DEVELOPMENT OF AIR SEAL SYSTEMS FOR MODERN JET ENGINES

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1. INTRODUCTION

Seal systems are used in jet engines in order to reduce gas path leakage between rotor/stator parts at tips of blades/vanes or vane inner shrouds, to control air streams for cooling and pressurisation, as well as to avoid oil leakage at bearing chambers (Fig.1).

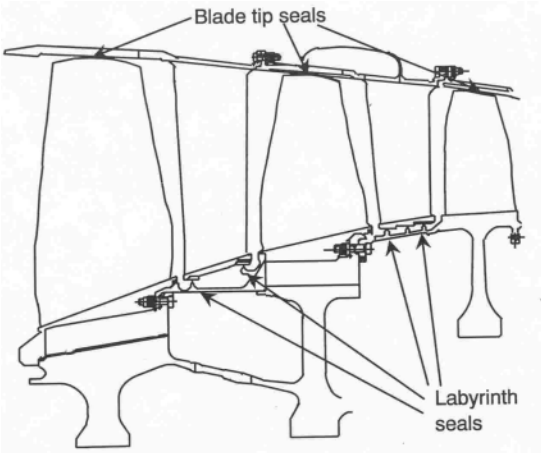

Fig. 1. Position of gas-path seals /1/

The performance requirements for an advanced jet engine is only achieved by low leakage of air flow in order to attain the high pressure ratios needed for high efficiencies and surge margin as well as low specific fuel consumption.

A seal system consists of the rotor part and the stator part. The rotor member can either be the tips of a blade row or the fins of a labyrinth seal. The stator member can be the rotor path for the blade tips or for the seal fin.

The rotor part (blade, fin) is either bare or protected against tip rub by

- hard coating on fins
- hard particles brazed onto the blade tips.

The stator part can be

- a bare surface
- a surface protected with a porous spray coating (abradable)
- open or filled honeycombs, brazed onto the stator surface
- rubber type layers glued onto the stator
- felt metal layers fixed by brazing or gluing
- sprayed ceramic layers for turbines.

Where Ti casings are used in the compressor section, an intermediate layer of zirconia is sprayed between bond and abradable coating to protect the casing against Ti fire.

Relative movement of rotor to stator and deformation of casings under operating conditions as well as eccentricity of rotor/stator generate larger gaps /2/. If the clearance is too small and the sealing system is not rub tolerant, this will result in damage to engine parts.

To restrict the damage effects of the conditions described above the gas path seals must allow sufficient radial and/or axial incursion of the rotor part. In other words, the seal part on the stator must be abradable: The same change of radial displacement by engine operation will either produce segmental rub-out of the abradable or reduction of the length of all blades and then result in 360° ring gap causing a larger leakage than the segmental gap in the stator (Fig.2) /3/.

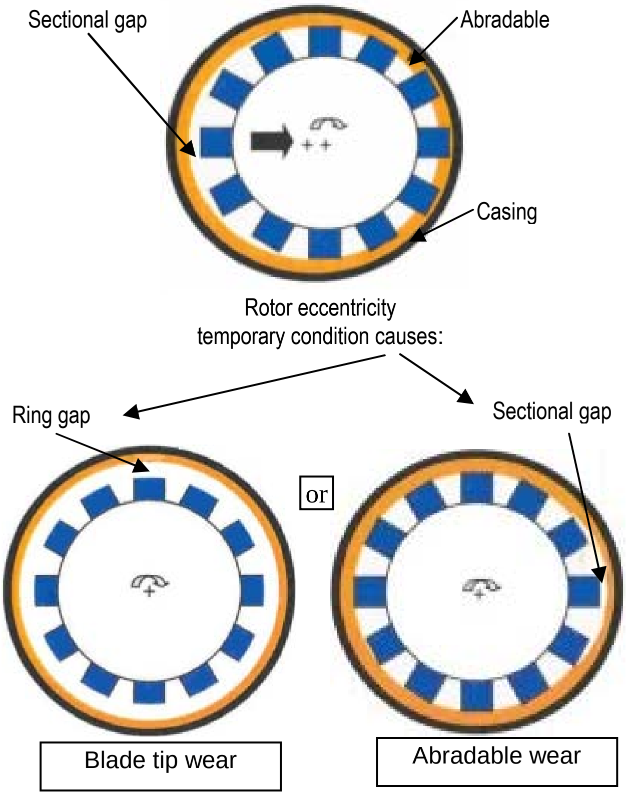

Fig. 2. Leakage areas as a function of blade and fin wear

Seal systems have to withstand the erosion forces of the air stream as well as rubs at extremely high speed. Operating conditions should not cause development of destructively high temperatures and stresses on rotating components. The repair of damaged rotor parts is difficult and very expensive.

Honeycomb seals are not suitable for blade tips in compressors due to the mini chambers which would allow air leakages at tip. Another disadvantage is the high brazing temperature for the application onto Ti casings.

Hence air seal systems represent one of the most challenging key technologies when adapted to the specific local requirements.

In this paper only the experience with abradable seal systems in compressors will be discussed.

2. EXPERIENCE WITH EXISTING ABRADABLE SEAL SYTEMS IN THE COMPRESSORS

Abradables are used for blade tip seals. The abradable coating consists eg either of flame or plasma sprayed powder of Ni/C, CoNiCrAlY-BN or NiCrAl-Bentonite. These layers are bonded onto the casing wall by NiAl spray coating to improve the adhesion of the abradable.

These seal systems can be the source of damage due to the rub energy conditions which produce heat. The local thermal expansion leads to additional contact on blade tip. The destructively high temperature can result in direct in-situ effects as well as indirect long-term effects (Fig.3).

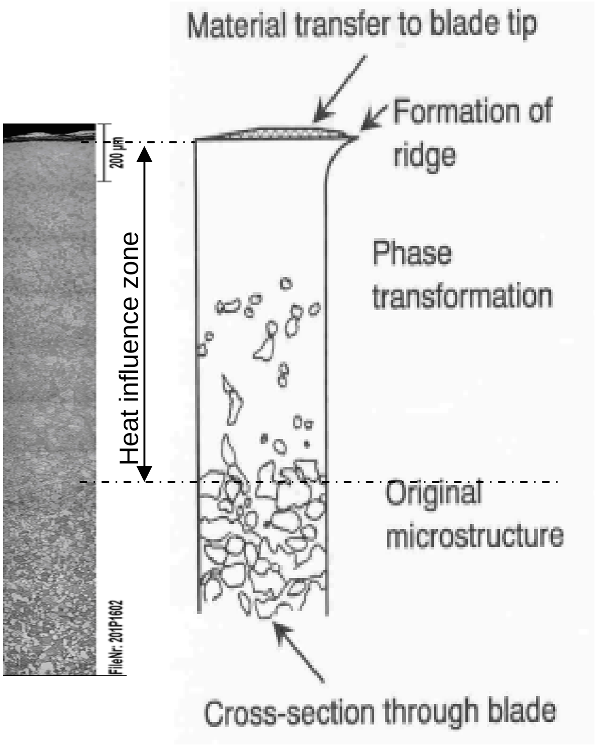

Fig. 3. Blade tip damage

Direct effects in context with abradable coatings can be:

- increased rub-off, densification of the abradable
- oxidation and more violent interactions as fin melting or Ti-fire on tips
- material transfer within the seal and possible distortion of rotor and seal lands
- thermal stress cracking on blade tips.

Indirect long-term effects in context with abradable can be:

- reduction of blade hardness in the tip zone overheated by tip rubbing
- fatigue stress cracking on blades (tips)
- increase of blade and fin wear.

Other damage from poor abradable is possible:

- coating plucking (Fig.4), which can be caused by casing vibration and rotor blade passing frequencies

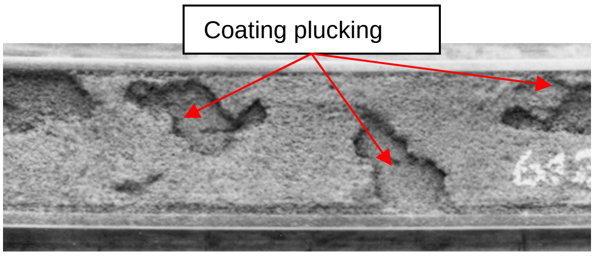

Fig. 4. Typical coating plucking

- coating chipping (Fig.5) because of insufficient bonding

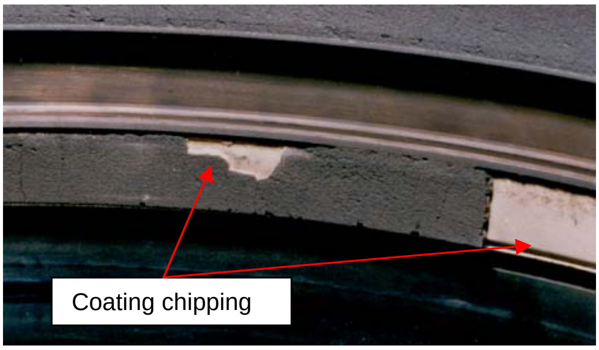

Fig. 5. Coating chipping due to bonding reason

- erosion from ingested hard particles (out-board) or of engine own rubbing/wearing products (Fig.6).

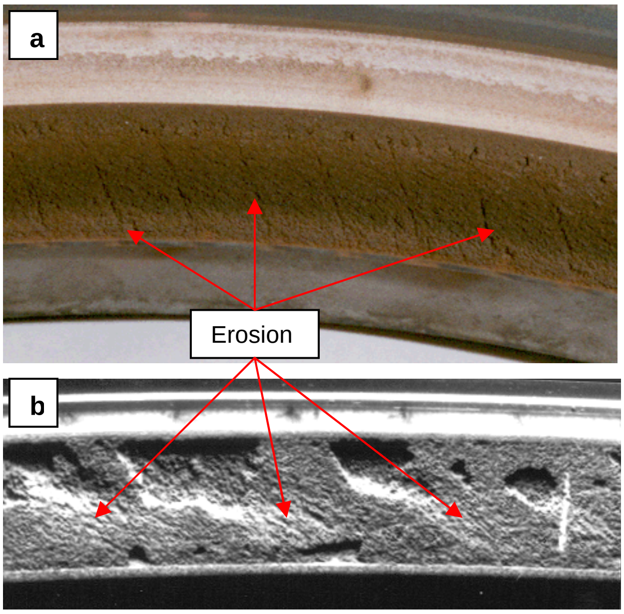

Fig. 6. Abradable coating damaged by
a. erosion
b. plucking and erosion

3. REQUIREMENTS FOR ABRADABLE SEAL SYSTEM

In order to minimize air leakage and to increase engine efficiency and surge margin, it is necessary to maintain smallest clearances possible between the rotating and stationary parts. The abradable sealing coatings just serve such purposes which allow blade tip incursion during the transient conditions. The ideal abradable must have follow properties:

- minimal rub on rotor parts of blades and fins
- gas and particulate material erosion resistance (not compatible with abradability)
- tip clearance control effects by heat insulation
- resistance to thermal cycles
- thermal expanding coefficient suitable for casing material
- long-term temperature stability
- resistance to rotor blade passing frequencies
- chemical resistance to salt water (corrosion), engine fuels, hydraulic oil, engine washing fluids, exhausts from rockets, engine contamination
- protection against Ti fire for Ti casing walls
- low energy rub or contact friction
- avoidance of self ignition and ignition of worn debris
- no material transfer from blade tips to abradable and vice versa
- no leakage through open porosity
- quick removal of the heated up grains
- smooth wear surface for minimal aerodynamic losses
- little, innocuous debris, not reactive to surfaces on downstream engine sections (bearings, blockage of turbine cooling air surfaces)
- reproducibility of manufacture of abradables
- easy repair
- low manufacturing cost.

While simple in concept, the seal materials must balance the conflicting requirements of abradability and erosion resistance, as well as good oxidation resistance for high temperature operation and thermal shock resistance. Applied on Ti casings the titanium fire containment must be sufficient.

To meet most of these properties spraying of multiple layers with different materials of different porosity has been developed. This procedure requires a complex manufacture with frequent change of spray materials accompanied by time lag between the single spraying processes (burner change, surface contamination problems, etc.).

Zirconia of different porosity offers a chance to meet the challenging requirements to seal systems of modern engines for increasing pressure ratios, temperatures and rotating speeds.

Zirconia coatings have long been used in compressors and turbines as Ti fire containment layer and temperature barrier coating (TBC) because of its character. A new seal system, zirconia abradable with cBN protected blade tips (Fig.7) has been developed by MTU.

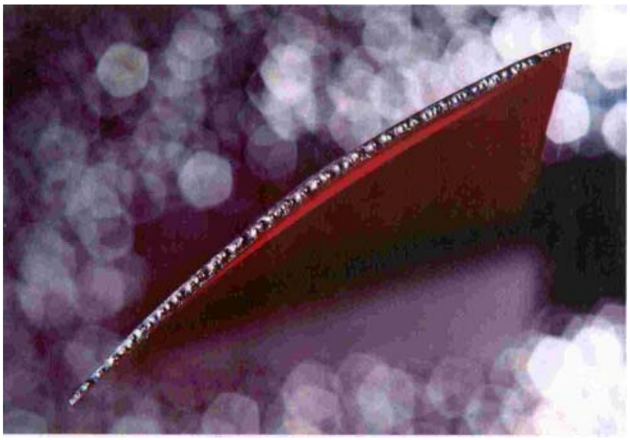

Fig. 7. cBN protected compressor blade tip

The aim of the present paper is to present the experience with zirconia abradable coatings based on the results of rig tests of rub-in, erosion, Ti fire and thermal fatigue, etc.

4. ZIRCONIA ABRADABLES

4.1. Desired Properties of Zirconia Coating

Modern jet engines need improved seal systems with partly conflicting properties (abradability ↔ erosion resistance).

On one hand good abradability as well as certain tip clearances control properties of the coating are desirable, both are controlled by the porosity. These effects allow smaller build-up gaps for blade tips and rotor fins and are needed in order to maintain tip gaps narrow during transient operating conditions.

On the other hand contradictory behaviour of the coating is demanded which is usually not compatible with abradability: High erosion and oxidation resistance of the abradable which maintains the operating tip gaps constant over long running time. For Ti casings also the protection against Ti fire is required. All these properties can be supported by a ‘dense’ coating structure of zirconia.

The physical properties of zirconia offer the chance to meet a smooth rotor path with sufficient erosion resistance and with good abradability, affected by the porosity of the coating.

The need for small tip clearances cannot be solved solely by improving abradables. More attention must also be paid to engine stiffness, casing roundness and bending and/or casing/rotor dynamics.

4.2. Production of Zirconia Coatings with Different Densities

To improve the abradability of zirconia coating its porosity has to be increased. Therefore, a complex spraying process was developed:

Zirconia powder with polyester was sprayed. Subsequent heat treatment leaves internal voids and at the same time high interparticle strengths.

The control of the amount of voids in the coating leads to the desired abradability. Fig.8 & 9 /4/ show the micro-structure of zirconia abradable coatings with different density.

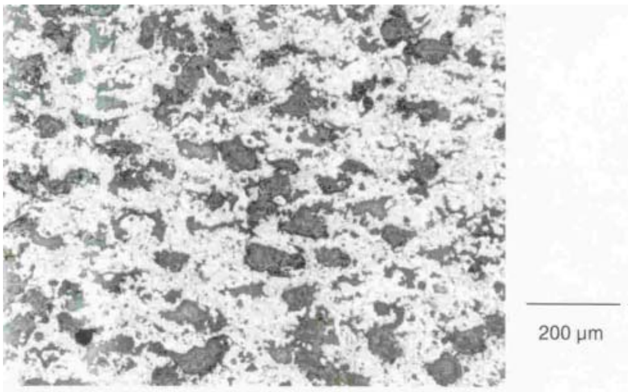

Fig. 8. Zirconia abradable coating with high porosity

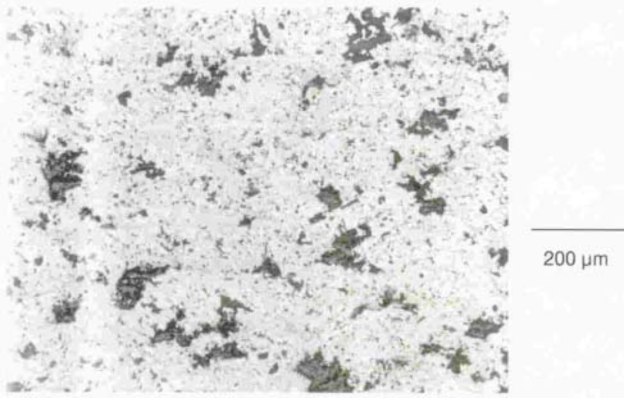

Fig. 9. Zirconia abradable coating with low porosity

The initial step towards developing a zirconia abradable sealing system was to produce a multiple layer. This is usually achieved by a combination of layers of different porosity. Each layer has different but in itself homogeneous properties for different purposes.

- A double layer system consisting of a dense zirconia layer on the casing covered by a porous layer with sufficient abradable properties (Fig.10).
- A triple layer system consisting of the double layer system plus an intermediate layer of a porosity between that of the two layers (Fig.11).

Multiple layer abradable sealing systems are easily produced. Under certain circumstances, however, a bonding problem may arise: The sudden change of properties from layer to layer can cause the spalling of the surface layer.

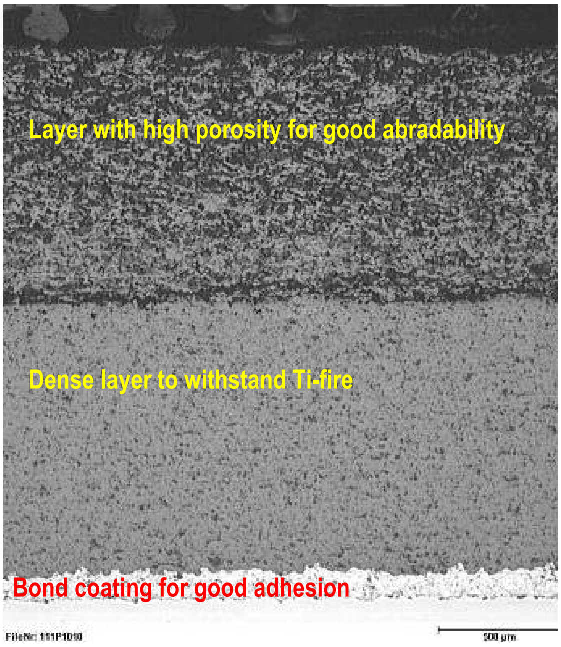

Fig. 10. Double layer abradable coating

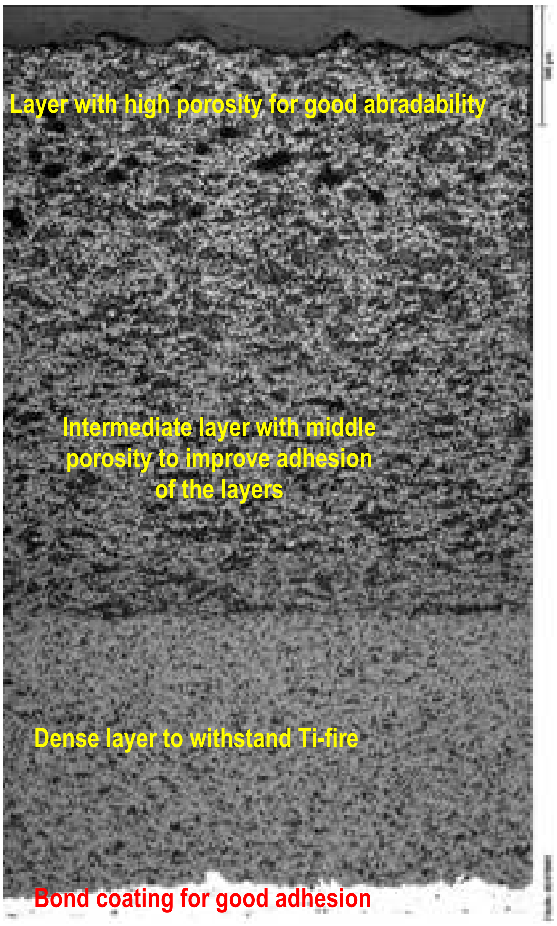

Fig. 11. Triple layer abradable coating

Therefore, a logical solution is an **one layer coating but with graduated porosity**: dense at casing wall, porous (abradable) at top of the layer has been specifically developed to counter this risk and to improve the erosion resistance of the abradable (Fig.12).

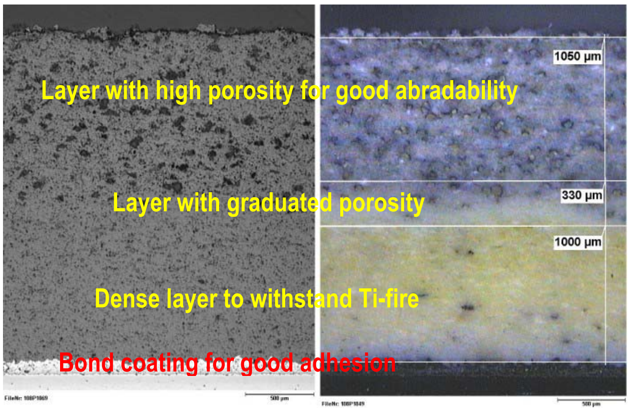

Fig. 12. Zirconia abradable with graduated porosity

5. SAMPLE AND RIG TESTS OF ZIRCONIA ABRADABLES

5.1. 4-Point Bending Test

Easy fracturing at interparticle boundaries and the brittle release of material provide for a low energy rub. This requires abradable material possessing a high expansion limit and a low E-module.

In order to determine the mechanical properties of the ceramic coating 4-point bending tests have been done.

Bars of zirconia abradable material with different porosities were produced by plasma spraying and then machined to samples in size of 4x4x50 mm (Fig.13). At 700°C, 900°C and 1000°C the 4-point bending tests were carried out for definiton of the E-moduli and the strain limits.

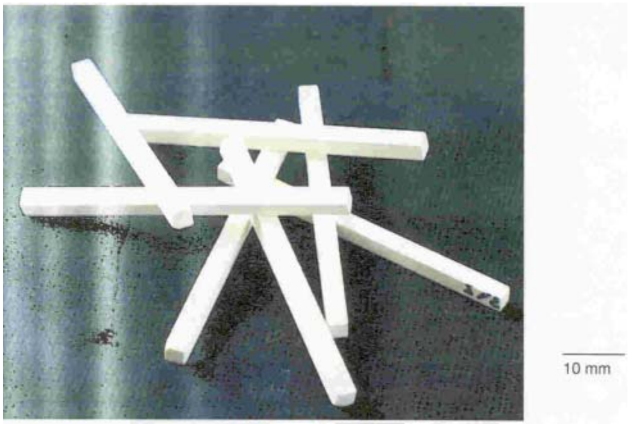

Fig. 13. Samples made of zirconia abradable for 4-point bend test.

The strenght/strain curve (Fig.14) starts with almost elastic behaviour, thus allowing the determination of the theoretical E-moduli for the zirconia coatings of different porosity. Increased strength results in pseudo-elastic behaviour which can be related to the porous lamellar micro structure of the coating and the partial stress relief by the induced micro cracking /5/. Further stress increase leads to spontaneous destruction of the coating.

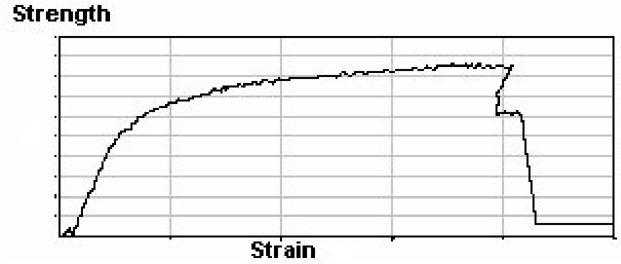

Fig. 14. Example of a typical strength/strain curve at 700°C.

Based on the test results zirconia test powder ‘XP160’ was chosen as surface layer material, as it has a higher expansion limit and a lower E-module compared to other tested materials. The rub-in test also identified this material with better abradability than the other materials.

5.2. Abradability Rig

A rig was specifically designed and built for testing the abradability of sealing materials for rotating machinery. The test rig consists of two major components:

- a rotor with one somewhat longer dummy blade (→ ‘rub-in’ blade) of Ti6Al4V with cBN grains brazed onto the tip in order to perform the incursion into the abradable
- a casing which is heated to the temperature level of the rotor stage in the engine using a high temperature gas jet. The casing is then driven into contact with the tip of the rotating ‘rub-in’ blade (Fig.15) /6/.

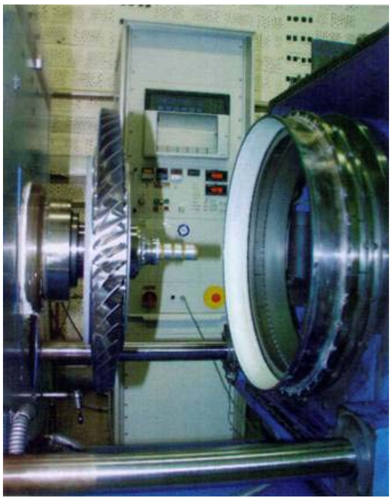

Fig. 15. Rig for testing abradability

The testing procedure is as follows:

- The rotor is accelerated to the required engine operating speed.
- During this time, the coated casing is heated-up to the required temperature, eg 340°C, which is measured using a thermocouple attached to the reverse side of the casing.
- The test is started by moving the casing radial towards the rotor at a set incursion speed of 10, 100 and 10000µm/s respectively.
- Abrading takes place until the required incursion depth 0.2mm and 0.4mm respectively is reached.
- The casing is quickly moved away from the tip of the ‘rub-in’ blade.

During the test the casing is continuously heated to hold the test temperature even when the sectional rub-in is taking place.

The temperature increments measured on the casing outer wall during testing are up to 30°C, depending on the conditions of blade thickness and chord length.

It has been demonstrated that the zirconia layer with the graduated porosity has very good abradability at 0.2mm incursion depth independently of the incursion speeds. There was no damage to the blade tip, a slight groove has been observed on the surface of the abradable due to the rub-in (Fig.16).

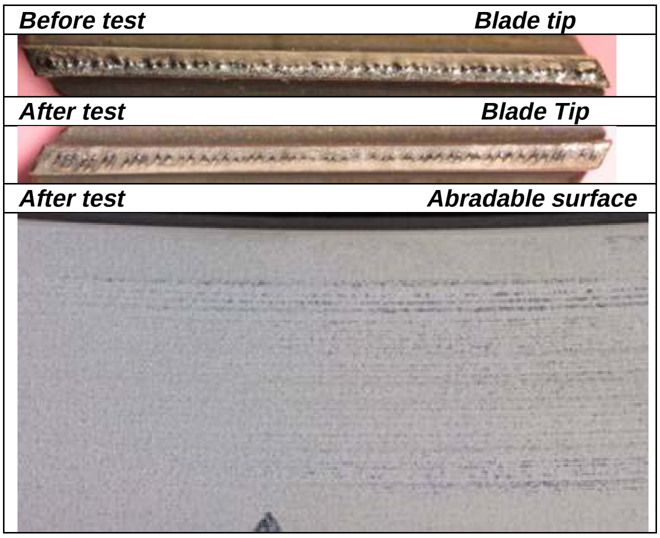

Fig. 16. Blade tip before and after rub-in test on abradable with graduated porosity, incursion depth 0.2 mm

At 0.4mm incursion depth the blade tip was overheated and the cBN protection completely rubbed off (Fig.17). This behaviour is not expected in turbo machines as there the rubbing work is shared in many blades and not restricted to only one ‘rub-in’ blade.

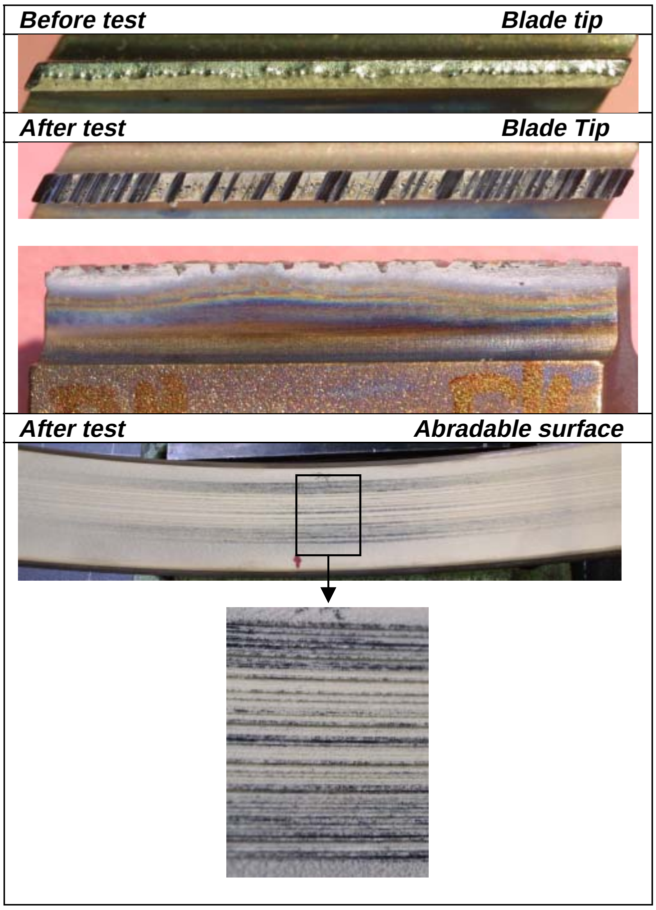

Fig. 17. Blade tip before and after rub-in test on abradable with graduated porosity, incursion depth 0.4 mm

5.3. Erosion Rig Test

The erosion test rig simulates foreign particles and debris impinging on surface of the abradable at high velocities, similar to those which might be found in the primary gas path of a turbo machine. The apparatus provides a high velocity gas stream impinging on a test sample set at different angles of attack to the direction of the gas flow. Sand or abrasive grit is added to the gas stream at a controlled weight rate. Testing is carried out at a given feed rate (5 g/h) for a fixed period of time with the impact velocity (250 m/s) of the particles. Fig.18 shows the typical erosion areas of abradables and indicates the erosion depths.

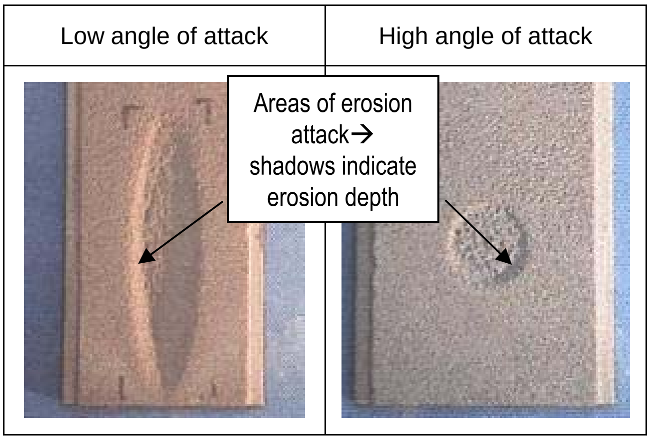

Fig. 18. Samples after test in erosion rig

Fig.19 shows the erosion depth vs the exposure time. The double layer reveals a linear increase and the layer with graduated porosity a logarithmic increase. At the beginning of the test, both sealing systems had identical erosion resistance. After 10 min exposure time the layer with graduated porosity showed better erosion resistance than the double layer. The longer the erosion test was run, the better the erosion resistance was for the layer with the graduated porosity compared with the double layer sealing system. This is presumably based on the graduated porosity.

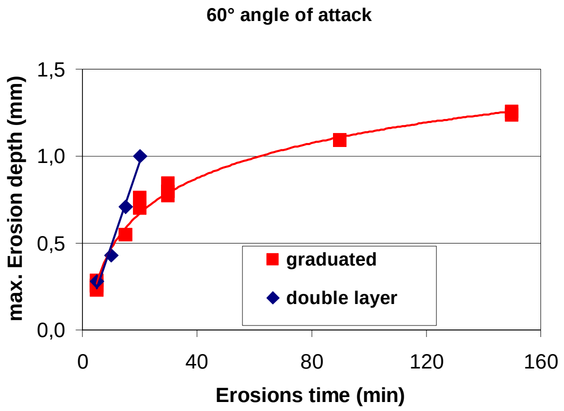

Fig. 19. Erosion depth vs erosion time of the double layer and the layer with graduated porosity, angle of attack 60°

The results were confirmed by tests with 10° angle of attack. Fig.20 shows the erosion times vs erosion depths.

The layer with the graduated porosity has a better long time erosion resistance than the multiple layer (here: double layer abradable).

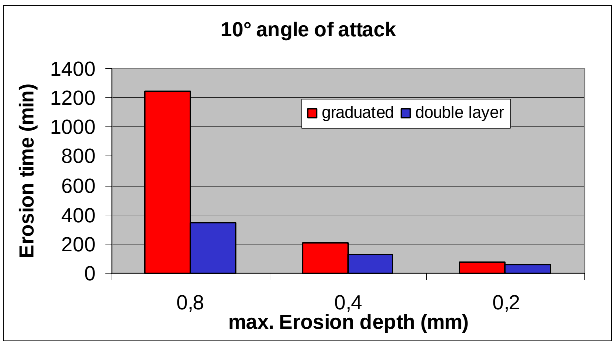

Fig. 20. Erosion times vs erosion depths for the double layer and the layer with the graduated porosity, angle of attack 10°

5.4. Titanium Fire Rig

The main components of the titanium fire rig are:

- test chamber
- air pre-heater
- adjustable specimen carrier for simulation of various impingement angels of the hot flash (simulating Ti fire)
- Ti stripe of defined mass, which is ignited in the test in order to simulate the effects and duration of the fire
- igniter
- exhaust diffuser with adjustable outlet
- instrumentation for measurement of temperature, pressure and air flow velocity
- TV camera to allow the processes inside the test chamber to be observed and recorded.

The distance between the specimen and the burning Ti stripe, the combustible mass of the stripe and the impingement area depend on the conditions in the engine such as air pressure, velocity of the airflow at the end of the acceleration path and the temperature of the preheated coating. During the test a piece of Ti stripe with a mass of approx. 12 grams (1/2 oz) was ignited. It was a very violent short conflagration accompanied by temperatures reaching up to 3300°C /7/. Such high temperatures destroy the sample.

For the evaluation of the effectiveness (containment) of the abradable system against Ti-fire the maximal burn-off depth on the coating was measured (Fig.21).

Fig.22 shows the maximal burn-off depth on abradable coatings of different abradable systems in relation to the gas flow velocity:

- The higher the flow velocity is, the more extensively the coatings were damaged.
- At the same gas flow velocity, the burn-off depth of the coatings decreases with increased hardness of the

tested coating. The hardness correlates with the density of the porous coating.

- All sealing systems had sufficient coating thickness left for Ti fire containment after the tests.

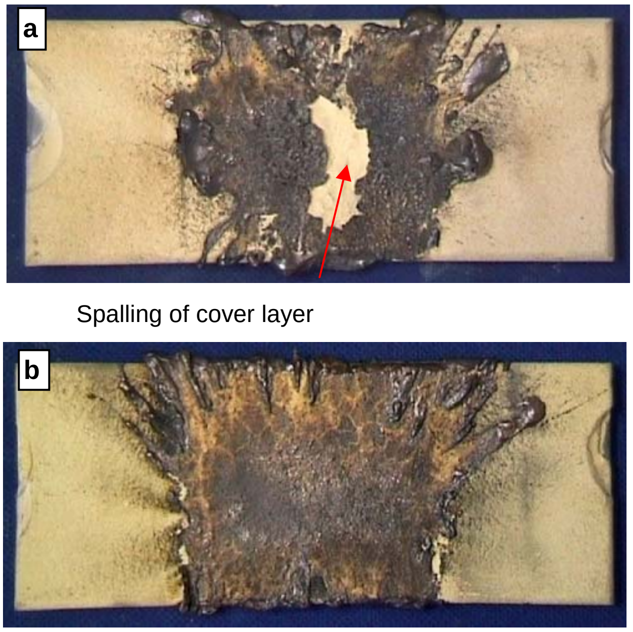

Fig. 21. Abradable coating sample after test in Ti-fire rig
a. double layer abradable
b. graduated porosity abradable

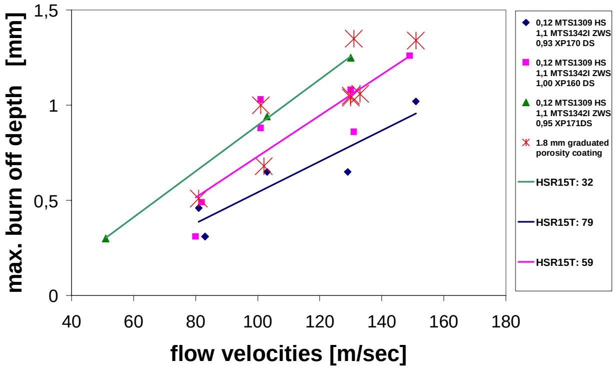

Fig. 22. Maximal burn-off from the coating thickness of different sealing systems

5.5. Thermal Fatigue Test

In this test the coated casing is heated up by a combustion chamber to the maximum component temperature of 600°C and subsequently cooled down with compressed air to about room temperature. A thermal cycle consists of 6 minutes heating and 6 minutes cooling, there are 5 cycles per hour. The temperature gradient through the coating is controlled at 180°C during cooling. The whole circumference of the coating system was inspected at the interface of bond coating by thermography and optical observations on the surface after test. Adhesive defects in abradables can be detected by thermography, see Fig.23 /3/.

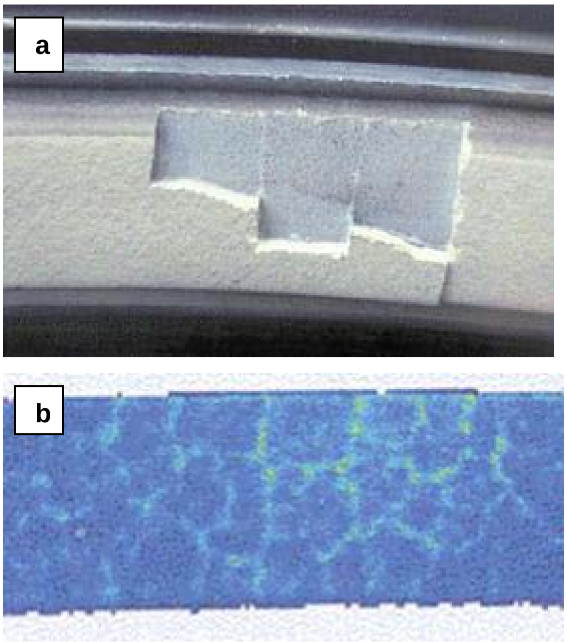

Fig. 23. After thermal fatigue test
a. chipping of abradable coating
b. thermography image indicating condition at bond coating

After 0, 10, 100 and 1000 test cycles no adhesive defect was detected at the bond coating interface and no cracks at the surface of the coating were observed up to 1000 cycles of thermal fatigue testing.

These results clearly proved that the zirconia abradable with graduated porosity developed by MTU has sufficient crack initiation resistance against cyclic loading of thermal shock.

6. CONCLUSIONS

Zirconia abradable coatings have been developed for seal systems. The main requirements as abradability, erosion resistance, high temperature resistance, thermal shock and Ti fire resistance have been evaluated in different rig tests.

- Zirconia abradable of ‘XP160’ type test powder with certain porosity is abradable by use of cBN protected Ti blades at either low or high incursion rates with 0.2mm incursion depth.
- The abradable layer with graduated porosity revealed its erosion resistance especially in long-time erosion test better than those of multiple layer systems.
- The tested zirconia abradables had sufficient coating thickness left for Ti-fire containment.
- Thermal fatigue tests up to 1000 cycles in the burner rig on coating with graduated porosity and multiple layers revealed the systems free of bonding defects.

The zirconia abradable coating with graduated porosity currently under investigation can help to solve the problems of conflicting requirements for seal materials in an advanced jet engine application and can be used in the compressors as well as in the turbine sections.

7. ACKNOWLEDGEMENT

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