Table of Contents

ON THE POTENTIAL OF METAL AND CERAMIC BASED ABRADABLES IN TURBINE SEAL APPLICATIONS

by

Dieter Sporer

Product Line Manager, Abradables

Sulzer Metco (Canada) Inc.

Schattwald, Austria

Scott Wilson

Project Leader, Abradables, Tribology and Materials

Sulzer Markets and Technology AG

Winterthur, Switzerland

Iacopo Giovannetti

Design Engineer

GE Oil & Gas/Nuovo Pignone

Florence, Italy

Arno Refke

Manager, Application Development Group

Sulzer Metco (Switzerland) AG

Wohlen, Switzerland

and

Massimo Giannozzi

Senior Materials Technologist

GE Oil & Gas/Nuovo Pignone

Florence, Italy

Dieter Sporer is Product Line Manager for Abradables for the Materials business unit of Sulzer Metco (Canada) Inc., in Schattwald, Austria. In this position he is responsible for global Marketing and Product Development for abradable materials. Dr. Sporer has 17 years of experience in powder metallurgy and high temperature materials design and manufacturing in various positions. His main focus over the past years has been on materials and structures for gas path sealing technology.

Dr. Sporer received his B.S. degree (Mechanical Engineering, 1989) and Ph.D. degree (1993) from the Technical University of Vienna. He is a member of the ASM.

Scott Wilson has been Project Leader since 2001 for abradables, tribology, and materials for the Materials & Surfaces group at Sulzer Innotec, in Winterthur, Switzerland. He is primarily responsible for abradable testing and R&D projects in collaboration with Sulzer Metco and OEMs.

After completing his Ph.D. degree (Materials Engineering, 1993) from the University of Cape Town in "Tribology of Aluminium Matrix Composites," he held a postdoc and research assistant fellowship position at the University of Windsor, Canada, followed by a two year position as research officer in the Tribology Group at the National Research Council of Canada, in Vancouver. He is a member of the ASM, Swiss Tribology, Swiss Association for Materials Science and Technology, and AAAS.

Iacopo Giovannetti is a Design Engineer at Nuovo Pignone/GE Oil & Gas, in Florence, Italy. He is a member of the Materials & Processes Engineering team. His activity is focused mainly on the research and development of new materials and coatings for oil and gas compressor and turbine applications.

Mr. Giovannetti received a B.S. degree (Mechanical Engineering, 2003) from the University of Florence. He completed his Ph.D. degree in "Design and Construction of Turbomachines," in 2007.

ABSTRACT

Abradable seals are employed in turbomachinery to reduce leakage gaps between stationary and rotating parts to improve efficiency and stall margin. Thermally sprayed abradable seals have been used in the compressor section of jet engines since the late 1960s. These seals are predominantly coatings made from composite materials that derive their abradability from the use of low shear strength materials or from a porous, friable coating structure. Due to the extreme temperatures on the turbine side of gas turbine engines, brazed or welded metallic structures made

from nickel (Ni) based alloys have typically been used to provide gas path sealing. When thermal shock resistant ceramics became available, oxide ceramic, mostly zirconia based high temperature abradable seals for the high pressure turbine stages were developed. For the highest temperature stages, thermally sprayed oxide ceramics with or without metallic strain isolators are frequently used. On stages with reduced temperatures both ceramic and metallic coatings of the MCrAlY type can be used.

This paper reviews the state-of-the-art in compressor and turbine clearance control materials and systems, whereby a focus is placed on novel thermally sprayed ceramic turbine seals with encouraging property combinations, which are achieved by the introduction of alternative stabilizers. Normally ceramic seal surfaces require hard tipping of the rotor blades to allow them to cut properly and suitable hard tipping solutions will be presented. However, examples will be given of recent developments aimed at developing ceramic abradables that can be cut by untipped blades. Examples will be given. Finally, the paper gives an overview of cuttability of thermally sprayed metallic turbine seal coatings by tipped and untipped blades at high temperature.

INTRODUCTION

Abradable materials and structures work in reducing tip clearances by allowing blades to cut into them without damaging the blade tips through overheating or wearing. Figure 1 schematically shows the advantage of applying abradable linings in rub interactions for a hypothetical turbine or compressor stage. For a given rotor displacement, the ideal abradable, characterized by a concentration of all wear in the seal with no blade wear, will allow the rotor to cut into the stator without any reduction in blade length that would translate into an increase of the unsealed gap. Increased clearance after rub interaction is restricted to a small, sickle-shaped area. In the case of an interaction against a nonabradable, as defined by all wear on the blades and none in the seal lining, a reduction of rotor diameter and consequently a large increase in clearance as compared to the starting scenario results. In real rub interactions, mixed mechanisms with some blade and seal wear will be observed.

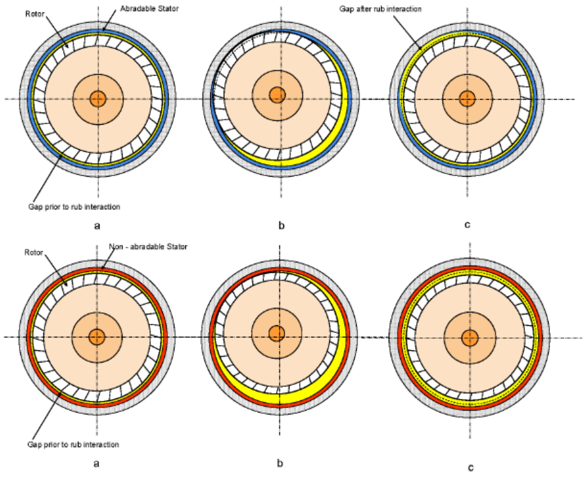


Figure 1. Evolution of Rotor Clearance During Rub Interactions. (a) Situation Prior to Rubbing, (b) Rub Interaction Caused by Main Shaft Bending, and (c) Situation and Clearance after Rub Interaction. Top: Ideal Abradable Interaction; Bottom: Nonabradable Interaction with Associated Large Increase in Rotor Clearance (Yellow).

GAS TURBINE COMPRESSOR AND STEAM TURBINE ABRADABLES

In commercial and military aero engine compressors, unshrouded rotor blades made from titanium alloys are used because of engine weight considerations. This blade selection requires that the abradable materials rubbing against the titanium (Ti) alloy tips are selected in a manner that excessive interface temperatures during rub interactions are avoided. This is required to:

- Prevent titanium fires, and
- Avoid heating of the blade tip to higher than the β-transus temperature of the titanium alloy, which would result in a material structure with reduced fatigue resistance, due to the involved metallurgical phase transformation.

Several thermally sprayed systems meeting the basic “titanium blade compatibilty” for untipped, bare blades have been developed and successfully used in engines. Aluminum based abradables, which derive their abradability basically from the low shear strength of the aluminum (Al) phase and melting upon overheating are used in today’s engines on stages with maximum operation temperatures of up to approximately 450°C (840°F). These coatings are processed by air plasma spraying and used in a more or less fully dense coating condition. However, filler phases interrupting the soft aluminum matrix and promoting coating removal upon blade incursions are generally added. An example is shown in Figure 2 where the microstructures of low temperature abradable coating systems are shown. In Figure 2a, lamellar graphite (dark particles) are embedded in an aluminum alloy matrix. In Figure 2b, the graphite filler has been replaced by hexagonal boron nitride and Figure 2c shows an Al alloy polyester abradable structure. These systems are all readily cut by untipped titanium alloy blades. The Al/polymer type abradables also show good cuttability by thin aluminum alloy blading typically found in turbocharger compressors.

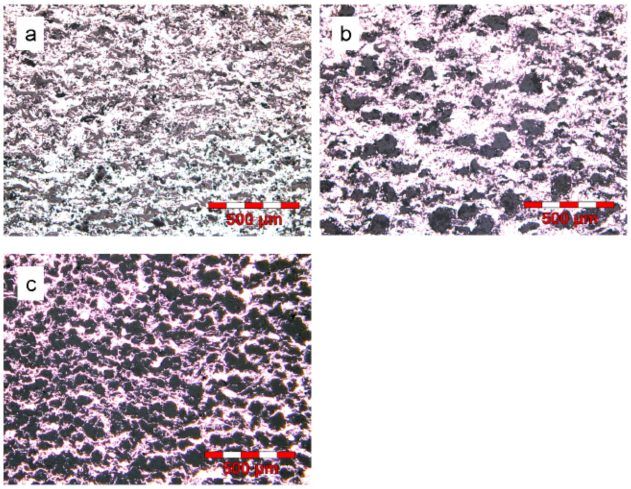


Figure 2. Aluminum Based, Low Temperature Abradable Systems. (a) Al Alloy/graphite Abradable, (b) Al Alloy/Hexagonal Boron Nitride (BN) System, and (c) Al Alloy Polyester Abradable. The Dark Phases Are the Graphite, BN, and Polyester.

When using metal matrices with higher melting temperature and shear strength than Aluminum or its alloys, the coating structure is typically porous to provide for abradability. This is necessary to compensate for the now missing large strain shear deformation capability and, under some incursion conditions, possible melting during rub interactions, both of which reduce friction/shear forces and limit the friction heating in the rub interface for Al systems. Porous coatings of pure nickel with randomly distributed lamellar graphite dislocator or solid lubricant particles represent a further titanium blade-friendly compressor abradable system. Due to their graphite content, Ni/graphite composite coatings are also limited in temperature capability to approximately 450°C (840°F). For higher service temperatures, alloyed Ni in combination with ceramic dislocators or ceramic based coatings will have to be used. An example of a metal based compressor abradable for use at temperatures up to 700°C (1290°F) is represented in Figure 3. The coating structure comprises a Ni matrix metal alloyed with chromium (Cr) and Al, thermally stable ceramic dislocator particles, and porosity. This type of abradable is typically used against untipped Ni based blades and has successfully been used in commercial and military jet engine compressors for more than two decades now and has accumulated millions of flight hours.

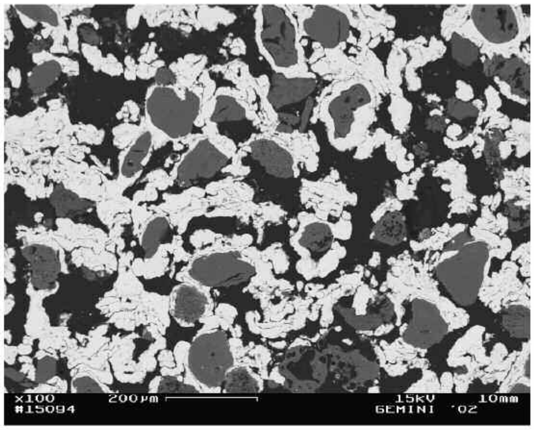


Figure 3. High Temperature NiCrAl Ceramic Compressor Abradable Comprising Ni Matrix Alloyed with Cr and Al (Bright Phase), Ceramic Dislocator Phase (Grey), and Coating Porosity (Black).

The abradable shown in Figure 3 has recently also been introduced in steam turbines. In this application the seal material applied to engine casings typically rubs against shrouded turbine blades fabricated from alloyed steel, but is also used against relatively thin seal strips of labyrinth type seals, for example in the region of the balancing piston. Unlike the situation in jet engine compressors, rub interactions in steam turbines typically occur at low relative speeds which challenges the abradability of the seal coating. In Figure 4 rub marks produced in the porous NiCrAl-ceramic seal by 0.25 mm (0.010 inch) thick seal strips made from low alloyed steel are shown together with the strip wear resulting from rubs at a rim speed of 136 m/s (445 ft/s) with 50 µm/s (0.002 inch/s) incursion rate at 500°C (930°F). Limited damage and wear of the seal strips is observed indicating acceptable abradability of the system under the given incursion conditions.

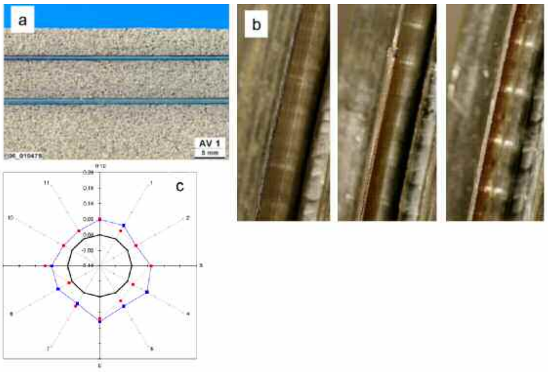


Figure 4. Rub Behavior of a NiCrAl Ceramic Porous Abradable Coating System. Rub Conditions Were: 136 m/s (445 ft/s) Rim Speed with an Incursion Speed of 50 µm/s (0.002 inch/s). Test Temperature 500°C (930°F). (a) Rub Marks in the Coating Produced by Radial Incursion of 0.25 mm (0.010 inch) Thick Seal Strips Made from Age Hardened Steel, (b) Surface Condition of Seal Strips after Rub Interaction, and (c) Wear of Seal Strips Measured at 12 Positions along the Seal Strip Circumference.

Field service experience with this coating in intermediate pressure modules of steam turbines at steam temperatures ranging from 350 to 580°C (660 to 1075°F) has reached 40,000 hours. Generally good abradability has been assessed for the system with sufficient environmental resistance of the coatings. On stages facing the highest temperatures, however, some abradable loss could be observed that was attributed to coating oxidation. Currently work is underway to modify the coating composition to provide for improved long-term steam oxidation resistance.

TURBINE SIDE ABRADABLES IN GAS TURBINES

In the low pressure turbine module of aero engine gas turbines, temperatures in the range of 650 to 1000°C (1200 to 1830°F) are encountered. Typically sealing technology in this part of the engines employs all-metallic structures such as honeycomb seals (Sporer and Shiembob, 2004), which derive their basic abradability from their low structural density. Unlike abradable coatings, honeycomb seals can be manufactured in wide depth ranges and are hence able to accommodate large radial rotor displacements or large radial blade incursions up to several millimeters. Peak temperatures seen in the high pressure turbine stages may be well in excess of 1000°C (1830°F) and challenge the limits of thin strip alloys, mostly Ni based materials, from which honeycomb seals are manufactured. For reasons of high temperature oxidation resistance, one of the main factors influencing high pressure turbine seal life, ceramic materials appear attractive. Rotor deflections/radial incursions are much smaller for high pressure turbine (HPT) modules and thermally sprayed coatings can be used. However, due to the cyclic nature of engine operation and the fact that the ceramic coatings are deposited on metallic structures, with a corresponding mismatch in the thermal expansion between substrate and coating, strain and thermal shock tolerant ceramics are required. For applications that are limited in maximum service temperature to below 850°C (1560°F), metallic based abradable coatings, typically having a matrix made from highly alloyed Ni or cobalt (Co), can be used. The following section reviews two material concepts: MCrAlY and zirconia based abradables.

MCrAlY Based Abradables

The material selection for high temperature metallic abradables requires that the coatings resist erosion and hot gas oxidation at the relevant service temperatures. The latter requires that all coating constituents resist the high temperature and the hot gas environment. Therefore MCrAlY (M = Ni and/or Co) materials, in the specific case here a CoNiCrAlY alloy, are used to provide a metal matrix. To weaken the structure and thereby provide for abradabilty, two specific coating characteristics are introduced:

- The distribution of a solid lubricant or dislocator phase, and
- A high degree of coating porosity.

As the solid lubricant/dislocator is required to resist high temperatures, hexagonal boron nitride (BN or hBN), also known as “white graphite,” is present in the spray powder composition as a CoNiCrAlY/BN agglomerate. Coatings are typically produced by air plasma spraying (APS). The APS process finely distributes the BN in the metal matrix thereby weakening it. Porosity is introduced into the coating by deposition of polyester particles that can be removed by a heat treatment in the 500°C (930°F) range, thereby leaving pores behind. Figure 5 shows a typical coating microstructure and the distribution of the various phases in an as-sprayed condition at high magnification. Figure 6 shows a macroscopic view of the coating microstructure showing the distribution of polyester that will create porosity after heat treatment. Typically the coatings have a 35 to 45 percent porosity, a density of approximately 3.2 g/cm^3 (0.116 lb/in^3) and a hardness of 65 to 75 when measured on the Rockwell R15Y scale using a 0.5 inch diameter steel indenter ball. The coatings are recommended for use at up to 850°C (1560°F) in oxidizing environments and are normally recommended to be cut by hard tipped blades.

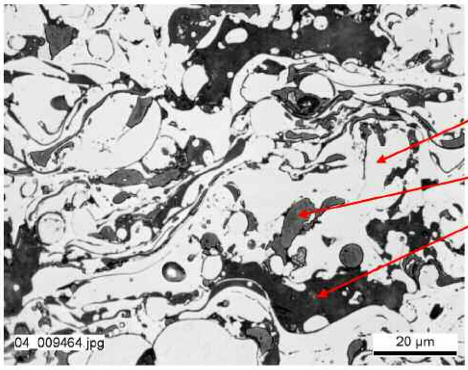


Figure 5. Microstructure of a CoNiCrAlY BN Polyester Abradable Structure Produced by APS.

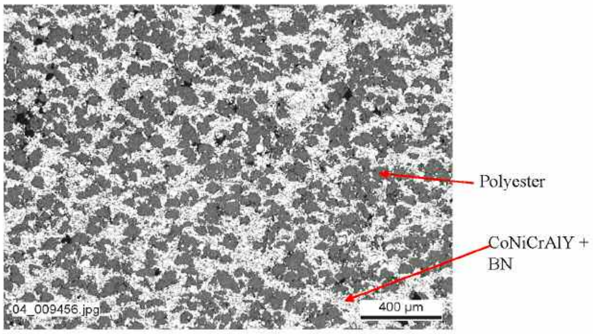


Figure 6. Same as Figure 5. Distribution of Porosity.

Zirconia Based Abradables

Due to its low thermal conductivity, yttria-stabilized zirconia (YSZ) has become a standard material for thermal barrier coatings as described by Stecura (1986) and Mack, et al. (2006). Thermally protecting turbine components with YSZ works because it is applied as a coating having numerous types of defects in its structure. These make the coatings tolerate thermal strains and stresses arising from differences in coefficient of thermal expansion compared to the metallic substrates and during engine transient operation also causing thermal shock loading. The desirable defects in YSZ thermal barrier coatings are mainly a result of the application process. Figure 7 shows such defects in an atmospheric plasma sprayed YSZ coating. The defects encountered are globular porosity, interlamellar or intersplat porosity, and splat boundaries, all of which can accommodate thermal mismatch strains on a microscopic scale.

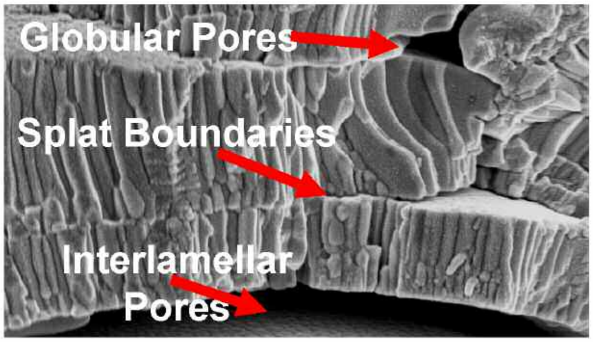


Figure 7. Structure of a Thermally Sprayed YSZ Thermal Barrier Coating with Porosity and Splat Interfaces as Desirable Coating Defects.

Standard YSZ coatings can be used as high temperature abradables. Their suitability for this application, however, does depend on the level of coating porosity and sintering resistance at high temperature. Moreover, ceramic coatings tend to be abrasive to metal alloy blades and hence normally require the rubbing blades to be fitted with a hard tipping that cuts into the YSZ. An example of a high pressure turbine stage ceramic seal assembly, as published by Gunston (1997) for an aero turbine engine, is shown in Figure 8. As the hard tipping of blades is expensive, an ideal ceramic abradable system avoids the need for the tip abrasive and allows bare metal blades to cut into it without excessive wear or overheating of the metal tip. In the following discussion the concept of coarse coating porosity and its effects on thermal shock life and abradability will be discussed. In such a concept the coarse porosity is introduced by fugitive filler phases, which are initially deposited in the coating during thermal spraying but that can be removed by a subsequent heat treatment to create porosity over and above the level of desired coating defects, as described above.

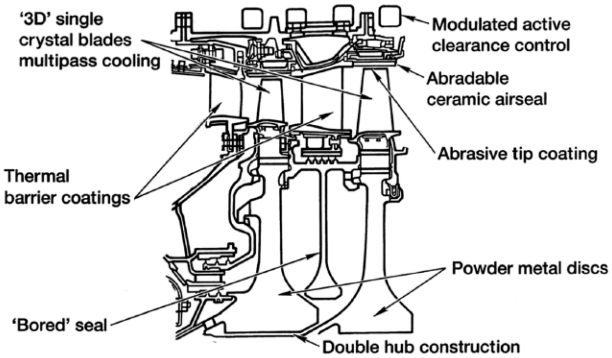
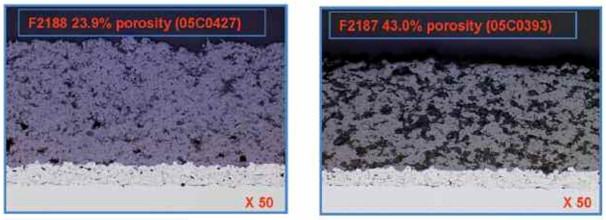


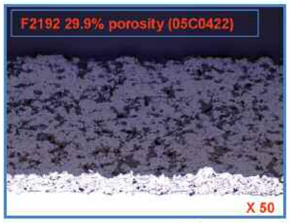
Figure 8. High Pressure Turbine Sealing Arrangement Using Ceramic Abradable, Blade Abrasive Tipping and Active Clearance Control. (Courtesy of Gunston, 1997)

Figure 9 shows microstructures of abradable coatings manufactured from yttria- and dysprosia-stabilized zirconia having various levels of porosity in their structure.



(a) YSZ; 24 % porosity

(b) YSZ; 43 % porosity



(c) DySZ; 30 % porosity

Figure 9. Microstructures of Ceramic Abradable Coatings Having Various Levels of Coarse Porosity Introduced by a Fugitive Filler Phase. (a) and (b) Yttria-Stabilized Zirconia Ceramic Matrix; (c) Dysprosia-Stabilized Zirconia.

The addition of filler phases to create additional, coarse porosity has two major advantages: First, it allows for coating porosities

Table of Contents

higher than what can be achieved with unfilled material variants, and second, the size of porosity can be predetermined by the size and distribution of the filler particles. This allows optimizing of critical coating properties such as thermal shock resistance, sintering resistance, and abradability.

Replacing the yttria in YSZ with alternative stabilizers can further improve the thermal properties of the coating. First, the thermal conductivity can be lowered, such as reported by Markoscan, et al. (2006), for dysprosia stabilization of zirconia, and second, the thermal shock behavior can be improved as demonstrated in Figure 10 for coatings having the yttria stabilizer replaced by ytterbia (Yb_2O_3) or dysprosia (Dy_2O_3). The test results shown in Figure 10 were obtained for thermocyclic loading of Ø 25.4 × 3 mm (Ø1 inch × 0.118 inch) buttons made from Hastelloy® X and carrying a 1000 µm (0.040 inch) thick ceramic APS top coat deposited over a 150 µm (0.006 inch) bond coat produced from a Ni-22Cr-10Al-1Y alloy. Cycle time was one hour with heating from 50°C (120°F) to 1100°C (2010°F) in 10 minutes, holding for 45 minutes, and cooling the samples to 50°C (120°F) with compressed air in five minutes. The thermal cycle employed is visualized in Figure 11. Failure criteria to report a thermal shock life was 20 percent ceramic top coating area loss. Figure 10 shows that the thermal shock life generally increases with the level of coating porosity and can be further enhanced by introducing alternative stabilizers. The improvement over standard YSZ coatings for the latter is significant. In the tests reported here, it is up to approximately fourfold.

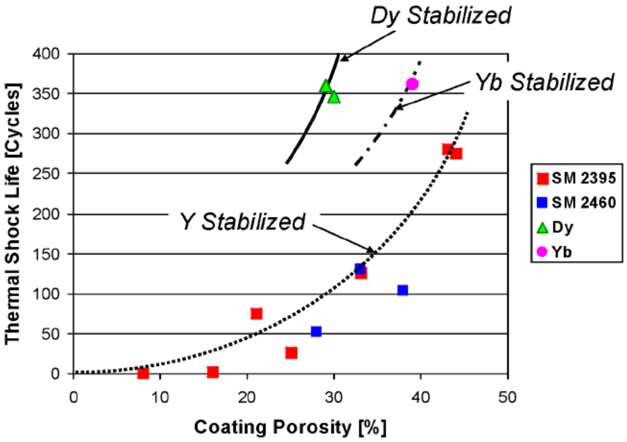


Figure 10. Thermal Shock Life of 1000 µm (0.040 inch) Thick Ceramic Abradable Coatings as a Function of Coating Porosity and Chemical Composition.

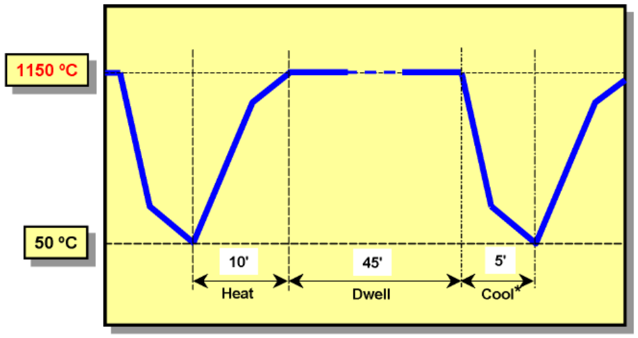


Figure 11. Furnace Cycle to Evaluate Thermal Shock Resistance of Ceramic Abradable Coatings.

Ceramic and Metallic Coating Rig Abradability Performance

The abradability of coatings was determined using a test rig fitted with dummy blades made from Inconel® 718. The test rig is capable of producing blade tip speeds of up to 430 m/s (1410 ft/s). It is equipped with a heating system that allows the shroud specimen to be heated up to a temperature of 1200°C (2190°F). Figure 12 shows a schematic of the test facility. Figure 13 shows the rig and rotor in a setup as used for testing dummy or OEM blades together with the mechanical drive system of the rig.

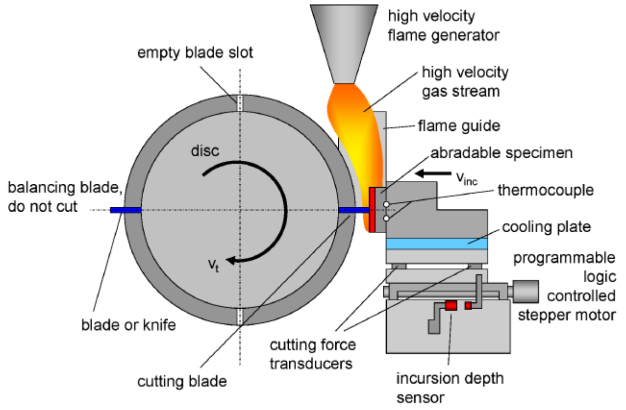


Figure 12. Schematic Representation of the Test Rig Used to Determine Abradability of Metallic and Ceramic High Temperature Abradable Coatings.

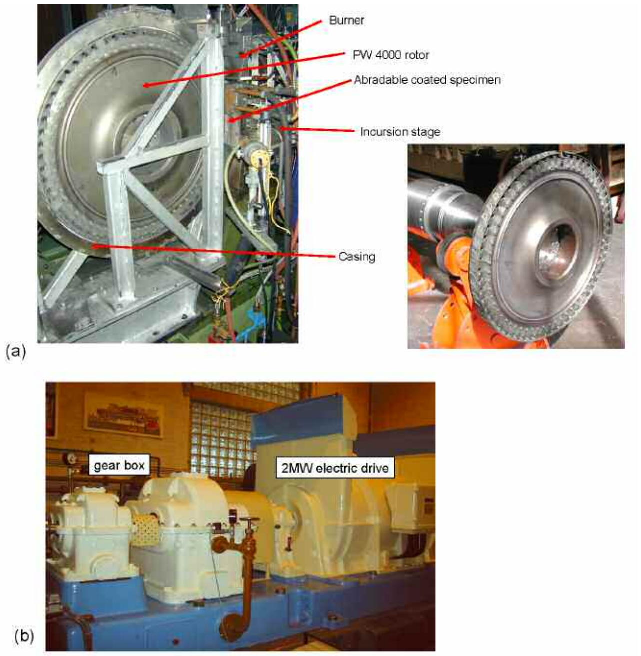


Figure 13. Test Rig. (a) Rotor and Setup for Testing with Dummy and Original Equipment Manufacturer Blades; (b) Mechanical Test Rig Drive.

Tests at 1100°C (2010°F)

In a first series of tests, YSZ coatings with low and very high porosity and dysprosia-stabilized zirconia (DySZ) coatings having medium porosity were compared in their abradabilty behavior to a dense, plasma sprayed CoNiCrAlY coating. The properties of the ceramic coatings are summarized in Table 1 where the erosion resistance is reported in seconds to erode 25 µm (0.001 inch) coating thickness as determined in a standard particle erosion test using 50 µm (0.002 inch) size Al_2O_3 grit impinging the surface at an angle of 20 degrees. The abradabilty tests were carried out at a shroud specimen/coating temperature of 1100°C (2010°F) and five tests per coating condition were run. It is because of this high test temperature that a dense MCrAlY coating was used as a baseline. Dense, plasma sprayed CoNiCrAlY coatings are used as abradable linings in high temperature turbine sealing applications. The test set parameters were selected to be: 5 and 500 µm/s (0.0002 and 0.02 inch/s) incursion rate at blade tip speeds of 250 m/s (820 ft/s) and 410 m/s (1345 ft/s) and an intermediate test condition using 50 µm/s (0.002 inch/s) incursion rate at a blade tip speed of 350 m/s (1150 ft/s). To demonstrate the capability of coatings to be cut by bare blades, untipped blade dummies having a tip section of 2 × 25 mm (0.080 inch × 1 inch) and fabricated from Inconel® alloy 718 were used. Figures 14 to 17 show the results of the abradability tests. In these figures the appearance of the rub path is shown along with the measured blade wear that is reported as a percentage of the total incursion depth, which is the sum of blade and coating wear depth.

Table 1. Properties of Ceramic Coatings Tested Against Untipped Inconel® 718 blades at 1100°C (2010°F). Ceramic Coatings Were Deposited over a NiCrAlY Bond Coat.

Ceramic Matrix	Coating Hardness	Coating Porosity	Coating Erosion Resistance
	HR15Y	%	s/mil
Yttria Stabilized Zirconia (YSZ)	94	24	2.03
Yttria Stabilized Zirconia (YSZ)	71	43	0.26
Dysprosia Stabilized Zirconia (DySZ)	82	30	0.80

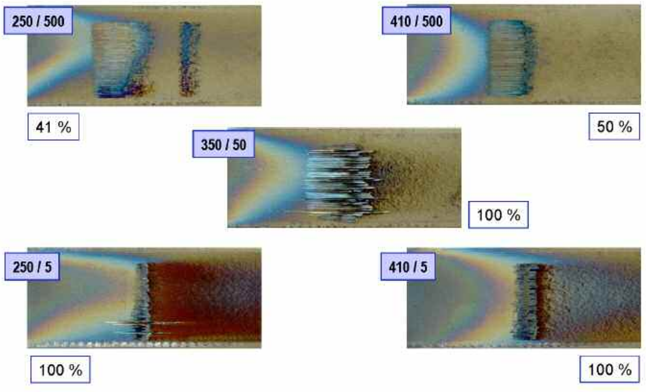


Figure 14. Abradability Results for a Dense CoNiCrAlY Coating Tested at 1100°C (2010°F) under Rig Set Conditions as Indicated. Blade Wear as a Percentage of Total Incursion.

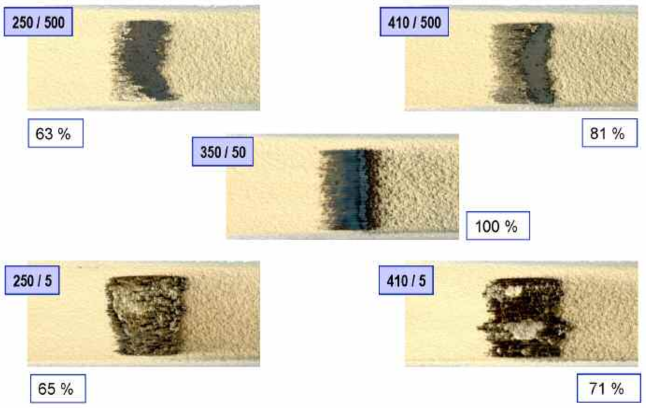


Figure 15. Abradability Results for a Porous (24 Percent) YSZ Ceramic Abaradable at 1100°C (2010°F) under Rig Set Conditions as Indicated. Blade Wear as a Percentage of Total Incursion.

Figure 16. Abradability Results for a Porous (43 Percent) YSZ Ceramic Abradable at 1100°C (2010°F) under Rig Set Conditions as Indicated. Blade Wear as a Percentage of Total Incursion.

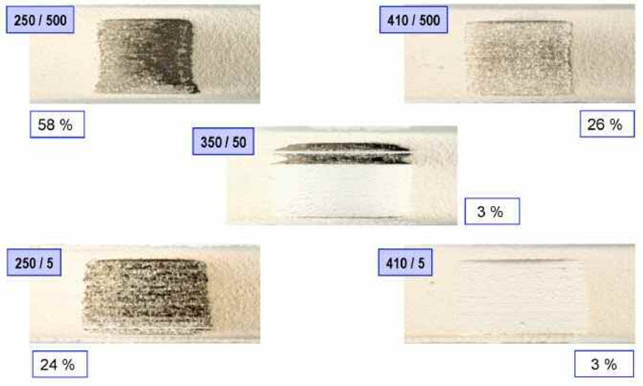


Figure 17. Abradability Results for a Porous (30 Percent) DySZ Ceramic Abaradable at 1100°C (2010°F) under Rig Set Conditions as Indicated. Blade Wear as a Percentage of Total Incursion.

As can be seen from Figure 14, the dense MCrAlY coating is not cut well by bare Inconel® 718 under the conditions selected. This is indicated by excessive blade wear and shallow/short rub paths, which also show a considerable amount of grooving arising from transfer of abradable material to the blade tip. A porosity of 24 percent in a porous YSZ coating is obviously not sufficient to provide for acceptable abradability as can be taken from Figure 15. The dark appearance of the rub path is a result of blade metal transferring to the shroud coating during the rub interaction. However, at a coating porosity of 43 percent, good cuttabilty of the ceramic by the test blade geometry is observed (Figure 16). Clean, deep cuts with little corresponding blade wear are observed for all test conditions selected. At 30 percent porosity the dysprosia-stabilized zirconia coating in Figure 17 shows good cuttability at blade tip speeds higher than 350 m/s (1150 ft/s). At lower speeds, blade metal transfer to the ceramic is observed.

Tests at 850°C (1560°F)

A direct comparison of rig abradabilty between metallic and ceramic coatings was undertaken at the upper temperature limit for the metallic seal, 850°C (1560°F). Coatings of the MCrAlY/BN type as described above were prepared by plasma spraying a CoNiCrAlY/BN/polyester composite blend with a plasma gun and heat treating the resulting coating at 500°C (930°F) to remove the polyester filler. The resultant coating had a hardness of 62 on the HR15Y scale.

Ceramic coatings for the tests were prepared from a YSZ/BN/polyester composite blend by spraying with a plasma gun and heat treating at 500°C (930°F) to drive the polymer filler off and thereby creating porosity. Two sets of ceramic coatings, A and B, were produced. The properties of these are summarized in Table 2.

Table 2. Properties of YSZ Coatings Tested at 850°C (1560°F). Ceramic Coatings Were Deposited over a NiCrAlY Bond Coat.

	Ceramic Matrix	Coating Hardness	Coating Porosity	Coating Erosion Resistance
		HR15Y	%	s/mil
A (F2193)	Yttria Stabilized Zirconia (YSZ)	95	15	3.20
B (F2191)	Yttria Stabilized Zirconia (YSZ)	85	31	0.73

The metallic and the two ceramic coatings were tested against both bare and cBN hard tipped Inconel® 718 blades. The softer and more porous YSZ abradable was tested against bare blades, the harder and more erosion resistant coating was tested against cBN tipped test blades. The test conditions selected were: 50 µm/s (0.002 inch/s) incursion rate at blade tip speeds of 250, 350, and 410 m/s (820, 1150, and 1345 ft/s).

Figure 18 shows the test results for the metallic coating. For both types of blade tips, good cuttabilty of the CoNiCrAlY/BN can be observed. The negative wear reported for the tests with bare blades indicates that the test blade slightly grew in length as a result of transfer of seal material from the abradable to the blade. The blade tip is shown in Figure 18 and the buildup on the blade is visible at the cutting edge of the blade. In contrast, the tests with the cBN reinforced tips result in slight wear. In general the observed transfer and wear are small and, with the exception of the test at 250 m/s (820 ft/s) for the untipped Inconel® 718 material, remain within a 6 percent limit.

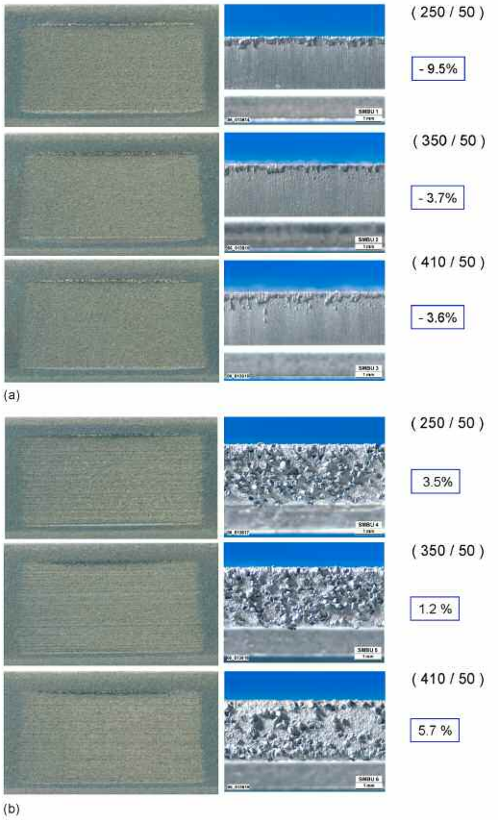


Figure 18. Abradability Test Results Obtained for a Porous CoNiCrAlY BN Abradable at 850°C (1560°F) with Bare (a) and cBN Reinforced Inconel® 718 (b) Test Blades. Left: Rub Path Appearance; Right: Appearance of Blade Tip after Test. Blade Wear as a Percentage of Total Incursion Depth Indicated.

The tests with the ceramic seals under the same conditions show blade material transfer from the tip to the ceramic for the lower speed test conditions with untipped blades (Figure 19a). Blade wear is excessive (Figure 19b). At the highest tip speed, 410 m/s (1345 ft/s), blade wear is moderate and no blade transfer to the seal can be observed. However, a ruptured, rough rub path appearance becomes apparent.

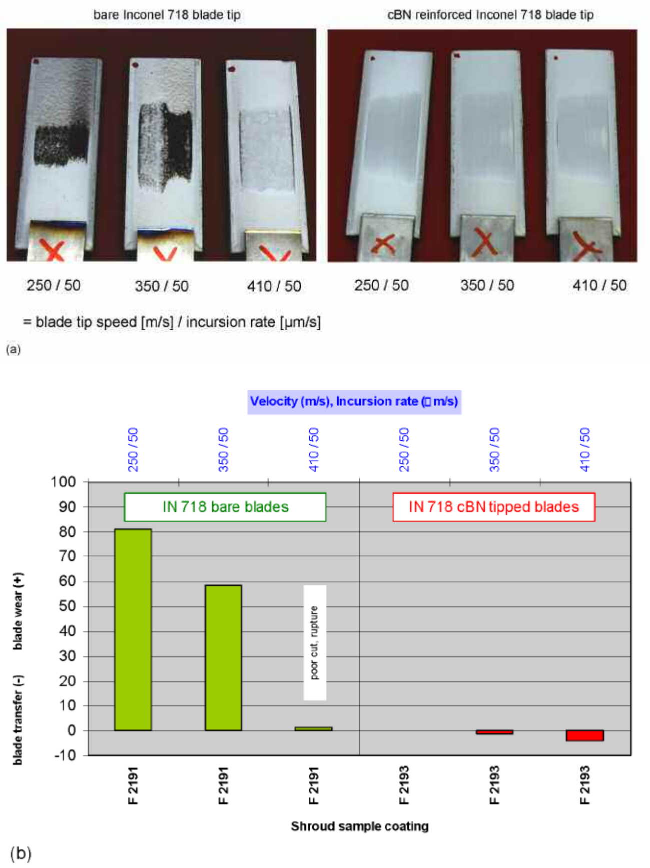


Figure 19. Test Results Obtained for YSZ Ceramic Coatings at a Test Temperature of 850°C (1560°F). Rub Path Appearance (a) and Blade Wear as a Percentage of Total Incursion (b). Bare Inconel® 718 Blades Left, cBN Hard Tipped Blade Right.

Cubic boron nitride (cBN) hard tipped blades cut a clean rub path into the ceramic abradable and no blade wear but very limited transfer of seal material to the reinforced blade tip is observed as shown in Figure 19.

CONCLUSIONS

Compressor abradables in jet engines use various aluminum based concepts to provide compatibility with titanium alloy blading. Typically these coatings are dense but contain various dislocators or solid lubricant phases to enhance abradability. For the highest temperatures in aero engine compressors, porous coatings having a Ni based metal matrix are used. These systems also find applications as abradable seals in steam turbines.

For very high temperature sealing in gas turbines, dense MCrAlY coatings without dislocator phases show very limited cuttability by bare Ni alloy blades at high temperature. CoNiCrAlY/BN abradables have a somewhat limited oxidation life at high temperatures, which is due to their high level of porosity. However, they are well cut by both bare and hard tipped Ni alloy blades at their maximum recommended service temperature of 850°C (1560°F). At that temperature, YSZ based abradables with a porosity of 30 percent require high blade tip speeds (> 350 m/s or

1150 ft/s) to start to show abradability by bare blades. Blades tipped with cBN cut YSZ abradables well at 850°C (1560°F) even if the porosity is reduced to 15 percent, which results in more erosion resistant coatings.

A high porosity level of 45 percent in a YSZ abradable ceramic coating provides good abradability at 1100°C (2010°F). Twenty-four percent coating porosity is not sufficient to produce the same result. Dysprosia-stabilized zirconia abradables with a level of 30 percent porosity show good cuttability at 1100°C (2010°F) by untipped blades for tip speeds of 350 m/s (1150 ft/s) and higher. This in combination with optimized thermal shock resistance and reduced thermal conductivity of this type of material provides an attractive coating property combination for high temperature abradable sealing applications.

Turbine designers will have to decide on a case-by-case basis whether metallic or ceramic abradables should be used and whether they can be cut by bare or hard tipped blades.

REFERENCES

Gunston B., 1997, *Jet and Turbine Aero Engines,* Patrick Stephens Limited (PSL).

Mack, D. E., Gross, S. M., Vaßen, R., and Stöver, D., 2006, "Metal-Glass Based Composites for Application in TBC-Systems," *Journal of Thermal Spray Technology, 15* (4), pp. 652- 656.

Markoscan, N., Nylen, P., Wigren, J., and Li, X. H., 2006, "Low Thermal Conductivity Coatings for Gas Turbine Applications," *Proceedings of the 2006 International Thermal Spray Conference,* Seattle, Washington, ASM International.

Sporer, D. and Shiembob, L. T., 2004, "Alloy Selection for Honeycomb Gas Path Seal Systems," *Proceedings ASME Turbo Expo 2004,* ASME Paper No. GT2004-53115, Vienna, Austria, ASME International.

Stecura, S., 1986, "Optimization of the Ni-Cr-Al-Y/ZrO_2-Y_2O_3 Thermal Barrier System," Advanced Ceramic Materials, *1* (1), pp. 68-76.

ACKNOWLEDGEMENTS

Abradable testing work as described in this article was in part carried out under the EESD-FP5 Project, *Innovative Abradable/Abrasive Materials for Improved Energy Efficiency in Gas Turbines*, acronym *ABRANEW*, project number NNE5-2001-411. The financial contribution received from the European Commission for carrying out this work is gratefully appreciated.

The authors would like to thank Praxair for providing the blade hard tipping with cubic boron nitride.