



HAL
open science

Experimental Evaluation of Abradable Seal Performance at High Temperature

Azzedine Dadouche, Martin Conlon, Waldemar Dmochowski, Brian Liko,
Jean-Pierre Bédard

► **To cite this version:**

Azzedine Dadouche, Martin Conlon, Waldemar Dmochowski, Brian Liko, Jean-Pierre Bédard. Experimental Evaluation of Abradable Seal Performance at High Temperature. ASME Turbo Expo 2008: Power for Land, Sea and Air, Jun 2008, Berlin, Germany. pp.143 - 150, 10.1115/GT2008-51228 . hal-01430519

HAL Id: hal-01430519

<https://hal.science/hal-01430519>

Submitted on 10 Jan 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

EXPERIMENTAL EVALUATION OF ABRADABLE SEAL PERFORMANCE AT HIGH TEMPERATURE

A. Dadouche, M. J. Conlon, W. Dmochowski, B. Liko and J.-P. Bedard

Gas Turbine Laboratory
Institute for Aerospace Research
National Research Council
Ottawa, Ontario, Canada

ABSTRACT

Abradable seals have been used in aero-engines and land-based gas turbines for more than three decades. They are applied to various sections of the engine in order to reduce gas leakage by optimizing the gap between rotating and stationary parts. This optimization represents a significant increase in efficiency and decrease in fuel consumption. Performance evaluation of any abradable seal includes measurement of its mechanical properties, abrasability tests and (ultimately) tests in engines. The aim of this paper is to study the effect of temperature on the rub performance of abradable seals. A series of experiments has been carried out in order to evaluate a commercially available seal material at different operating conditions. The effect of operating temperature on contact force, abrasion scar appearance and blade wear is examined and analyzed. A microstructural analysis of the rub scar has also been performed.

INTRODUCTION

Abradable seals are widely used in aero-engines and land-based gas turbines (for power generation) to minimize gas leakage between the blades and the casing. Abradable application on stationary parts results in an optimal gas path and increased efficiency. Reducing leaks around the rotating parts serves to maximize the amount of working gas and minimize power loss. Fuel consumption represents 53% of the operating cost of an aircraft [1, 2], emphasising the importance of implementing a good seal with minimal gap. Abradables have to be carefully designed to accommodate rub situations that might result from maneuver-

ing and landing loads, vibration of casing and rotor, thermal expansion of the engine rotor, centrifugal and gyroscopic forces, as well as poor assembly and machining tolerances, without damage to the engine components. To illustrate the importance of a good seal, an extra gap of five thousandths of an inch (0.127 mm or 0.005 in) can increase the fuel consumption by 0.5% [3]. On the other hand, a gain of 0.3 to 1% in power output and up to 5% in efficiency could be realized through seal system improvements [4, 5].

Typically, metallic abradable coatings are used in the compressor side of a gas turbine and ceramic materials are used in the turbine side. The choice of material for a given application depends on the operating environment, particularly the temperature to which the coating will be exposed, rubbing element material and geometry, seal durability and economics [6]. A variety of seals have been developed over the last few decades and are now commercially available, however, as engine technology evolves towards higher power density there is a need to develop abradables capable of performing under severe operating conditions such as extremely high temperatures and abrasive environments. Most aircraft engines operate with temperatures greater than 1000°C in their turbine sections; the F110, M88, F100 and EJ200 have turbine inlet temperatures of 1427°C , 1570°C , 1399°C and 1477°C , respectively [7].

A typical abradable seal material is purchased in powder form, and may be deposited by several different thermal spray techniques. These techniques are well established in the industry

and include deposition by combustion (flame), plasma, and high-velocity oxyfuel (HVOF) spray. Thermal spray offers several advantages, including simple overhaul and repair, and a variety of coating materials are available [1]. Examples of some of the abrasives already on the market are:

- Aluminum-alloy-polyester that can be either plasma or HVOF sprayed and is suitable for service at temperatures as high as $343^{\circ}C$ ($650^{\circ}F$),
- Aluminum-alloy-graphite that can be either combustion or plasma sprayed and is suitable for service at temperatures up to $482^{\circ}C$ ($900^{\circ}F$),
- Nickel-graphite (15 to 25 weight % graphite) that can be used up to $343^{\circ}C$ ($650^{\circ}F$) and offers better corrosion resistance and,
- Ni-Cr-Fe-Al-BN abrasives that are combustion sprayed and used for engine sections that reach temperatures of up to $816^{\circ}C$ ($1500^{\circ}F$).

Abradable materials must satisfy many requirements to be considered as an efficient seal system, and these have been extensively discussed in the literature. Novinski [8,9] summarizes the design criteria for abrasives, their microstructure and application to various gas turbine sections. From a design point of view, abrasives must meet the following expectations:

- Be abrasible and durable:
 - Be readily abrasible
 - Have a consistent microstructure
 - Be resistant to impact from abrasive particles traveling through the engine at high velocity and to degradation at elevated temperatures
 - Be resistant to salt water and engine fuel
 - Be resistant to oxidation
- Rub and age well with stable mechanical properties in the harsh environment of gas turbine engines
- Wear by disintegrating into fine particles; debris must not damage any components downstream within the gas turbine
- Cause minimal wear of blade tips or knife edges
- Generate low contact friction
- Maintain a smooth surface in order to reduce aerodynamic losses, despite releasing wear debris
- Rubbing should break the bond between particles rather than melt the particles themselves

Some of those requirements such as abrasibility and durability are contradictory; however, designing a seal system that performs well involves striking a balance between these opposing requirements.

There is no standard method or procedure for testing abrasible materials. Mechanical properties of an abrasible material, such

as hardness and ultimate tensile strength, are not guarantees of good performance [6], therefore additional testing must be carried out to establish which materials would be good candidates for further development. These other testing methods may include a porosity analysis through imaging on cross-sectional micrographs, erosion resistance testing (ASTM G76), oxidation life and abrasibility testing. Abrasibility tests could be performed at room temperature or in an environment similar to that seen during service. Usually results from abrasible testing provide sufficient confidence to apply coatings to engine sections for testing. To-date, there has been good correlation between wear rig results and engine results [6].

This paper presents the results of an experimental investigation carried out to determine the effects of temperature on the wear performance of a commercially available abrasible seal. Some realistic service conditions such as thermal growth and dynamic loading have been simulated during tests on the National Research Council Canada's abrasible test rig.

RIG DESCRIPTION AND TEST PARAMETERS

The wear rig used to carry out the tests is shown in Fig. 1. This rig simulates operational wear using a simulated turbine blade or knife-edge. It consists of a rotor driven by an air turbine and supported on hybrid rolling-element bearings. The rotor can be spun up to $40,000\text{ rpm}$, which corresponds to a blade tip speed of 425 m s^{-1} (1400 ft s^{-1}). The motion of the table on which the test coupon holder is mounted is controlled axially and radially through two servomotors. Its speed varies from 0.0025 mm s^{-1} to 0.76 mm s^{-1} (0.0001 in s^{-1} to 0.03 in s^{-1}). The test coupon's fixture is adaptable for testing both flat and curved profiles. The rig is also capable of testing heated abrasibles up to a temperature of $600^{\circ}C$ using a ceramic-encased, wire-wound resistor located at the back of the test coupon.

The rig is equipped with various sensors measuring rub temperature, rubbing forces (both radial and tangential), speed and seal incursion rate. After each test, blade and abrasible seal wear is measured. Other parameters such as vibration and bearing and environment temperatures are monitored while testing. All data are acquired using a computerized data acquisition system.

As mentioned earlier, the abrasible seal analyzed in this study is commercially available; it is a Cobalt-Nickel-based material ($Co\ 25Ni\ 16Cr\ 6.5Al\ 0.5Y$) used in the high pressure compressor section of gas turbines where the temperature could reach $600^{\circ}C$. The powder was sprayed on flat Hastelloy X substrates, ground flat to produce a smooth seal surface and then heat treated to burn off the polymer, resulting in a porous material (Fig. 2). The tests were performed using untipped Inconel 718 material blades with a tip width of 6.35 mm (0.25 in).

Table 1. Test conditions

	Room Temperature	High Temperature
Blade Speed ($m s^{-1}$)	{152, 305, 396}	{152, 305}
Incursion Rate ($mm s^{-1}$)	{0.00254, 0.127, 0.381, 0.762}	{0.00254, 0.127, 0.381, 0.762}

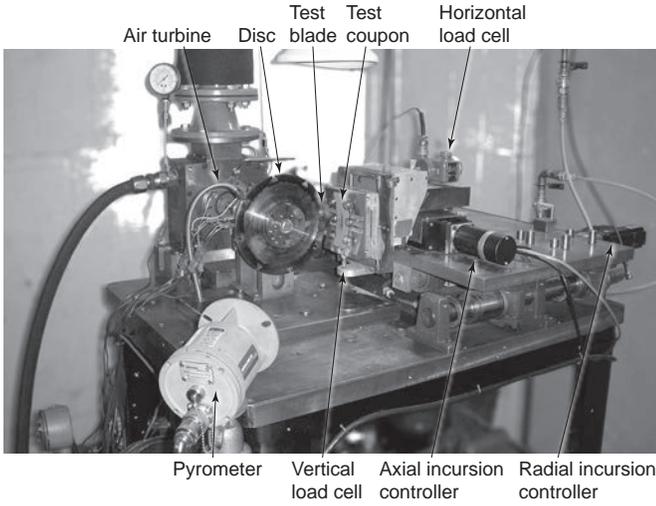


Figure 1. Abradable test rig

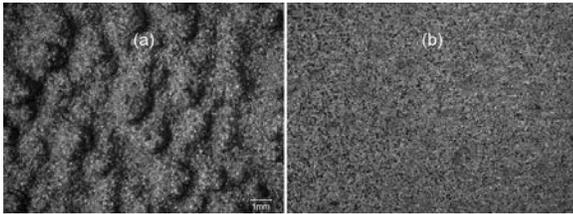


Figure 2. Abradable coupons (a) as sprayed, and (b) after grinding

The most important test parameters when evaluating abradable seal performance are blade tip speed, incursion rate and environment temperature. These parameters must replicate the operating conditions that abradable seals are normally subjected to. Usually such parameters are specified by end users or manufacturers; for this study, a test matrix has been selected to cover various conditions encountered in gas turbines such as thermal growth, excessive external loading and engine vibration. Table 1 shows the test parameters used in this study. It is important to mention that only the seal was heated during the high temperature tests and, depending on the disk's rotational speed, the seal surface temperature drops due to the windage generated by the disk

rotation. It is also worth mentioning that all tests were carried out using a single working blade with a total of 1 mm (0.040 in) seal incursion. A second, shorter and thicker blade, located 180 degrees from the test blade was used for balancing. In a real application, multiple blades rub against the seal material; using a single blade creates an extreme operating condition.

DATA ANALYSIS AND DISCUSSION BLADE AND SEAL WEAR

Quantification of the blade and seal wear due to their interference during the abrasion process is rather difficult because of the complexity of the rubbing phenomenon. In Fig. 3, an estimation of the blade material loss is presented for different incursion rates and blade speeds for tests done at room temperature. As the wear bars show, for blades speed of $152 m s^{-1}$ and $305 m s^{-1}$, the material loss is only marginally affected by the incursion rate. However, for a speed of $396 m s^{-1}$ the material loss is noticeably affected by incursion rate; the wear at the lowest incursion rate ($0.00254 mm s^{-1}$) is only 12% of that at the higher incursion rate ($0.762 mm s^{-1}$). It is important to highlight that the measured blade material loss represents an estimation rather than a quantification; in many cases seal material or wear fragments were transferred to the blade tip, filling some of its gouges and furrows (Fig. 4). For an incursion rate of $0.127 mm s^{-1}$ and blade speed of $305 m s^{-1}$ (Fig. 3), the masses of the blades after testing were slightly higher than the baseline mass, which is an indication of seal transfer to the blade tip. As a result of that, the wear bar for this specific case is negative. During the tests, the blades become slightly polished at their leading and trailing cutting edges and seal particles adhere to the blade tip, appearing as gray and burnt (high temperature oxidation) areas throughout the tip surface (Fig. 5a and 5b). In Fig. 5a and 5b, one can notice a small number of vertical streaks which were formed during manufacturing; Fig. 5c shows an untested blade tip.

Figures 6 and 7 present a comparison between the blade material loss at room- and high-temperature for various incursion rates and a blade speed of $152 m s^{-1}$ and $305 m s^{-1}$, respectively. Generally the room temperature tests exhibit higher blade wear compared to the heated tests for all incursion rates. (The cases where the room temperature tests show lower or no blade wear were discussed in the previous paragraph.) The examination of

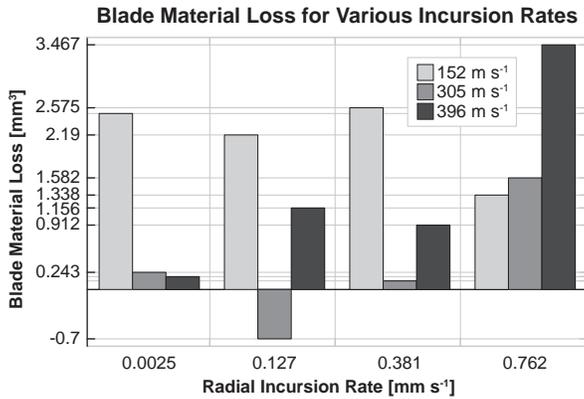


Figure 3. Blade material loss at room temperature

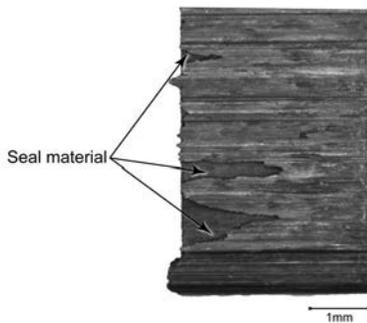


Figure 4. Seal particle adhesion on blade tip

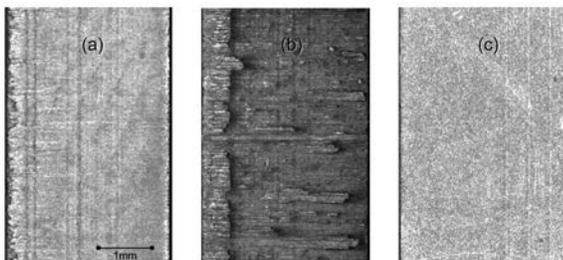


Figure 5. Sample blades (a) room temperature 0.127 mm s^{-1} incursion rate 305 m s^{-1} blade tip speed, (b) same test conditions, and (c) untested blade

the blades following the tests revealed that those tested at high temperature appeared better both in terms of wear and severity of the scratches. As an example, Fig. 8 shows two blades tested at room and high temperature at a relatively high incursion rate of 0.381 mm s^{-1} and a low speed of 152 m s^{-1} . The blade tested at room temperature (Fig. 8a) is characterized by deep grinding

marks, discoloration, burning, and material deformation at the blade edges, whereas the blade tested at high temperature suffered minimal wear and only slight discoloration. The abrasible seal at room temperature must be harder and its mechanical properties must be higher than those at high temperature. This may lead to a severe interaction with the blade during the abrasion where the hard microscopic abrasible particles score the blade tip as the seal moves towards it.

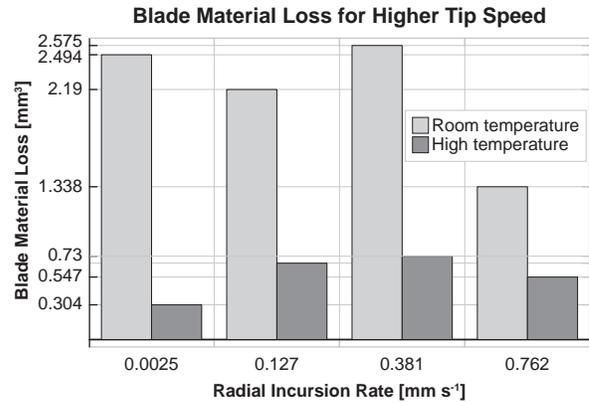


Figure 6. Blade material loss at 152 m s^{-1} blade tip speed

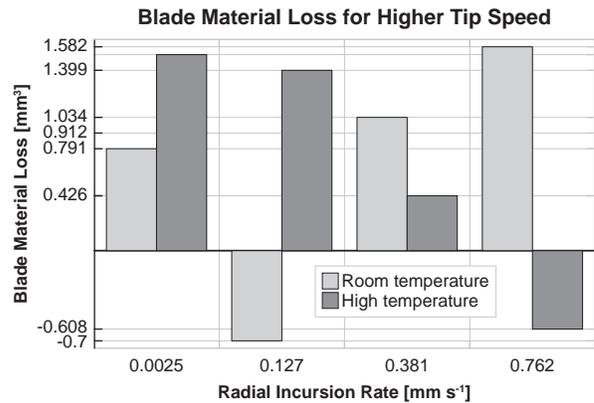


Figure 7. Blade material loss at 305 m s^{-1} blade tip speed

Estimating the seal material lost during the abrasion is challenging due to the porosity of the abrasible and the irregularities of the rub scar; this is especially true for the high temperature

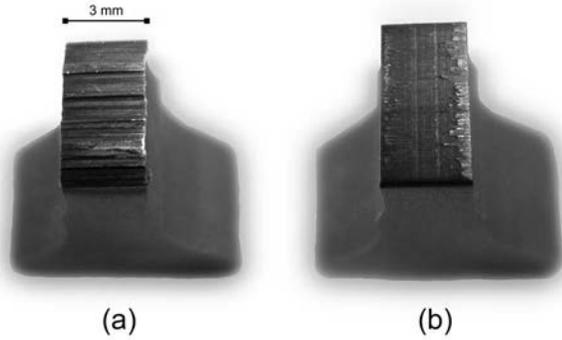


Figure 8. Blade tips after abrasion at test conditions of 0.381 m s^{-1} and 152 m s^{-1} (a) room temperature, and (b) high temperature

tests. However, measurement of the scar depth at its mid section produced consistent values ranging from 0.9 mm to 1.14 mm throughout its width depending on the test conditions.

The scar appearance represents but one of the important criteria when evaluating abradable seals. All room temperature tests produced smoother rub grooves when compared with the high temperature tests, which produced scars which were typically rough and irregular. Moreover, the room temperature tests at the lowest incursion rate resulted in a better scar finish than the higher incursion rate tests, especially for higher blade tip speeds. Figures 9 and 10 show the different scars obtained for room temperature and heated tests at a low blade tip speed of 152 m s^{-1} and various incursion rates. A comparison between the two figures highlights the significant differences in terms of scar appearance and uniformity: the room temperature test scars are mostly regular and uniform, whereas all the high temperature scars are irregular with a large number of gouges due to tearing and spalling rather than disintegration into fine particles.

Figure 11 shows scanning electron microscope (SEM) images of a small portion of the rub scar tested at the highest incursion rate (0.762 m s^{-1}) and lowest blade tip speed (152 m s^{-1}). As the images show, the room temperature test (Fig. 11a) results in a smoother rubbing surface when compared to the high temperature test (Fig. 11b).

CUTTING FORCES

There are three control parameters that can affect the cutting forces in these tests: incursion rate, blade speed and temperature. It is useful to look at the test data in terms of each parameter in turn. We normalize the time data using the incursion interval. This means that the area under the force curve is a sort of “specific impulse” for the duration of the rub. This facilitates comparison between rubs at different incursion rates.

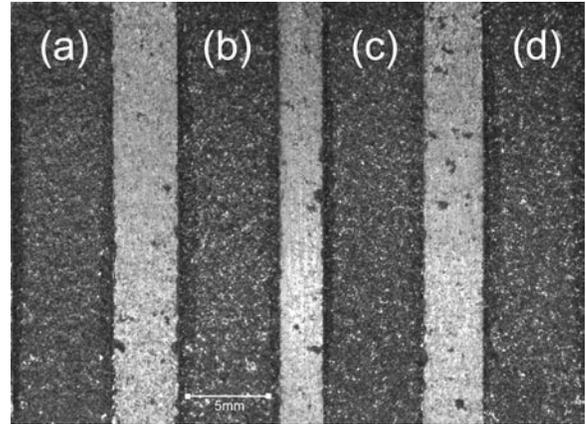


Figure 9. Rub scar appearance for a room temperature test at a blade speed of 152 m s^{-1} and incursion rate of (a) 0.00254 m s^{-1} , (b) 0.127 m s^{-1} , (c) 0.381 m s^{-1} , and (d) 0.762 m s^{-1}

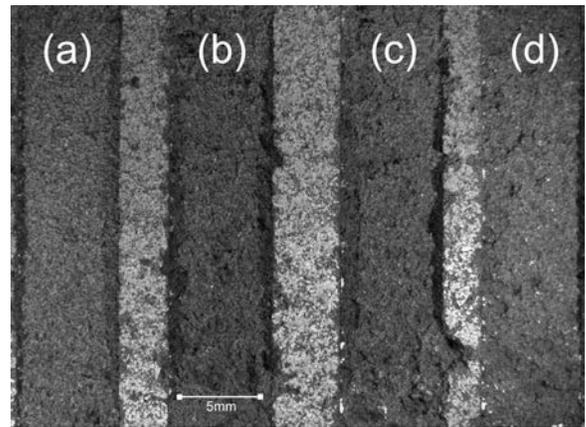


Figure 10. Rub scar appearance for a high temperature test at a blade speed of 152 m s^{-1} and incursion rate of (a) 0.00254 m s^{-1} , (b) 0.127 m s^{-1} , (c) 0.381 m s^{-1} , and (d) 0.762 m s^{-1}

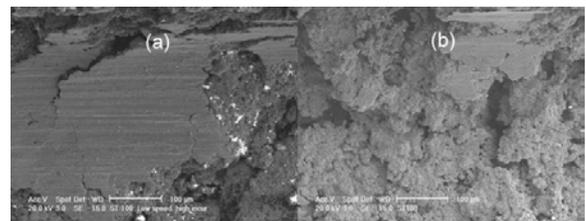


Figure 11. SEM images of rub scars at an incursion rate of 0.762 m s^{-1} and a blade tip speed of 152 m s^{-1} at (a) room temperature, and (b) high temperature

For an idealized rub, we would expect the reaction forces to increase nonlinearly as

$$F_r(t) \propto \arccos\left(1 - \frac{i(t)}{r}\right) \quad (1)$$

where F_r is the net reaction force, i is the incursion distance and r is the rotor radius. In reality we see this predictable force increase only at the lowest incursion rate, $0.00254 \text{ mm s}^{-1}$, as shown in Fig. 12. Figure 12 presents the tangential component of the rub force plotted versus rub interval fraction for three different blade tip speeds.

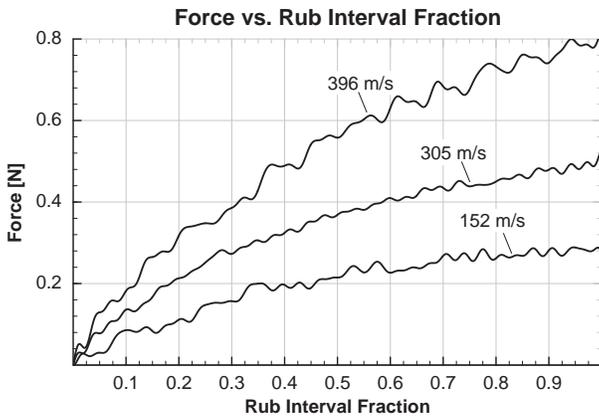


Figure 12. Force versus rub interval fraction for a $0.00254 \text{ mm s}^{-1}$ incursion rate

THE EFFECT OF INCURSION RATE

For higher incursion rates we would expect larger rubbing forces, however the incursion itself happens over a much shorter time interval, which illustrates the utility of normalizing the incursion time with respect to the rub interval. Table 2 outlines the percent change in specific impulse for different blade speeds, comparing the highest incursion rate with the lowest. We see that for all but the lowest blade speed the specific impulse is higher at the higher incursion rate. The trend is parabolic with respect to blade tip speed, as might be expected.

THE EFFECT OF BLADE SPEED

As seen in Fig. 12, the specific impulse of the lowest-speed incursion increases with blade speed. This is not the case for

Table 2. Relative change in specific impulse with increased incursion rate (for different blade speeds)

Blade Speed (m s^{-1})	Specific Impulse (% Change)
152	-400
305	+20
396	+70

the highest incursion rate, as outlined in Tab. 3, where the higher blade speed produces a lower specific impulse. This may be due to the abrasion mechanism; the higher incursion rate is two orders of magnitude larger than the lowest-speed incursion, and one could expect a substantial difference in the two abrasions. Indeed, as discussed previously, there is a distinct difference in the scar appearance for the two abrasion rates. The low-speed incursion rate produces a much smoother scar than the high incursion rate.

Table 3. Relative change in specific impulse with blade speed (for different incursion rates)

Blade Speed (m s^{-1})	Incursion Rate (mm s^{-1})			
	0.00254	0.127	0.381	0.762
152	—	—	—	—
305	+90%	—	—	-70%
396	+200%	—	—	-80%

THE EFFECT OF TEMPERATURE

Table 4 presents the effect of temperature on the specific impulse for the four incursion rates. For all but the lowest incursion rate increasing the seal temperature results in decreased cutting forces. This effect is independent of blade speed, as seen in Fig. 13–16 which compare ambient and high-temperature cutting forces for the two extreme incursion rates, and two different blade speeds.

Table 4. Relative change in specific impulse with increased temperature (for different incursion rates)

Blade Speed ($m s^{-1}$)	Incursion Rate ($mm s^{-1}$)			
	0.00254	0.127	0.381	0.762
152	+70%	-90%	-60%	-40%
305	+60%	—	—	-40%

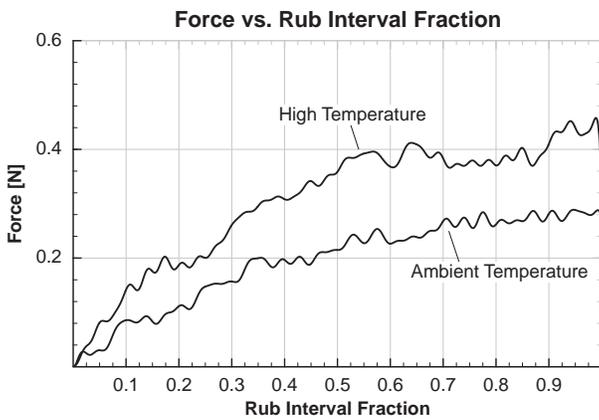


Figure 13. Force versus rub interval fraction for a $0.00254 mm s^{-1}$ incursion rate and $152 m s^{-1}$ blade speed at different temperatures

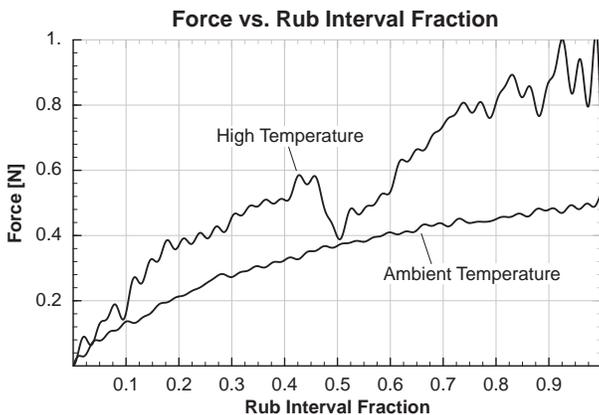


Figure 14. Force versus rub interval fraction for a $0.00254 mm s^{-1}$ incursion rate and $305 m s^{-1}$ blade speed at different temperatures

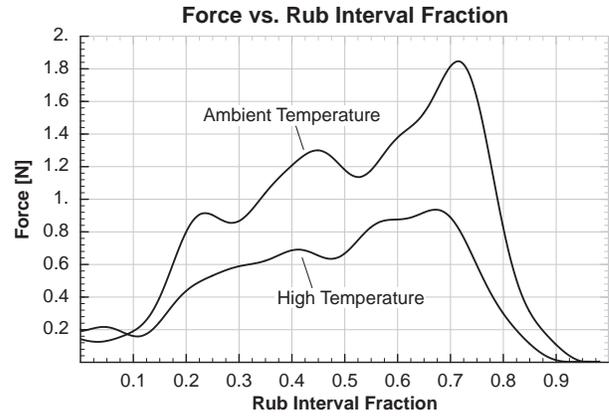


Figure 15. Force versus rub interval fraction for a $0.762 mm s^{-1}$ incursion rate and $152 m s^{-1}$ blade speed at different temperatures

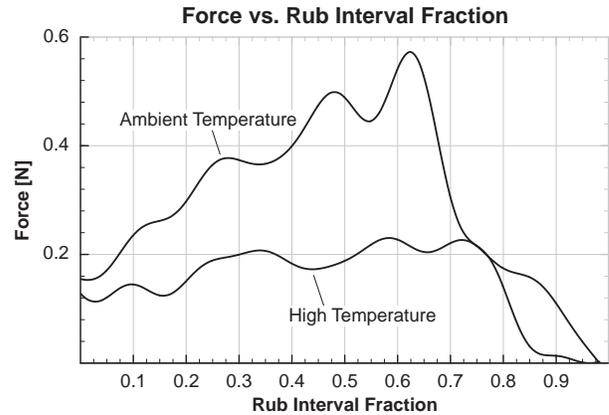


Figure 16. Force versus rub interval fraction for a $0.762 mm s^{-1}$ incursion rate and $305 m s^{-1}$ blade speed at different temperatures

Figures 13 and 14 present the tangential cutting force for ambient and high temperature tests with an incursion rate of $0.00254 mm s^{-1}$ and blade speeds of $152 m s^{-1}$ and $305 m s^{-1}$ (respectively). For this low incursion rate both the ambient and high temperature force profiles display the trend predicted by Eq. 1. The forces recorded during the high-temperature testing are more variable, which corresponds well with the rougher scar appearance. In Fig. 14 in particular, we see that the high temperature cutting force drops suddenly just under halfway through the rub. The force eventually recovers to the expected level, suggesting that perhaps a chunk of seal material broke off at that point during the rub.

In Figures 15 and 16 we see the tangential force profiles for ambient and high temperature tests with an incursion rate of 0.762 mm s^{-1} and blade speeds of 152 m s^{-1} and 305 m s^{-1} (respectively). For this incursion rate, the cutting forces are higher for the ambient tests and similarly higher for the lower blade speeds, as previously summarized in Tab. 3 and Tab. 4.

CONCLUSIONS

The effect of testing abrasible seals at high temperature was studied and analyzed in this paper for a better evaluation of their performance characteristics. Blade material loss, rub scar and interaction forces were analyzed for different test conditions and parameters. However, there is a need to complement this study by heating both seal and blade for an accurate assessment. The main conclusions drawn from this study are as follows:

- Testing abrasibles at high temperature affects the rub characteristics.
- Heating the seal results in less blade wear and a rougher scar surface.
- The blade tip may sustain severe wear at room temperature, especially at high incursion rates.
- Evaluation of abrasible seal performance at room temperature should be followed by testing at high temperatures.
- Rub forces are substantially affected by temperature, and in a less-than-intuitive manner, which necessitates high-temperature testing.
- Forces are also affected by blade speed and incursion rate, and larger forces seem to correlate well with rougher scar appearance.

REFERENCES

- [1] Novinski, E. R., 1991. "THSP coatings save aircraft engines". *Welding Design and Fabrication*, April, pp. 26–28.
- [2] Stern, J. A., 1976. Aircraft propulsion — a key to fuel conservation: An aircraft manufacturer's view. Tech. rep., SAE Paper 760538.
- [3] Ferguson, J. G., 1978. "Use of coatings in turbomachinery gas path seals". AGARD Seal Tehcnology in Gas Turbine Engines. SEE N79-11056 02-07.
- [4] Chupp, R. E., Lau, Y.-C., Gharispor, F., Baldwin, D. J., Ng, C., McGovern, T., and Berkeley, D., 2004. "Development of higher temperature abrasible seals for gas turbine applications". ASME Turbo Expo 2004: Power for Land, Sea and Air.
- [5] Schmid, R. K., 1996. "1200° reached". *Sulzer Technical Review*, February, pp. 34–37.
- [6] Hajmrle, K., Fiala, P., Chilkowich, A. P., and Shiembob, L. T., 2004. "Abradable seals for gas turbines and other rotary equipment". ASME Turbo Expo 2004: Power for Land, Sea and Air.
- [7] FORECAST INTERNATIONAL, 2004. *Gas Turbine Forecast*, July.
- [8] Novinski, E. R., 1989. "The selection and performance of thermal sprayed abrasible seal coatings for gas turbine engines". SAE Annual Aerospace/Airline Plating and Metal Finishing Forum and Exposition.
- [9] Novinski, E. R., 1991. "The design of thermal sprayed abrasible seal coatings for gas turbine engines". 4th National Thermal Spray Conference, pp. 451–456.