Interfaces—Weak Links, Yet Great Opportunities

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Abstract

Inadequate turbomachine interface design can rapidly degrade system performance, yet provide great opportunity for improvements. Engineered coatings of seals and bearing interfaces are major issues in the operational life of power systems. Coatings, films, and combined use of both metals and ceramics play a major role in maintaining component life. Interface coatings, like lubricants, are sacrificial for the benefit of the component. Bearing and sealing surfaces are routinely protected by tribologically paired coatings such as silicon diamondlike coatings (SiDLC) in combination with an oil-lubricated wave bearing that prolongs bearing operational life. Likewise, of several methods used or researched for detecting interface failures, dopants within coatings show failures in functionally graded ceramic coatings. The Bozzolo-Ferrante-Smith (BFS) materials models and quantum mechanical tools, employed in interface design, are discussed.

Introduction

As designers seek to extract greater performance from turbine engines, all elements are being scrutinized for possible performance benefits including interfaces found in bearings and seals.

How well and how long interfaces will be effective in doing their job depends directly on understanding the binding energies of those interfaces and the requirements for the application. Each application has unique requirements that depend on the integrity of their interfaces, which in turn depend on substrate coated materials.

Conventional concepts of clearance interfaces in rotating machines involve bearing and seal interface coatings, materials, and fluid films [1,2]. Bearings control machine loads and dynamics. Sealing controls leakages, coolant flows, and "trim"

dynamics (unrecovered bearing loads) and are usually the most cost-effective method of enhancing performance, Hendricks et al. [3,4].

Interface coating materials are subjected to abrasion, erosion, oxidation, incursive rubs, foreign object damage, and deposits. They are also exposed to extremes in thermal, mechanical, and aerodynamic loadings (Fig. 1), including positive and negative strain ranges, large case distortions, and impact loadings. No one coating material or sealing device can effectively satisfy these variations throughout an airframe or engine (Fig. 2) and must be properly tailored to maintain each interface. Most interface coatings are composites fabricated on substrates and can be readily refurbished either in situ or by removal. It is to be noted that fully decoupled turbomachine interfaces induce large electrostatic charge gradients which can be detrimental to the health and longevity of the engine. Such interfaces must have charge release paths designed into the system.

Herein we look at some applications of coatings and materials to bearings and seals as well as some interface tools and advanced methods for detection of interface failure.

Blade-Shroud Interface Abradable Materials and Coatings

Baseline Studies

Each system differs and as such, each abradable interface has to be tribologically designed for that application. Ghasripoor et al. [6] characterized three types of coating materials: (1) aluminum silicon polyester (AlSi-(PE)), (2) aluminum silicon graphite (AlSiC), and (3) aluminum silicon hexagonal boron nitride (AlSi-hBN). The latter two are usually classified as solid lubricants while the polymer fillers of the first tend to burn out leaving a more porous structure contributing to relatively benign blade rubs.
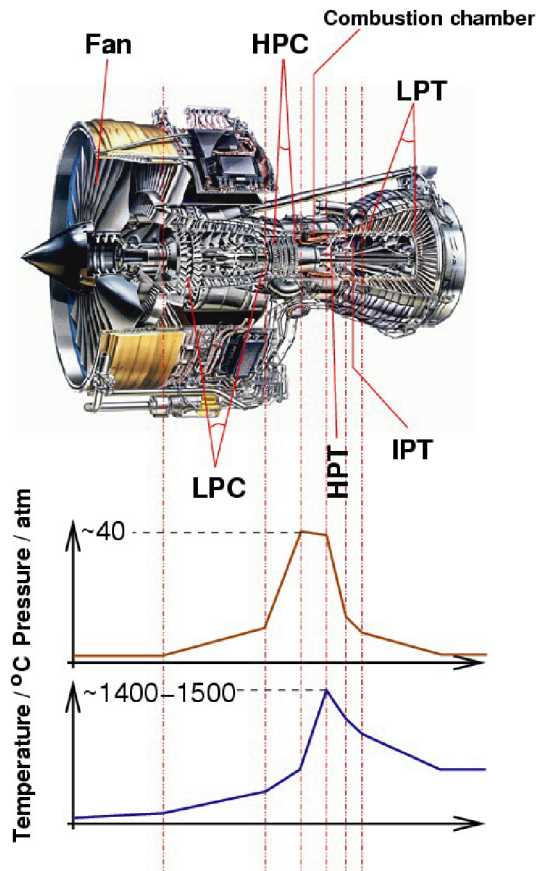
Figure 1.—Pressure and temperatures through-
out Rolls-Royce Trent gas turbine (Michael
Cervenka, Rolls-Royce) (from [5]).

AlSiC or AlSi-hBN materials are brittle, so they break more readily and have distributed networks. As a result they generally exhibit a benign microrupture wear mechanism. Material smears are minor even though the AlSi matrix may appear to have been partially molten. Graphite is abrasive to blade tips at temperatures below 200 °C (390 °F), yet the hBN should be less of a problem as it crushes more readily. AlSi without fillers tends not to microrupture and suffers from hot spot formation; AlSi and AlSi-PE can both rupture and spall with severe damage at high incursion rates with massive melting above 400 °C (750 °F).

Gas Turbine

Coatings that are created by adding a fugitive polymer such as PE or polyimide to the base metal alloy, together with a brittle intermetallic phase such as β-NiAl (325 mesh) increase the brittle nature of the metal matrix. This increases the abradability of the coating at elevated temperatures and improves oxidation resistance of the coating [7,8]. Coatings having about 12 wt% PE have been found to exhibit excellent abradability for turbine shroud coatings. An abradable coating thickness in the range between 1.016 and 1.524 mm (0.040 and 0.060 in.) provides the best performance for turbine shrouds exposed to gas temperatures between 750 °C (1380 °F) and 1010 °C (1850 °F). Tests included tip velocities to 375 m/s (1230 ft/s) comparable to Class E industrial machines.

Aero-Fan

Polymer-based shroud sealing, as in fan blade tip sealing, must have good casting properties as these materials are difficult to machine but can be ground or spot filled.
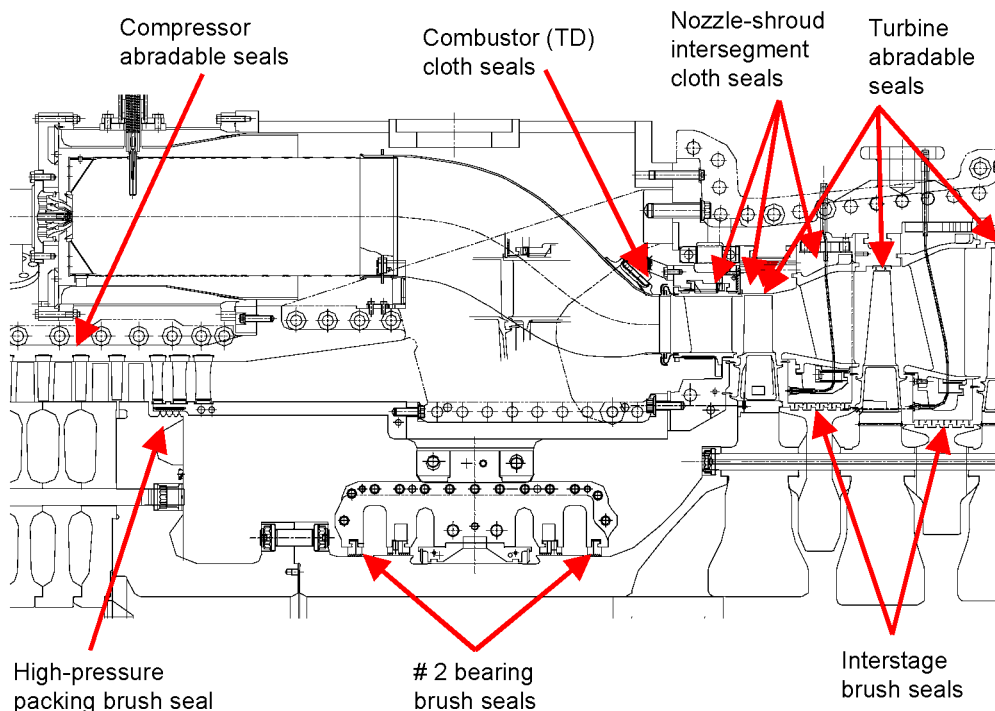

Figure 2.—Advanced dynamic seals locations in a Frame 7EA gas turbine (from [7]).

Compressor

CoNiCrAlY-hBN-15 wt% PE shows excellent abradability with nickel-based superalloy and steel blades to 700 °C (1290 °F) [9]. For titanium blades, CoNiCrAlY-hBN-20 wt% PE is a variant of those used for steel and Ni-superalloy materials and labeled as CoNi-20PE. The hardness is determined largely by the PE content. As-sprayed coatings with 40 to 50 vol% nonmetallic and less than 12 percent PE gave repeatable coating hardness with moderate reductions due to heat treatment. Titanium has half the modulus of nickel-based alloys and a propensity to burn in high-pressure oxygen and nitrogen mixtures. Military aircraft have been lost to titanium fires as a result of blade-case interaction.

Nava et al. [10] tested proprietary mixtures of flame spray (FS) and air plasma spray (APS) Ni-14Cr-8Fe-5.5BN-3.5Al (Metco 301 (Sulzer, Ltd., Winterthur, Switzerland)), APS Al-8Si-20BN (Metco 320 (Sulzer, Ltd., Winterthur, Switzerland)), and APS Al-17Cu-15Cr-13Fe (Praxair AL–147 (Praxair, Inc., Danbury, CT)). A compromise between oxidation resistance and abradability is achieved using APS AlSi-BN. In an industrial application, the abradable shroud seal life was 30 000 hr at temperatures up to 482 °C (900 °F). Schmidt et al. [11] relates that initially compressor temperatures were limited to 350 °C (660 °F), but with α-titanium alloys, temperatures of 550 to 600 °C (1020 to 1110 °F) are possible with creep and oxidation limiting life. Expectant life of compressor shroud seals are 50 000 to 100 000 hr in commercial aero and industrial gas turbines while military operations may be in the 100s of hours.

Other

APS thermal barrier coatings (TBCs) are used in the combustor and, for some engines, first vanes (nozzles) and first-stage blades of the high-pressure compressor (HPT). EB–PVD TBCs are used on the first-stage and some second-stage blades as well as first-stage vanes (nozzles). TBCs are not commonly used in the LPT due to lower heat flux and are less effective in decreasing component temperature. APS ceramics are also used on shroud seals (blade outer air seals) where they function as both a thermal barrier for the metallic shroud and abradable seal.

Processing

Vacuum brazing results in quality control problems, as it is difficult to ensure good bonding. Thermal spraying, such as APS and FS, are most widely used for compressor shroud seals; however, feltmetals are responsive to higher temperatures. Standardized testing needs to be addressed for use of abradables in engine design.

Interface Rub Mechanics

For blade and vane seal rubbing, the basic issues center on a material that mitigates blade wear while providing a durable interface that enhances engine efficiency. Blade rubs engender debris, which must be released to escape sliding contact wear of the blade tip and plowing of the interface [11]. In the high-pressure turbine (HPT) (760 °C (1400 °F) to 1150 °C (2100 °F)) interface, yttria-stabilized zirconia (YSZ) with controlled porosity is used. If blade wear is a problem, designers have devised ways to put cubic BN or SiC grits on the tips to minimize the blade wear for tight running clearances; the shroud is then cut instead. (Note: With blade-cooling boundary layers, the interface temperatures are significantly less than gas path temperatures which can be >1400 °C (2550 °F) (e.g., Fig. 1). It is the weakness of the interface that is limiting and not the ceramic itself.

Material released below surface speeds of 100 m/s is primarily forward expelled chips (cutting); while above 100 m/s the expelled particles are released backward (grinding). Blade tip wear and material transfer are dominant issues. As such, the cutting tip needs to be thin (1 to 3 mm), as thicker tips trap materials and destroy the sealing interface. For these purposes, material release, porosity, and structural strength can be controlled in both thermal sprayed coatings and fibermetals.

Some abradables are compacted when rubbed; blade tip wear increases and abradable porosity decreases. Other abradables, such as honeycomb, deform when impacted at high speeds, and the cell walls will rupture. Honeycomb wear is most pronounced at the brazed web where cell thickness doubles, which in turn impacts rotor wear. Blade tip coatings and saw teeth are employed to mitigate blade wear or damage.

The better AlSi-plastic and Ni-graphite coatings avoid the onset of adhesive melting wear and favor cutting wear. Borel et al. [12] mapped incursion velocity as a function of tangential velocity. Figure 3 shows a typical map for an AlSi-PE coating on a 3-mm-thick titanium blade. Ideally one would want near-zero rubbing over the entire circumference, which would tend to optimize the running clearances.
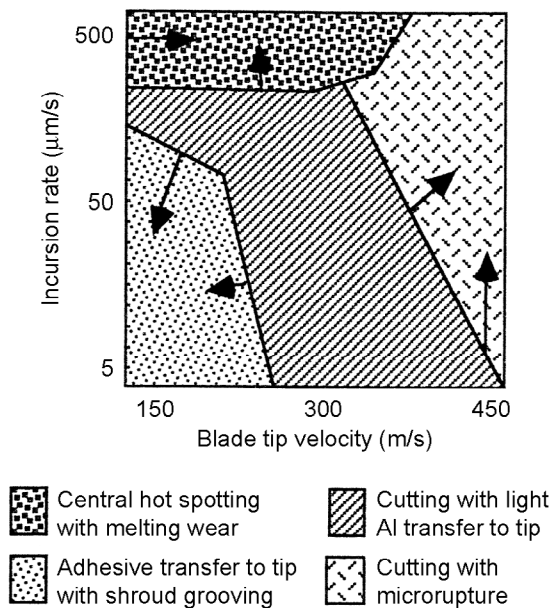

Figure 3.—Wear map of the AlSi polyester (PE) coating at room temperature as a function of incursion rate and blade tip velocity (from [2]).

Standardization

As gas velocities and tip speed increase in modern turbine engines, the task of selecting the best abradable materials becomes more challenging. Often materials that have low tensile strength exhibit the best abradability but have poor erosion resistance. The converse is also often true, as illustrated in Fig. 4 and characterized in Table 1. Because of these conflicting material characteristics, Chappel et al. [13,14] called for standardized test techniques to ensure effective selection of materials for the application.

TABLE 1.—OVERALL PERFORMANCE RANKINGS OF ABRADABLE MATERIALS USED BY CHAPPEL [13,14]

Abradable material		Abradability[a]		Erosion resistance[a]
		High speed	Low speed	
fiber metal 1	Ultimate tensile strength, 1050 psi; braze bonded; density, 22%	1	1	3
fiber metal 2	Ultimate tensile strength, 2150 psi; braze bonded; density, 23%	1	1	1
Honeycomb	Hastelloy-X[b] 0.05-mm foil, 1.59-mm cell	2	3	2
Nickel-graphite	Sulzer Metco 307NS (spray)	3	1	2
CoNiCrAlY/ hBN/PE[c]	Sulzer Metco 2043 (spray)	3	3	1

[a]Where 1 = best and 3 = worst.
[b]Haynes International, Inc., Kokomo, Indiana.
[c]Hexagonal boron nitride (hBN) acts as a release agent and polyester (PE) controls porosity.

For industrial power systems under the conditions tested and the materials considered in Table 1, fibermetal has the best abradability-erosion characteristics. Honeycomb materials collected on the blade tips and sprayed materials are less satisfactory. These relative ratings are displayed in Table 1.

Chupp et al. [15,16] report abradable seals afford tighter closure of cold clearances between the rotor and case. A general classification in terms of interface materials, coatings, location in a gas turbine engine and a type of process for application and operating temperatures are given in Table 2.

TABLE 2.—ABRADABLE MATERIAL CLASSIFICATION [10, 12, 13, 14]

Abradable material	Location[a]
AlSi + filler	LPC: 400 °C (750 °F)
Ni- or Co-based	LPC, HPC: ambient to 760 °C (1400 °F)
YSZ and cBN or SiC	HPT: 760 °C (1400 °F) to 1150 °C (2100 °F)

[a]LPC is low-pressure compressor.
HPC is high-pressure compressor.
HPT is high-pressure turbine.

Inroads to industrial standards have been initiated, yet more comparison tests are required before standardization becomes a reality.

Liquid (Oil) Lubricated Interfaces

One recent application for coatings in bearings to enhance conventional operational life as well as potential oil-out conditions was advanced by Dimofte et al. [17] who tested wave bearing coatings applied to both the rotor and stator (or sleeve). When the oil supply pressures are decreased, bearing interface surfaces can be destroyed due to rub, yet with the
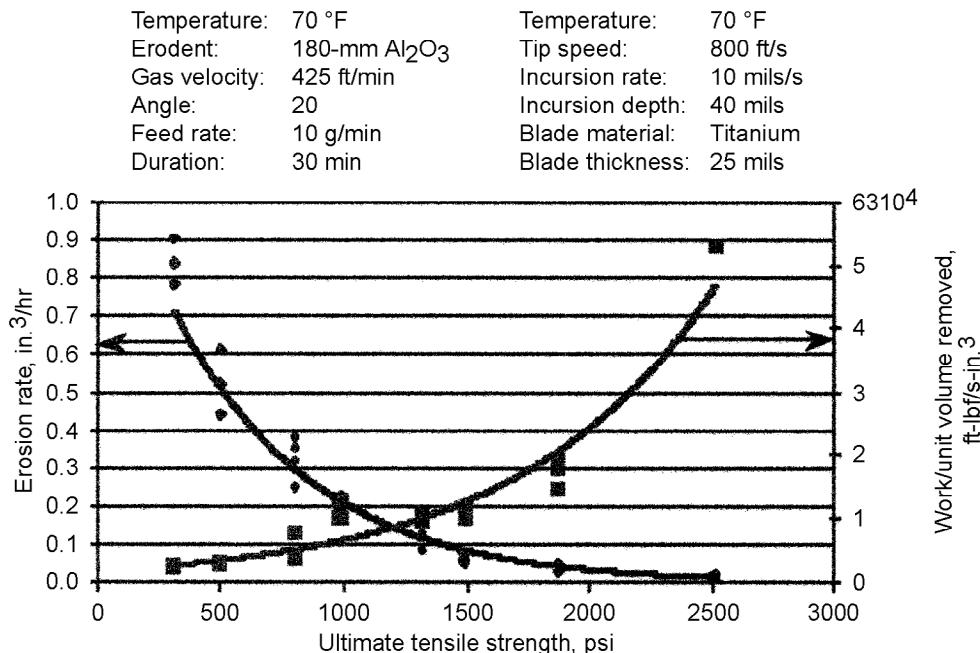
Temperature: 70 °F
Erodent: 180-mm Al_2O_3
Gas velocity: 425 ft/min
Angle: 20
Feed rate: 10 g/min
Duration: 30 min

Temperature: 70 °F
Tip speed: 800 ft/s
Incursion rate: 10 mils/s
Incursion depth: 40 mils
Blade material: Titanium
Blade thickness: 25 mils

Figure 4.—Erosion and abradability as function of ultimate tensile strength (from [13]). (Courtesy Technetics Corp.)

pumping action of a three-node wave bearing with three feed holes, decreasing the supply pressure did not significantly harm bearing operations until the supply was cut off (0 MPa). In these instances, residual particulates in the lubricant oil itself are major contributors to bearing damage and must be carefully controlled, and in these tests control could have been better. Nevertheless, Dimofte examined the following coatings with varying degrees of success: (1) SiDLC, (2) DLC, (3) tungsten carbide/carbon (WC/C), and (4) titanium carbide (TiC). SiDLC performed well for 1000 start-stop cycles followed by 50 oil-off cycles, where friction torque lockup occurred in about 10 min. WC/C also did well except at oil-off, where it degraded rapidly due to higher friction. TiC failed at oil-off while DLC ran 20 min but seized on the first cycle thereafter.

For new coated bearings operating at low supply pressures both SiDLC and WC/C performed well, yet at oil-off WC/C degraded rapidly—3 min versus 2½ hr for SiDLC.

The posttest rotor and stator SiDLC-coated interfaces are optically relatively smooth and uniform (Figs. 5 and 6). The uniformity is also confirmed by surface profiling after a 1000 start-stop cycles test series (Fig. 7). Here the surface profiles of the SiDLC coatings illustrate the posttest surface roughness and consistency of the sleeve and rotor coatings (Figs. 7(a) and (b), respectively). The profilometer readings are quite uniform and generally within 2 μm, with the exception of the rotor where "scratches" up to 4.5 μm can be seen. The area examined is highlighted by the white line.

Tribologically, SiDLC performed very well.

Interface Tools

There are many thermodynamic and computational methods used in characterizing materials. One of the better known is the BFS model, which has been successfully applied to known materials and developing new materials, [e.g., 18]. Yet more recently, Quantum mechanics (QM) tools are proving useful to macromechanics issues [19] and will play a prominent role in applications of coatings and thin films. Consider a typical layered thermal barrier coating (TBC) (250 to 500 μm yttria stabilized zirconia (YSZ); 10-25 μm Al_2O_3 (thermally grown); 100 to 150 μm NiCoCrAlY (bond coat)) over a superalloy (Ni or Ni_3Al base) turbine blade. QM predictions show that fracturing the ZrO_2 requires a unit energy of 2400 mJ/m^2, while Al_2O_3 requires 3000 mJ/m^2. For the ZrO_2/Al_2O_3 interface adhesion is 1200 mJ/m^2, and it is 500 mJ/m^2 for the Al_2O_3/Ni interface (Fig. 8). Weaker adhesion and stress concentration at the interface are sources of failure. The transitional elements are suggested as the "interface glue."

Failure Detection Methods

There are many methods used to determine interface failures such as dye penetration, ultrasound, surface waves, and rotational dynamics, to cite a few [20]. A recent novel method of incorporating material variants (dopants) to define interface failures also provides for health monitoring—crack and temperature detection. Europium oxide Eu_2O_3 fluoresces red or blue when illuminated by ultraviolet light, while terbium oxide Tb_4O_7 (terbia) produces green light. Bencic and Eldridge [21]
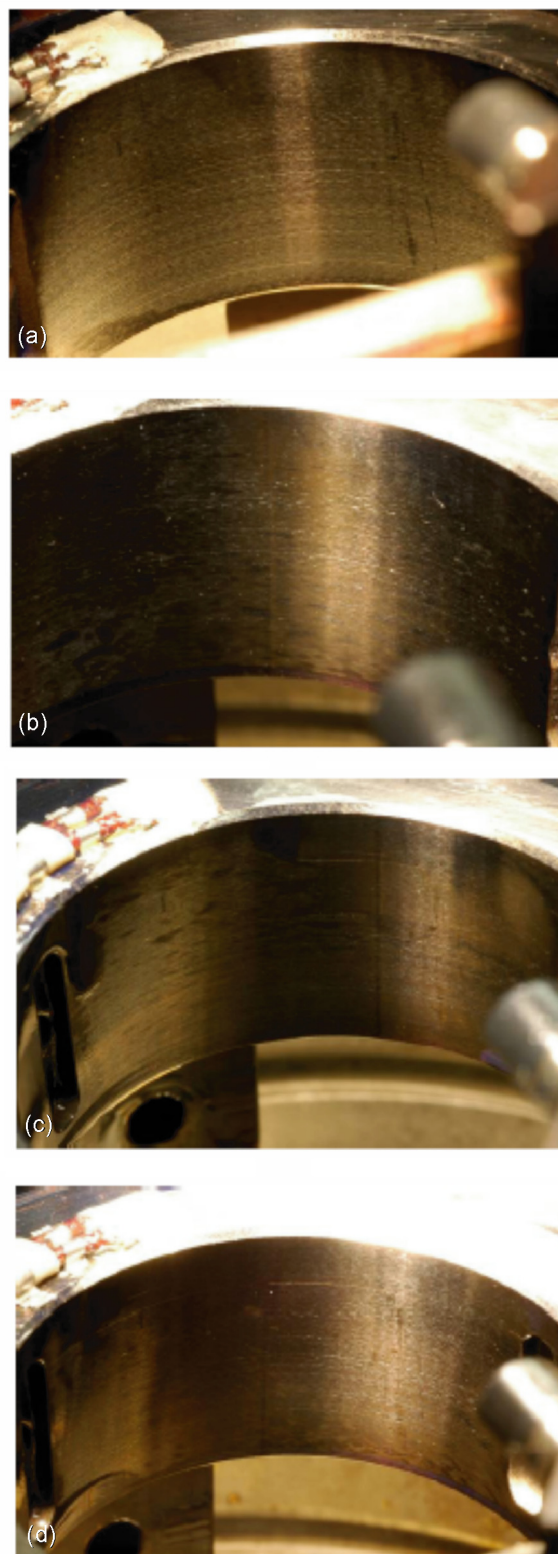

Figure 5.—Wave bearing journal sleeve with SiDLC coating at decreasing oil supply pressure (OSP) (from [10]). (a) 1st hour at 0.07 MPa. (b) 2nd hour at 0.035 MPa. (c) 3rd hour at 0.01 MPa. (d) 4th hour at 0 MPa.
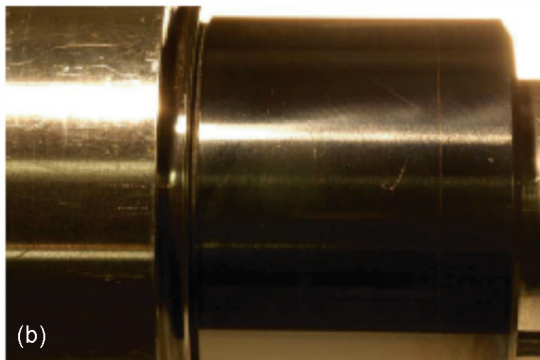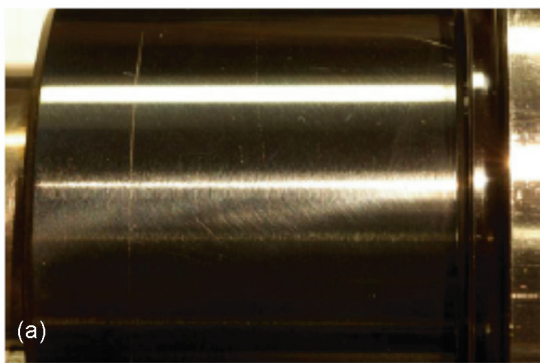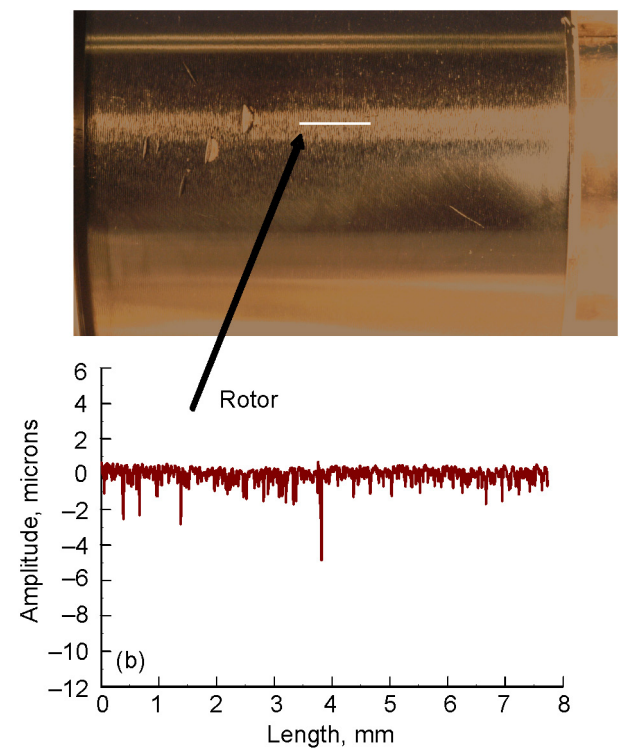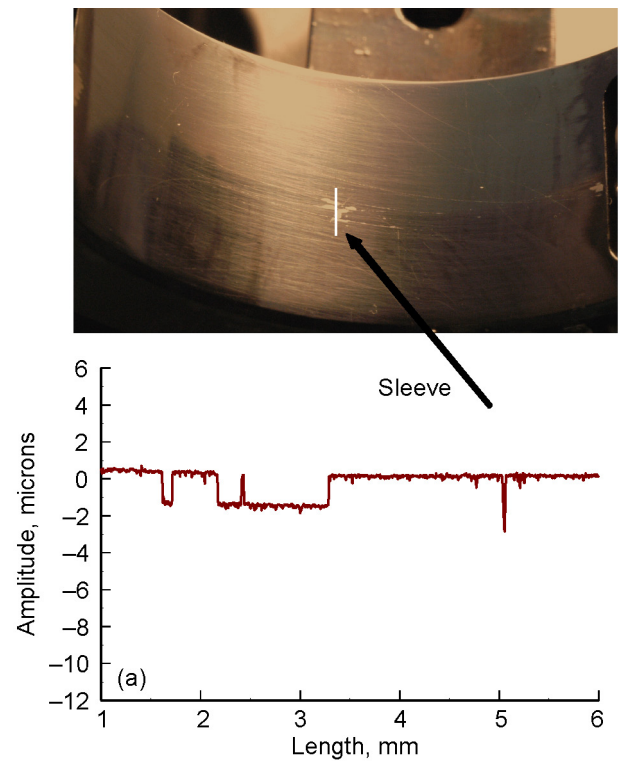
Figure 6.—Wave bearing rotor with SiDLC coating at decreasing oil supply pressure (OSP) (from [10]). (a) 1st hour at 0.07 MPa. (b) 2nd hour at 0.035 MPa. (c) 3rd hour at 0.01 MPa. (d) 4th hour at 0 MPa.

Figure 7.—Wave bearing surface profiles of SiDLC coatings after 1000 start-stop cycles. (a) Sleeve. (b) Rotor.
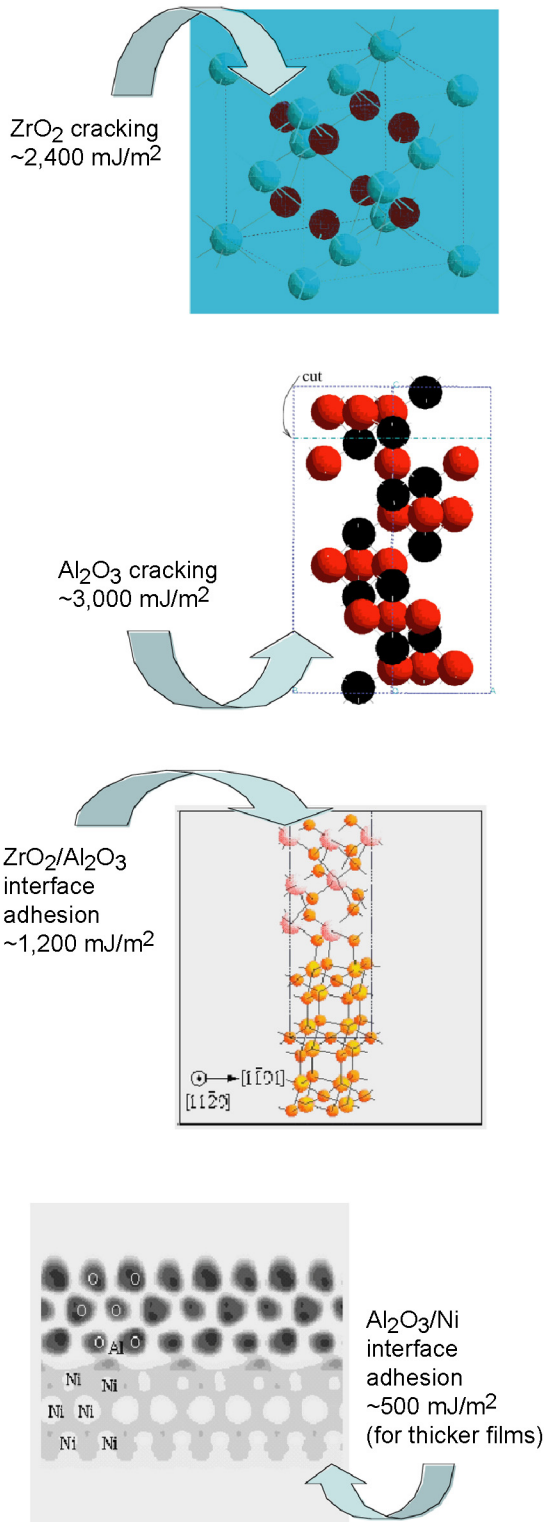
noted that YSZ is opaque to ultraviolet excitation, but translucent to visible light: Tb^{3+} at 543 nm (green) and Eu^{3+} at 606 nm (red). Tests were conducted on a Rene N5 (General Electric Company, Fairfield, CT) superalloy substrate with a PtAl bond coat and graded topcoat of 50 μm (7YSZ + 0.5Tb), 50 μm (7YSZ + 0.5 Eu), and 50 μm (7YSZ) (nominal thicknesses).

If the surface is flawed over 50 μm, ultraviolet excitation will reflect strong red light. With flaws >100 μm depth, strong green light becomes visible (Fig. 9). Further, the luminescence decay with time of pulsed ultraviolet light can be used to determine temperature.

Figure 8.—Density functional theory calculation prediction on the basis of adhesion illustrating interfaces as likely sites for material failures (from [19]).
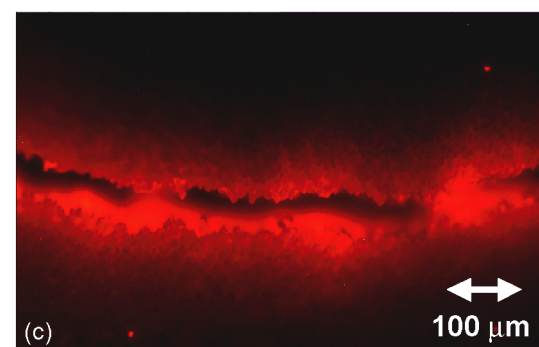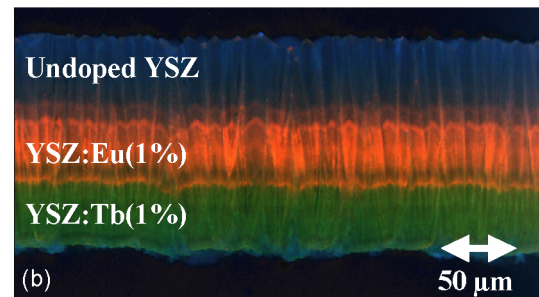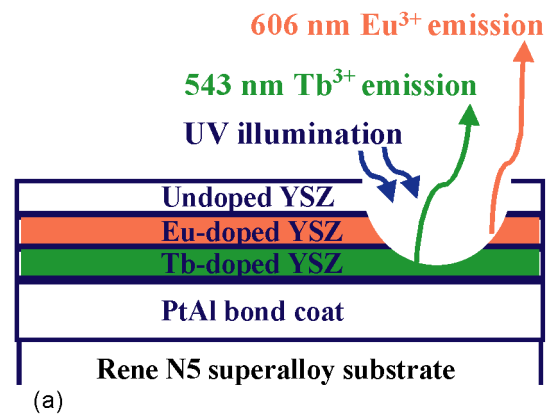

Figure 9.—Smart coatings for health monitoring and nondestructive evaluation (from [21]). (a) Rene N5 superalloy with doped TBC schematic. (b) Coating after 100-hr 1200 °C test under ultraviolet light. (c) Eu fluorescence showing crack in TBC.

Summary

Properly engineered interfaces can improve performance and external turbomachine service lives. No one geometry, coating, or material is satisfactory for general use. Each interface coating must be assessed in terms of its operational requirements. Coatings, films, and functionally graded materials (e.g. both metals and ceramics) play a major role in maintaining interface integrity for blade (or vane) shroud and platform performance.

1. For the aeroturbomachine, the fan shroud seals have several forms but generally include polymers that can be repaired on the wing.

2. For the low-pressure compressor (LPC) (ambient to 400 °C (750 °F)) interface, feltmetals and AlSi with fillers are used. For the midrange (MPC) and high-pressure compressors (HPC) (ambient to 760 °C (1400 °F)), Ni- or Co-based materials are used.

3. In the high-pressure turbine (HPT) interface, TBCs such as yttria-stabilized zirconia (YSZ) with controlled porosity are used. To mitigate wear, blade tips are often coated with cubic BN or SiC grits. For tight running clearances, the shroud is then cut instead of wearing the blade.

4. The TBC can withstand high thermal loading, yet the metallic substrate cannot. Again, it is the weakness of the interface that is limiting and not the ceramic itself.

5. Bearing and sealing surfaces are routinely protected by coatings. For instance, a recent application of silicon diamondlike coating (SiDLC) in combination with a wave-bearing interface has proven very effective in prolonging bearing life even when the oil supply is intermittent or stopped altogether. This is an important advancement as it paves the way for future systems to continue to provide power while allowing for an orderly shut down of the machine.

6. Several methods are being used or being developed for detecting interface failures, yet doping of coatings represents an innovative method of detecting such failures in coated ceramic materials.

How well and how long interfaces will be effective in doing their jobs depends directly on understanding the binding energies of those interfaces and the requirements for the application. Of the many materials models, one of the better known is the Bozzolo-Ferrante-Smith (BFS) model to assist in designing interface materials. Recent developments in the application of quantum mechanical methods are also available to assist the designer in understanding the interface.

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14. ABSTRACT
Inadequate turbomachine interface design can rapidly degrade system performance, yet provide great opportunity for improvements. Engineered coatings of seals and bearing interfaces are major issues in the operational life of power systems. Coatings, films, and combined use of both metals and ceramics play a major role in maintaining component life. Interface coatings, like lubricants, are sacrificial for the benefit of the component. Bearing and sealing surfaces are routinely protected by tribologically paired coatings such as silicon diamondlike coatings (SiDLC) in combination with an oil-lubricated wave bearing that prolongs bearing operational life. Likewise, of several methods used or researched for detecting interface failures, dopants within coatings show failures in functionally graded ceramic coatings. The Bozzolo-Ferrante-Smith (BFS) materials models and quantum mechanical tools, employed in interface design, are discussed.

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