designed to focus upon the important performance drivers identified in this study, in efforts to improve coating thermal shock resistance and process variability.

6.2 Hardness Measurement Study

A wide range of coating evaluation techniques have been developed for investigating material properties and coating performance criteria. Most of these are unavailable or impractical for use at manufacturing facilities. As a result, these facilities rely solely on R15Y hardness measurements to evaluate the properties of an abradable coating. Hardness limits are specified for each coating, designed to ensure the material is structurally and compositionally sound.

Hardness testing provides a quick and simple measure of coating integrity, adopted from traditional combustion sprayed coatings, where hardness has been shown to provide a good indication of porosity. However, there are concerns that coating hardness provides a less robust measure of the material and structural characteristics for more complex, multiphase, fully dense, plasma coatings systems. Of particular concern is the process variability associated with R15Y hardness testing of abradable coating materials. Rolls-Royce hardness limits are typically generous, allowing a wide range of coating hardness.

6.21 Hardness Measurement Study – Introduction

The Rockwell R15Y test uses a ½″ diameter steel ball to indent the coating material. A hardness measurement is taken over a substantial area of material, which is essential in obtaining hardness values from heterogeneous materials like abradable coatings. The hardness value is obtained from the depth change following the loading of the steel sphere from a small preliminary force up to 15N as shown in Figure 111. Each Rockwell hardness point corresponds to a depth of 0.002mm. Rolls-Royce specifications require the preparation of an abradable surface prior to hardness testing in order to reduce as-sprayed surface roughness.

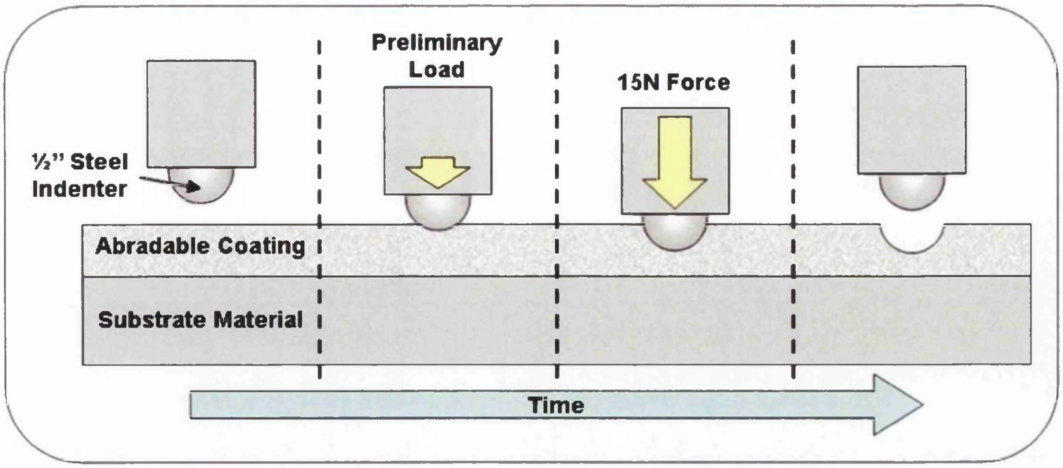

Figure 111. Rockwell (R15Y) hardness

A Gauge Reproducibility and Repeatability study, or Gauge R&R study, was carried out to investigate the process variability associated with the R15Y hardness measurement of Metco 320 abradable coatings. A Gauge R&R study provides statistical variability information for both batch-to-batch and cross facility data.

6.22 Hardness Measurement Study – Experimental Design

Metco 320 test pieces were sprayed using Rolls-Royce standard parameters at MPS in Nottingham. Six test pieces were in a single spray and coated to a thickness of 2mm on a rotating stage in order to mimic the spraying of a compressor rotor path shroud. Following spraying, each test piece was sectioned into three and labelled 1, 2 and 3.

Six sets of specimens 1, 2 and 3 were then sent to six overhaul facilities all of which currently spray Metco 320 abradable coatings. Each facility was requested to measure the hardness of test pieces, using their standard R15Y measuring processes. The facilities were not informed of the as-sprayed hardness of the coatings, or that all coatings were sprayed simultaneously. In addition each facility was asked to supply a microstructural image of test piece 1.

6.23 Hardness Measurement Study – Results

MPS sprayed six Metco 320 test pieces and measured a hardness of 55 R15Y. This value is not included within the Gauge R&R study and does not necessarily represent the 'true' coating hardness. However, it is reasonable to assume that all the test pieces produced have a consistent hardness and coating structure.

Hardness measurements were taken from each test piece prior to dispatch to overhaul facilities to ensure consistency. A hardness value of 57 R15Y was recorded.

Table 21 shows all the R15Y hardness measurements of test pieces 1, 2 and 3 from the six overhaul facilities.

Table 21. R15Y hardness measurements of Metco 320 test pieces from overhaul facilities

Specimen Set	Facility Name	Test Piece	1	2	3	4	5	6	7	8	9	10	Av. Hardness
A	MTU Hannover	1	42	38	40	44	44	48	44	43	44	44	**43.1**
		2	38	42	45	47	44	40	47	47	45	46	**44.1**
		3	42	40	46	45	51	49	50	51	49	48	**47.1**
B	Lufthansa Technik	1	45	47	47	43							**45.5**
		2	50	50	50	52							**50.5**
		3	55	51	52	50							**52.0**
C	IHI Mizuho	1	52.4	49.5	47.5	48.5	51	52.8	50	49.2	50	50.2	**50.1**
		2	55	54	52	54	51.8	52.5	52.5	56	54.2	55	**53.7**
		3	50.8	50.2	53	53.8	54.4	54	55	54	55.5	53	**53.4**
D	MTU Zuhai	1	35	43.4	40.5	34.6	38.8						**38.5**
		2	38.9	39.1	42.3	38.6	38.2						**39.4**
		3	42	36.4	38	47.3	40.3						**40.8**
E	East Kilbride	1	57.8	52.2	54.8	55.6	60.3	55.8					**56.1**
		2	58.3	56.5	56	57.3	57.4	57					**57.1**
		3	53.9	54.1	51.6	53.6	55.7	52.8					**53.6**
F	Pratt and Whitney	1	22	23	37	37	46						**33.0**
		2	42	41	39	30	44						**39.2**
		3	34	48	47	32	24						**37.0**

Figure 112 shows a box plot of hardness results, gathered from each facility for direct comparison of average hardness values, together with batch-to-batch variability.

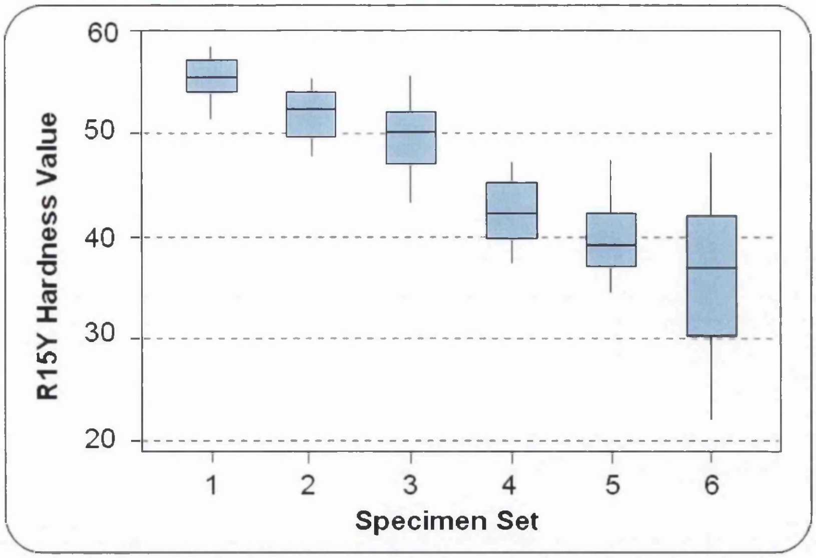

Figure 112. Box plot of R15Y hardness data showing batch and facility variability

The hardness results generated by each overhaul facility were used with Minitab software to calculate the statistical variability of hardness measurements.

The process indicates that the variance in Metco 320 coating hardness is approximately 20% for a single coating, tested by an individual operator. Overhaul facilities at East Kilbride, IHI Mizuho and MTU Hannover showed the least amount of process variability. The variability in hardness measurement on the same coating between the different overhaul facilities is 75%. However, the Gauge R&R results indicate that some operators displayed more variability than others.

Pratt and Whitney hardness results demonstrated significantly more variability than the other facilities. Following inspection of the test pieces it was found that hardness measurements had been obtained from unprepared coating surfaces. The as-sprayed coating surface has macro-roughness, which places a significant influence on the apparent superficial hardness of the coating.

6.24 Hardness Measurement Study – Discussion

The results of the Gauge R&R study shown above highlight a wide range of process variability associated with the R15Y hardness measurement of abradable coating materials. In addition to test-to-test variance observed at a single facility, a considerable amount of cross facility variance was recognised. Clearly, within the hardness measurement of a single abradable coating, there are a number of potential sources of process variability:

Surface Preparation

Rolls-Royce quality specification requires that abradable coatings are prepared using a 120-220 Grit grinding paper. If surface preparation is either not carried out or insufficient, surface roughness can have a significant influence on the apparent supeficial coating hardness.

Hardness Testing

Prior to testing, a calibration hardness test should be carried out on a calibration block of known hardness. At least five R15Y hardness tests should be carried out on a flat abradable test piece. Indents should be no less than 1.5x diameter apart.

Hardness Calculation

Due to the heterogeneous nature of an abradable coating structure, an average hardness should be calculated from the 5 hardness readings. Metco 320 coating hardness is required to be between average limits of 45-70 R15Y, with no single value outside a range of 40-80.

The Gauge R&R results indicated that the Pratt and Whitney facility produced the largest test-to-test variance, together with the lowest average R15Y hardness value. Following inspection of the test pieces it was found that hardness measurements had been taken from unprepared coating surfaces. The 'as-sprayed' coating surface has macro-roughness, contributing to low and variable hardness readings.

Results from other overhaul facilities showed comparable variance, although there was significant variability between facilities. Assuming that other facilities carried out correct surface preparation, significant process variability results from differences between equipment and test operators. For a process to be robust it is essential that influences of inconsistencies in test apparatus or operator do not occur.

6.25 Hardness Measurement Study - Conclusions

A Gauge R&R study was carried out to investigate the process variability associated with the R15Y hardness measurement of abradable coatings. Six overhaul facilities took part in the investigation, which evaluated the variability of Metco 320 coating materials sprayed in a single sprayed run at MPS in Nottingham. All of these coatings were assumed to be of the same hardness, structure and composition.

The Gauge R&R results indicate a variance of approximately 20% in Metco 320 coating hardness for a single coating, tested by an individual facility. This result is influenced by the considerable amount of variance observed at the Pratt and Whitney facility. East Kilbride, IHI Mizuho and MTU Hannover overhaul facilities reflected the least amount of process variability.

The variability between the different overhaul facilities in Metco 320 hardness measurements on the same coating is 75%. However, the Gauge R&R results indicate that some operators displayed more variability than others with the Pratt and Whitney facility producing a significantly lower average hardness value.

Evaluation of the Pratt and Whitey test pieces concluded that surface preparation of the coating material had not been carried out prior to hardness testing.

The Metco 320 hardness data discussed within the Gauge R&R study has highlighted the sensitivity of the R15Y hardness testing of abradable coatings. In addition to variance resulting from process non-conformance, including insufficient coating surface preparation, it is clear that significant variability exists within the results, due to equipment and operator inconsistencies.

R15Y hardness testing is currently the principal measure of coating conformance. There is evidence that the process is not robust and as a result, generates significant batch-to-batch and cross facility variability. As abradable coatings become more compositionally and structurally complex, there is need for a more accurate measure of coating integrity with less inherent variability. Alternative and modified coating test methods are currently being investigated for the source control of abradable coating materials.

Hardness testing with a 3/4" diameter ball has been shown to reduce batch-to-batch hardness results, although there is no evidence to indicate that this also reduced cross facility variance. Scratch testing is an alternative assessment technique for coating materials and correlations have been shown to exist between hardness and scratch test data.

Scratch testing could provide a more consistent property measurement technique for heterogeneous coating structures as it provides a measure of properties across the coating surfaces rather than at multiple point measurements (Bull *et al* 1988). However, interpretation of scratch test results is more involved and currently requires specialist software.

In the short term, R15Y hardness data from this study is being used as part of a Source Control Programme, aimed at reducing the variability of manufacture of Metco 320 abradable coatings at both new manufacture and overhaul facilities.

6.3 Abradables Database of Knowledge – Learning From Experience

Understanding the influence of spray parameters and process variables on the performance of abradable coatings is reliant upon information gathered from service experience and failure investigations. It is therefore necessary to have systems in place for effectively capturing this knowledge in a useful and efficient manner.

The Abradables Database of Knowledge (ADK) is a web-based knowledge management system, developed for storing useful coating property and specification information in addition to service experience data. The ADK is globally accessible to all Rolls-Royce employees via the Rolls-Royce intranet.

6.31 Abradables Database of Knowledge – Overview

Figure 113 provides a screen shot of the ADK and highlights a number of key features associated with the system.

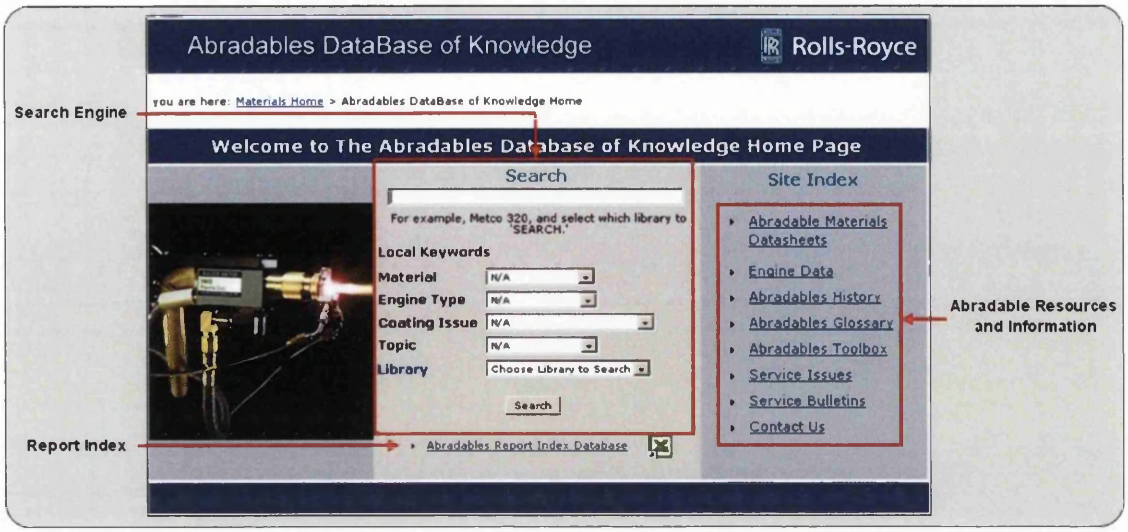

Figure 113. Screen-shot of Abradables Database of Knowledge

Central to the ADK is The Search Engine, which allows users to search all pages containing a keyword or related to specific categories. This provides easy access to a range of coating materials and engine experience data. All data contained within the database of knowledge is cross referenced with papers and literature, which are stored in the Report Index.

The Report Index is an Excel based, filing system containing over 400 documents. These include internal and external reports and papers relating to abradable coatings, their manufacture and specific service issues or development programmes. The Report Index is also searchable via a series of predefined categories.

Other resources accessible via the Site Index, as shown in Figure 113, are as follows:

Abradable Materials Datasheets

Materials Datasheets contain all property data for the current suite of abradable coatings. This includes materials property data generated via the Freestanding Coating Process.

Engine Data

For quick reference, all abradable – blade and fin material combinations are listed for the large civil engines. Additional operational envelope data highlights blade tip and a' data for normal operation.

Abradables History

This provides an overview of abradable technologies and material and process developments over the past 35 years. Limitations of past and present abradable systems are highlighted in relation to specific service issues.

Abradables Glossary

This is a glossary of commonly used abradable terminology with definitions and, where necessary, examples of use.

Abradables Toolbox

The Toolbox contains a number of useful applications and equations, including those discussed in this thesis for calculating various parameters and material properties. For example, an a' Calculator determines a' values for specific engine stages and RPM's. The application also calculates equivalent incursion rate for a number of Abradability Facilities, including the Alstom and Innotec rigs.

Service Issues

As a reference database, information generated from extensive service experience is stored within the ADK. Service returns are shown, along with key service and coating data like the Metco 320 coating shown in Figure 114, which displays thermal fatigue cracking following 4420 cycles.

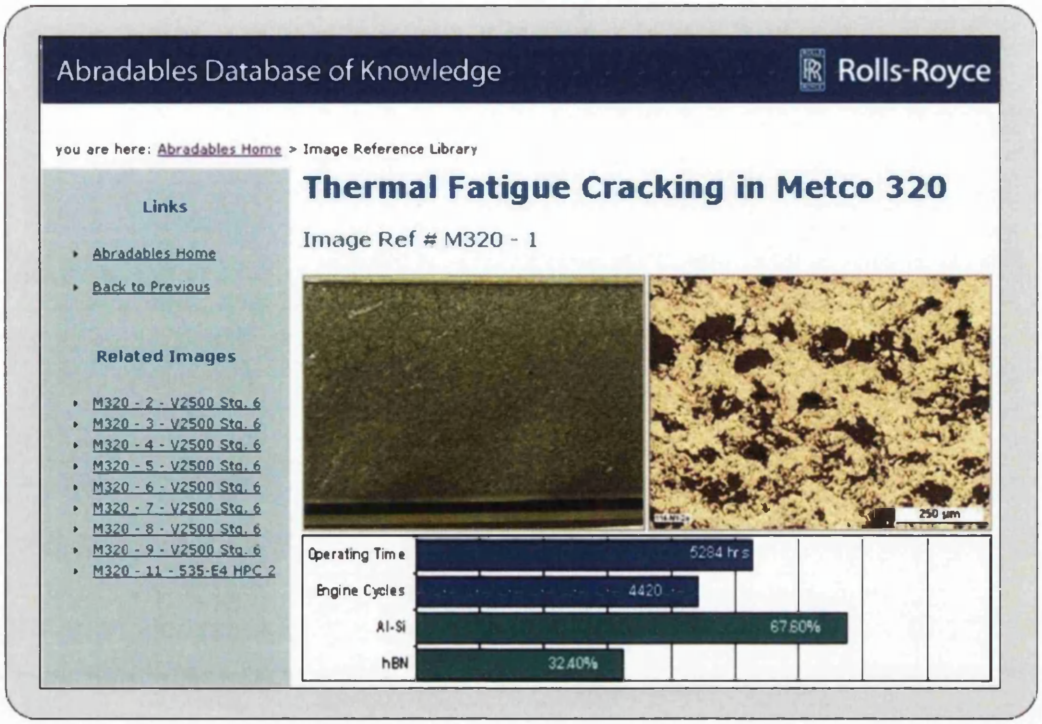

Figure 114. Service experience stored on the Abradables Database of Knowledge

Service Bulletins

Production parameters, powder composition and material property data are contained within coating Service Bulletins. These documents are produced by coating manufacturers as reference for spray facilities at new manufacturing and overhaul.

6.32 Abradables Database of Knowledge – Conclusions

The ADK provides a powerful resource for Rolls-Royce coatings engineers and designers around the world. The search facilities allow access to a range of coating property data and service experience in an effective manner.

The usefulness of any database is clearly dependent upon ensuring that the all information is maintained, up to date and accurate. As new materials property data is generated using methodology that includes the Freestanding Coating Process, relevant information will be added to the database. An ongoing programme in collaboration with Rolls-Royce overhaul in Derby allows service experience to be effectively captured within the database.

The ADK is now being used as a template for all coating technologies within the Surface Engineering Group at Rolls-Royce and has led to the development of web-based databases for thermal barrier and wear resistant coatings.

7. Discussion

The purpose of research carried out within this EngD programme was to generate a fundamental understanding of abradable materials by focusing upon key topic areas that are required in order to understand the material properties, performance drivers and manufacturing control of abradable coatings. Within these topic areas, packages of work have been carried out, which apply materials science to a technology area that has traditionally been regarded as a 'black art'.

7.1 Discussion – Development of New Test Methodology

Historically, abradable coating materials have been regarded as extremely brittle, low-strength materials (Zheng, 2004). A limited range of test methodology has restricted the detailed understanding of abradable systems and a more fundamental understanding of their properties and characteristics. In the absence of accurate property data, the development of abradable coating systems has resulted from incremental improvements and modifications, as opposed to informed design, based upon accurate coating property data.

Within this EngD programme a number of projects have been undertaken, aimed at generating accurate material properties and coating performance data. A range of new test processes and techniques has also been developed to provide more reliable property and coating characteristics. A range of state-of-the art test facilities have subsequently provided significant coating performance data in support of new coating development.

The Freestanding Coating Process (Section 4.2) has been developed during this EngD programme to provide a technique for the accurate generation of representative coating property data. Initial work has focused upon tensile testing at ambient temperature. Stress verses strain plots of Metco 320 abradable test pieces, as shown in Figure 36, indicate that the failure mode is progressive as opposed to purely brittle. This is an important result, which could influence ways in which future abradable materials are analysed and critically modelled.

The progressive failure mode is indicated by a non-linear (or non-elastic) stress/strain plot. These results indicate that the abradable material undergoes permanent (or plastic) damage under extremely low loads. It is possible to quantify the amount of plastic deformation within a material by generating a hysteresis plot under a cyclic tensile load. In order to better understand the failure mechanism associated with an abradable coating under a tensile load it is useful to consider the microstructure of these materials.

The structure of Metco 320 abradable coatings was investigated within initial Freestanding Coating testing, revealing an Al-Si matrix phase, within which are randomly distributed particles of hBN (Sulzer Metco 2006). The extremely low-strength and highly lubricious properties of hBN indicate that it is reasonable to assume that it is the hBN phases within the material, which plastically deform first (Ooi *et al* 2006). The interfaces between hBN particles and the Al-Si matrix, together with adjacent Al-Si, containing oxide layers and micro-porosity, form a network of weakening planes within the material structure. It is these interfaces which fail ahead of any transgranular crack formation within the Al-Si matrix.

Further analysis of the fracture mechanics of abradable materials is necessary to fully understand these unique progressive failures. It is clear from the results of initial Freestanding Coating testing that thermal or mechanical tensile loading on an abradable, even at low stress levels, will induce damage and significantly lower the coating's strength. This concurs with service and laboratory test experience where cracking has been shown to result from thermal fatigue, due to the relatively small loads created by the mismatch in the coefficients of thermal expansion between the abradable coating and substrate materials (Roth-F 2002).

The material property data discussed above indicates that the functionality of an abradable seal is dependent upon a degree of inherent weakness to ensure adequate abradability performance (Zheng 2004). Sufficient structural integrity is also necessary for the system to withstand the thermal, mechanical and environmental conditions of a gas turbine compressor. Further Freestanding Coating testing will be required to develop a better understanding of the complex behaviour of abradable coating materials under a range of representative operational conditions. Details of this proposed work are discussed in Section 9.1.

7.2 Discussion – Definition of Performance Drivers

The complex abradability mechanics of a number of abradable systems have been investigated within this EngD programme. A number of specialised abradability facilities have been used to evaluate the abradability performance under various engine representative conditions. To ensure that the correct facilities were selected for these test programmes, an Abradability Rig Strategy has been developed to assess the commercially available abradability facilities, aligning the most capable against the business and technical requirements of Rolls-Royce. These facilities have been used to produce accurate and representative abradability data, which has provided a detailed understanding of a range of abradability mechanisms associated with the current suite of abradable coating materials.

The Schmid (1997) model of abradability is the most widely accepted description of how an ideal abradable should perform under the action of an incurring compressor blade. Analysis carried out within this EngD programme has shown that in all but a very small number of abradability conditions, the current range of abradables do not perform in this way.

Aluminium based abradables, including Metco 320, have been observed to melt and transfer to compressor blade tips as a result of excessive frictional heating during low incursion rate rubs. Section 5.1 discussed an investigation into the propensity of Metco 320 to pick-up on a blade tip as a result of the amount of residual organic binder within the coating, which follows spraying under low incursion rate rubs. In severe cases, pick-up of abradable material on a blade tip can open up tip clearances, which can result in an engine stall and/or hung-start (Binden 1989). Service experience has also shown that gramophone grooving is evident on coatings within the first 50 engine cycles.

The cross-linking acrylic latex binder material within Metco 320 is designed to hold Al-Si and hBN particles together during the spray process (Sulzer Metco 2006); however, the binder has no known benefits to the functionality of Metco 320 abradable coating during service. Residual binder is thought to burn out over extended time at operational temperatures.

To investigate the influence of binder content abradability performance of Metco 320, abradability testing was carried out using the Sulzer Innotec high-temperature abradability facility. Metco 320 test pieces were heat treated to burn out the residual binder for comparison with 'as sprayed' coating material.

For Metco 320 to melt or significantly soften during service, rub temperatures need to approach the melting point of the Al+8%Si matrix material of 614°C. This is significantly higher than the maximum operating temperature of 450°C, which represents maximum hot day take-off temperature. Additional heating at low incursion rates is the result of inefficient cutting or abradability, which generates frictional heating at the contact between blade tip and abradable surface.

The abradability investigation focused upon low incursion rate and dwell rubs, similar to the conditions associated with the climb phase of a flight cycle. Pick-up and gramophone grooving were successfully generated on the Sulzer Innotec rig tests.

Video footage of the tests indicated that the melting and transfer of the abradable material generated a cyclic abradability condition. This suggests that, as the rub temperature approaches the melting point of the abradable, transfer takes place and in doing so, reduces the contact area between blade tip and abradable coating. This reduces frictional effects until the blade tip has re-established a coherent rub track, at which point heat accumulates once again.

The cyclic transfer of abradable material means that blade tip measurements following testing can contain large amounts of scatter. However, on all low incursion rate rub trials a reduction in the amount of pick-up on blade tips was observed for the heat treated coatings. The results of the dwell test abradability trials, where a zero incursion rate was used, were less conclusive but vibrations during testing may have resulted in these inconsistencies.

Although the binder material within Metco 320 is designed to assist during the spraying process, clearly there is an effect on abradability performance of the coating. The additional structural integrity produced by the binder, particularly in relation to the otherwise extremely low strength hBN particles, appears to reduce the coating's propensity to abrade under low incursion rate rubs.

Inherent variability within the thermal spray process results in a range of residual binder contents from coating-to-coating. A post-spray heat treatment could be used to reduce the amount of residual binder to a minimum; however this would increase the cost and time associated with producing new and overhauled parts. Further abradability testing is therefore required to validate this process for manufacture.

Organic binders, including the self cross-linking acrylic latex used in Metco 320, which is unstable at spray plume temperatures, will inevitably increase the variability of the coating properties. Where possible, alternative high-temperature binders or cladding techniques should be used to reduce this variability.

It is not only aluminium abradable coatings, which have been observed to transfer and pick-up as a result of frictional heating. The abradability assessment discussed in Section 5.2 investigated the abradability performance of nickel based, Hastelloy X feltmetal, which has been observed to melt and transfer to seal fin tips during service.

The Alstom Abradability Facility was used to carry out a range of abradability trials, aimed at establishing the operational conditions under which material transfer and pick-up occur. A further purpose of the trials was to gain an understanding of this wear-aggressive mechanism. Testing was carried out on engine shrouds using a 360° seal fin produced from thirty-six 10° seal segments, mounted onto a specially designed test rig disc. Additional tests were carried out using seal fins tipped with Praxair TPT406 abrasive coating, to evaluate the effectiveness of this system in reducing melting and transfer, resulting from high frictional heating.

Abradability testing focused on conditions within the operational envelope of the Trent 900 HP compressor seal fins. Tests were carried out at a range of incursion rates and fin tip speeds with rub loads and temperatures being measured during testing.

Seal fin wear and feltmetal melting, due to excessive frictional heat, was successfully generated at high incursion rate, high fin tip speed conditions. Pyrometer measurements from these tests indicated seal fin tip temperatures of approximately 1130°C. TPT406 tipped seal fins tested under these conditions were found to cut effectively with no significant frictional heating effects. As a result, TPT406 is currently being introduced on production engines in order to optimise sealing performance.

As a function of contact time, the frictional heating observed during high energy rub testing is thought to be highly dependent upon rub track length. This is an extemely significant theory, as the rub track within an engine can extend to a full 360° around the rotor path.

The abradability mechanism identified within the studies discussed above indicates that, for both aluminium and nickel systems, highly inefficient cutting can lead to excessive frictional heating during specific rub conditions. The influence of blade tip speed and incursion rate on the dominant abradability mechanism was also highlighted in Section 5.3, which discussed the results of abradability data from new nickel systems developed during the Seal Coat Programme (Chandler 2006).

All of the programmes discussed above have highlighted the need for a comprehensive abradability investigation, in order to determine all abradability mechanisms associated with the current range of abradable systems. The abradability investigation discussed in Section 5.4 investigated the abradability performance of different abradable material types over a range of abradability conditions.

All of the abradable coatings investigated within the abradability investigation displayed a number of abradability mechanisms, which were dependent upon both blade tip speed and incursion rate. From these observations and the load and temperature data generated during testing it is clear that the dominant mechanism of abradability is defined by a combination of thermal and mechanical attributes.

7.3 Discussion – Implementation of Technology

In addition to the advances made in understanding coating properties and performance characteristics, a number of packages of work have been carried out to investigate the relationship between coating properties and spray process parameters. There is evidence to indicate that key coating properties and structural characteristics can be strongly influenced by relatively modest changes to thermal spray parameters used during manufacture.

As the Freestanding Coating Process has shown (Section 4.9), abradable materials deform in a progressive failure mode under relatively low loads. These properties make abradable coatings highly susceptible to failure under moderately low stresses, which can occur due to the effects of both thermal and mechanical loads, generated within the engine.

Thermal fatigue cracking has been observed in service as a result of the stresses generated due to the mismatch in coefficients of thermal expansion between the coating and substrate materials. The DOE investigation discussed in Section 6.1 was used to define the key relationships between the spray parameters, coating properties and structural characteristics of Metco 320 abradable coating materials.

From the thermal, mechanical and microstructural assessment of Metco 320 abradable coatings, produced in the DOE study, a number of important spray parameter coating property relationships have been identified. In addition to standard R15Y hardness measurements taken from all the test pieces produced, image analysis software was successfully used to quantify the hBN of these characteristics. The Thermal Shock Test Method was used to evaluate the amount and severity of thermally induced cracking.

The DOE identified relationships between the amount and size distribution of hBN particles within the Al-Si coating matrix, coating hardness and the thermal shock resistance of the material. The hBN dislocator particles are designed to improve the abradability performance of the coating during service and results from the DOE revealed that hBN is also highly susceptible to failure, due to thermally induced stresses within the coating material.

During the spray process hBN particles degrade as a result of the extremely high temperature within the spray plume. The amount of degradation and resultant hBN particle breakdown is dependent upon a combination of particle duration and temperature in the plume, resulting from the spray parameters used.

Image analysis of the coating microstructures has identified that degraded hBN forms a fine despersion of weak particles distributed throughout the Al-Si coating matrix. These particles appear to provide low-energy pathways for crack propagation under an applied load and this failure mode is consistent with the progressive failure modes observed during Freestanding Coating Testing discussed in Section 4.2. The amount of fine hBN may also be established from the hardness of the coating, using regression calculations defined within this investigation.

To maximise the thermal fatigue properties of Metco 320 it is necessary to minimise hBN degradation during manufacture. To identify the statistically significant spray parameters responsible for producing fine hBN particles, Minitab software has been used.

A validation programme is currently being carried out to investigate the thermal shock resistance of Metco 320 coatings produced at a number of commercial overhaul facilities. Coating evaluation will be carried out on test pieces sprayed alongside engine components in order to gain representative results. Coating material will be assessed against key criteria, designed to focus upon the important performance drivers identified in this study, in efforts to improve coating thermal shock resistance and process variability.

Data generated from the work discussed above will provide a more robust manufacturing control. Current manufacturing criteria are based upon coating hardness, which as the Gauge R&R data discussed in Section 6.2 indicates, is a highly variable measure. The investigation highlights significant variability from batch-to-batch measurements and between different facilities.

To deal with the increasing demands of the compressor, as abradable systems become more complex it is essential that control limits and measurement techniques become more robust. Possible control procedures are currently under review and details of these are further discussed within Section 9.1.

A considerable amount of information is available from engine experience and it is essential that this information is captured and used effectively for future abradable development. The Abradables Database of Knowledge discussed in Section 6.3 is web-based and located on the Rolls-Royce intranet system. This provides an effective storage system for coating, engine and service experience data in a user-friendly and globally accessible system.

The usefulness of any database is clearly dependent on ensuring that all information is maintained and up to date. As new material property data is generated using methodology like the Freestanding Coating Process, it will be added to the database. An ongoing programme in collaboration with Rolls-Royce overhaul in Derby allows service experience to be captured within the database in an effecient and cost effective manner.

8. Conclusions

Abradable coating materials have been used within the compressor stages of gas turbine engines for over 35 years. Despite considerable service experience, expertise and fundamental materials knowledge within this field, technology remains limited.

Historically, abradable materials have been regarded as a 'black art' concept, due to the lack of accurate material property data, robust coating design and controlled manufacturing processes. Increasingly demanding targets within the aerospace industry, driven by high fuel prices and evermore-stringent authority environmental regulations, have increased the need for optimised compressor abradables.

Research carried out within this EngD programme has helped considerably in obtaining a fundamental understanding of abradable materials by focusing upon the following three key topic areas:

- iv) Development of Test Methodologies
- v) Definition of Performance Drivers
- vi) Implementation of Technology

Within these topic areas programmes of work have been carried out, aiming to fill gaps in current knowledge and to provide knowledge and techniques for future coating development. Significant advances have been made in all aspects of abradable understanding and the knowledge generated is now being successfully implemented within the Abradable Strategy of Rolls-Royce (Sellars 2005).

Critical to understanding the material systems at a fundamental level is the ability to generate accurate and representative property data and the Freestanding Coating Process has been developed for this purpose. By spraying onto dissolvable moulds, accurate coating test pieces can be created, which are then tested on standard laboratory equipment. As a generic coating technique, the Freestanding Coating Process has wide reaching capabilities with numerous possible applications.

The Schmid (1997) model of abradability provides the most widely accepted description of how an ideal abradable should perform under the action of an incurring compressor blade. Research carried out within this EngD programme has indicated that, in all but a very small number of abradability conditions, the current range of abradables does not perform according to this model, but fails in a more progressive ductile manner.

Abradability tests have been carried out on a range of abradable coatings, using the latest state-of-the-art test facilities, in addition to feltmetal systems, to understand their complex abradability behaviour under representative conditions. This generated knowledge will allow optimisation of current coatings and will be embodied in the design of the next generation of abradable systems.

Understanding the basic material properties and key performance drivers of an abradable system is clearly important but, without the ability to implement this knowledge at the manufacturing stage, this information is useless. Design of Experiments and Gauge R&R techniques have been used to investigate the influence of spray process parameters and to evaluate quality control sensitivity. This knowledge has been captured within Source Control documents and best practice specifications to ensure the robust manufacture of abradable systems at new manufacture and overhaul facilities.

Research within this EngD programme has generated important materials, and process capability knowledge aimed at supporting the current suite of abradable systems. In addition, strategic packages of work have focused upon the development of novel concept abradable solutions.

Metallic foam materials are currently being used for an increasing number of industrial applications, due to their unique combination of high energy absorbing, ultra-light weight properties. This work has provided the basis for a development programme, which will involve the testing and evaluation of bespoke metallic foams against key performance criteria, for use as abradable materials,

As the demands from regulators and airlines for greater aeroengine performance increase, the need for reliable and effective compressor sealing will become evermore critical. Further detailed understanding of the science of abradable materials should therefore be enabled by the knowledge and techniques developed within this EngD programme.

9 Future Work

The time restrictions of an EngD programme clearly limit the extent of possible research and this is particularly true in cases involving a relatively embryonic technology like abradable materials. The research carried out within this EngD project has focused upon generating a fundamental understanding of abradable materials by understanding their properties, performance drivers and manufacturing controls. Within the four year EngD programme considerable progress has been made within these key topic areas. There are now opportunities to further develop the understanding of abradable systems as a result of the test methods, knowledge and process optimisation developed within this programme.

9.1 Future Work – Investigation of Abradable Coating Properties

Significant advances in test methodology have provided a range of techniques, characterising key material properties. Most notably, the Freestanding Coating Process enables the accurate generation of representative material property data. Initial work has focused upon tensile testing at ambient temperatures. However, extensive opportunities now exist to use this process in investigating a range of material properties, all of which are important to the effective operation of an abradable coating in service.

Fatigue

Thermal fatigue, resulting from the mismatch in coefficients of thermal expansion between coating and substrate materials, can significantly degrade an abradable coating (Roth-F 2002). Increasingly, laboratory based Thermomechanical Fatigue (TMF) testing is being utilised in simulating the complete range of stresses generated during a flight cycle. Sophisticated test rigs are capable of simulating biaxial loading and dynamic temperature conditions within controlled environments (Castelli and Ellis 1992) and TMF testing of Freestanding Coating test pieces could provide a better understanding of the fatigue properties of abradable coating materials.

Erosion

Ensuring that an abradable coating has sufficient erosion resistance to withstand the aggressive environment of a modern gas turbine compressor is essential for effective clearance control. Although erosion resistance has traditionally been associated with coating hardness, there is evidence to indicate that other material properties, including toughness, are also significant.

Material toughness is defined by the amount of energy a volume of material can withstand prior to fracture. A number of standardised test procedures are available for evaluating material toughness, depending upon the loading conditions required, which are dependent upon the angle of impingement. In simplistic terms, low impingement angles produce shear failures whereas at 90° impingement the failures occur as a result of low material ductility.

An abradable coating sits directly within the gas stream of the compressor and is thus subjected to a barrage of abrasive particulates, ingested during engine operation (Tilly 1979). The resultant angle of impingement of the gas stream flow on the abradable is constantly varying as a result of rotating compressor blades and the engine's variable thrust. However, the use of fluid dynamics makes it possible to identify the predominant gas stream loading angle upon the abradable, which will thus define an important characteristic of the erosive process.

Freestanding Coating test pieces could be used to investigate the toughness properties of abradable coatings using standard test equipment at a range of operational temperatures. This investigation should provide quantitative property data, which will facilitate the development of new, erosion resistant, abradable materials, and an assessment of the influence of spray parameter variability on these properties.

Density

Historically, abradable coatings have been assessed at the manufacturing stage using the R15Y hardness test, which effectively provides a simplistic evaluation of the amount of porosity and/or dislocator within the coating metal matrix.

The latest generation of nickel based abradables are designed to produce an extremely soft coating, which is 'titanium friendly' and hence reduces the risk of a titanium fire event. Typically, the systems have an R15Y hardness value of around zero and there is therefore a risk that the traditional R15Y test does not provide sufficient sensitivity for approval of 'as manufactured', new formulation, abradable coatings.

It is possible to measure the density of a coating material and thus define the proportion of dislocator or porosity to metal matrix, using Freestanding Coating technology. A disk of abradable coating, sprayed alongside a manufactured part, could be produced using a specially designed Aquapour mould. By measuring the thickness of the disk for a known diameter and the disc mass, it would be possible to determine the density of the coating material as shown in Figure 115. In this way the 'Disk Density' measure could provide a simple alternative quality control technique for extremely soft abradables, where R15Y hardness is found to provide insufficient accuracy.

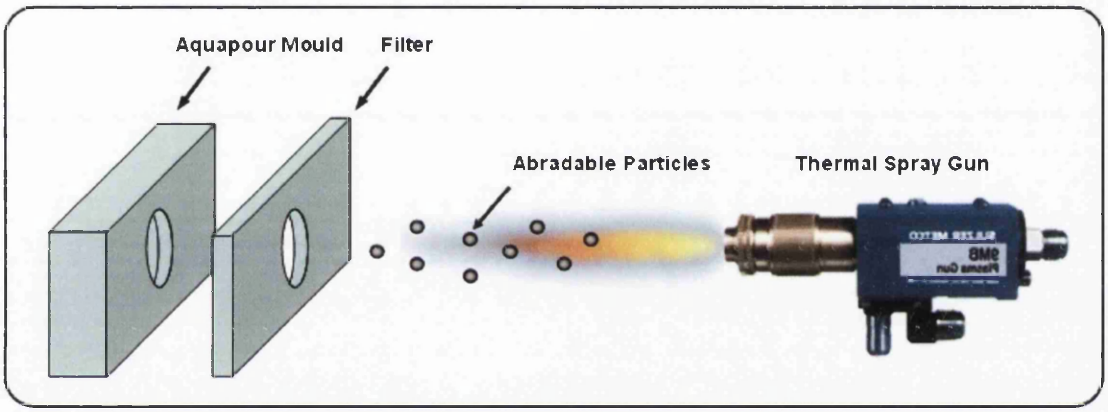

Figure 115. Equipment arrangement for disk diameter assessment

Clearly, substantial work would need to be carried out on the accuracy of this process to establish it as a quality control technique. This should include comparing the hardness and other key coating characteristics against measured coating density to ensure that the process is capable of providing the necessary sensitivity and robustness.

9.2 Future Work – Next Generation Abradable Materials

The work carried out on metallic foam materials discussed in Section 5.5 has highlighted the possibility of using these novel materials for compressor clearance control. However, there is scope for further development work in order to optimise existing material concepts for the specialised properties required of a compressor abradable.

Critically, the deformation mechanism of the metallic materials, following interaction with an incurring compressor blade, will define the effectiveness of the system during service. Techniques developed within this EngD programme enable detailed analysis of the internal structure of a metallic foam material to take place. By understanding the loading on the metallic materials under various abradability conditions, structural and compositional modification could be carried out in order to optimise the material.

In addition to the optimisation of pre-existing metallic foam materials is the concept of thermally sprayed foams. This material concept is at present in the very early stages of development and currently patented pending.

Powder cladding technology is well established and used to produce a range of composite powders for the thermal spraying market (Sporer and Hajmrle 2000). Techniques have also been developed for producing closed cell metallic foams by the introduction of a blowing agent into the melt to produce a gaseous phase during decomposition (Banhart 2005).

Powder particles could therefore be produced in which a blowing agent is clad with an appropriate metal shell so that during spraying the blowing agent degrades, producing areas of porosity within a metallic matrix. This would reduce material variability as a result of segregation during the spraying of different material densities.

The amount and size distribution of porosity within a foamed coating could be tailored by modification of the blowing agent particle size and the thickness of the metallic clad, in order to optimise abradability performance.

Further investigation is required to evaluate the variability produced during the spraying process, and the abradability performance of metallic foams produced in this way. In order to ring-fence this technology a patent for the use of thermally sprayed metallic foams has been filed for use in Europe and America.

9.3 Future Work – Abradable Repair Options

Total care packages or 'power by the hour' agreements, which have become standard within the aerospace industry, mean that it is now the responsibility of the engine manufacturer to ensure the engine is functioning correctly. As a result, the reliability, and where necessary, repairability of gas turbine components is an area of huge interest to Rolls-Royce and other engine manufacturers.

In recent years new repair techniques have been developed, which allow components to be serviced or repaired on-wing and Borescope holes can be used to access areas of the engine core. These are now being used for operations that include the dressing of damaged compressor blades in a process known as 'Boro-blending' or bonding lock-plugs in possition using 'Boro-bonding'.

Although abradable coating materials account for a fraction of the cost of some critical components, the costs associated with an unscheduled overhaul due to an abradable failure can be as much as £500K. Under a total care package agreement, these costs, which result from the time an aircraft spends on the ground during an engine or compressor module strip, must be met by the engine manufacturer.

At present there are no techniques for repairing compressor abradables in-situ and therefore, relatively minor damage can result in an unscheduled overhaul. Huge potential cost saving benefits have therefore become associated with robust repair options, which allow the repair of abradable coating damage.

High temperature adhesives or cements are stable at temperatures in excess of 1000°C. These materials are generally in the form of ceramic, composite based cements, and applied as a slurry containing ceramic powder and binder. These cements cure at ambient temperature to form a brittle structure, capable of bonding with most metallic surfaces.

It is possible that, by additions of dislocator particles like polyester, or for higher temperature applications graphite, will allow the ductility and critical abradability of ceramic cements to be dramatically improved. Such an 'Abradable Adhesive' could then be applied to areas of rotor path shroud, via a tube attached to a borescope probe, where abradable coating has been lost or damaged.

An evaluation of the abradability performance and erosion resistance of abradable glue would be necessary to ensure that additions of dislocator phases were sufficient to provide the necessary material properties. In order to ring-fence this technology a patent application has been filed in Europe and America.

9.4 Future Work – Conclusions

The work carried out within this EngD programme has enhanced the knowledge of abradable coating materials and provided a number of valuable techniques and processes for their evaluation and control. It is necessary to progress all areas of abradable research in efforts to develop more robust coatings and novel clearance control systems, whilst also controlling their manufacture.

The increasingly extreme operating conditions of a gas turbine engine bring about the inevitable need for a balance between the properties required to provide effective abradability performance and those needed to ensure the longevity of the system. Where unforeseen failures occur, for example due to damage from foreign objects ingested into an engine, on-wing repair options should be made available to mitigate against the need for unscheduled overhauls.

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