JTTEE5 6:167-175
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PVD Thermal Barrier Coating Applications and Process Development for Aircraft Engines

D.V. Rigney, R. Viguie, D.J. Wortman, and D.W. Skelly

Thermal barrier coatings (TBCs) have been developed for application to aircraft engine components to improve service life in an increasingly hostile thermal environment. The choice of TBC type is related to the component, intended use, and economics. Selection of electron beam physical vapor deposition processing for turbine blade is due in part to part size, surface finish requirements, thickness control needs, and hole closure issues. Process development of PVD TBCs has been carried out at several different sites, including GE Aircraft Engines (GEAE). The influence of processing variables on microstructure is discussed, along with the GEAE development coater and initial experiences of pilot line operation.

Keywords electron beam physical vapor deposition, high-pressure turbine airfoils, process parameters, thermal barrier coatings, yttria-stabilized zirconia

1. Introduction

TURBINE INLET temperature increases have necessitated the use of thermal barrier coatings (TBCs) on turbine airfoils and other components for advanced engines. Such coatings provide an insulating layer of yttria-stabilized zirconia (YSZ) on the surface of the turbine airfoil. The low thermal conductivity of zirconia allows internal cooling air to more effectively cool the part, lessening the amount needed to achieve the design temperature. By requiring less cooling air, overall engine performance is improved, and by reducing the part temperature and thermally induced strains, component life is increased.

Two types of TBCs have been developed for aircraft engine use: plasma spray and physical vapor deposition (PVD). Numerous versions of plasma spray TBCs have been used successfully on a wide range of components. The initial applications were in the combustor and afterburner, where atmospheric plasma spray (APS) bond coats of NiCrAlY were successful with a porous 7% YSZ top coat. In the late 1980s, plasma spray TBCs were introduced to stationary nozzle components in the turbine. Here, higher temperatures forced the use of low-pressure plasma spray MCrAlY bond coats for improved oxidation protection and longer life. During this same period, PVD TBCs were developed to the point where production introduction on both turbine blades and vanes was practical.

2. Design Requirements and Cost Issues

Sufficient experience has been gained to allow the designer and materials application engineer to select TBCs for specific applications. Selection of a plasma spray or PVD TBC is based on the ability of the coating to meet the performance and cost requirements of the application. Limited comparative information on plasma and PVD TBCs (Ref 1) shows that PVD TBCs have longer lives in both burner rig tests and engine tests. However, improvements in plasma spray TBC processing and bond coat composition (Ref 2) may have reduced the differences significantly. Tests in an industrial power engine with plasma spray TBCs have been carried out for up to 20,000 h at GE Aircraft Engines (GEAE).

Apart from the life issue, other significant differences between the two types of coatings drive the selection process: surface finish, hole closure, and cost. The PVD TBCs are much smoother as deposited (1.4 to 1.5 μm, or 56 to 60 μin., versus >5 μm, or 200 μin.). After surface finish improvement, PVD still has the advantage, with better than 0.75 μm (30 μin.) possible. The importance of surface finish depends on the application, as shown in Fig. 1. On stage 1 airfoils, with high pressures and velocities, a smooth finish is important; on latter stages, this is not as important. Surface finish on combustor and endwall surfaces also is less important.

Most high-pressure turbine (HPT) airfoils in advanced aircraft engines have many small (0.25 to 0.5 mm, or 0.010 to 0.020 in., diam) cooling holes that can be closed or the flow reduced by

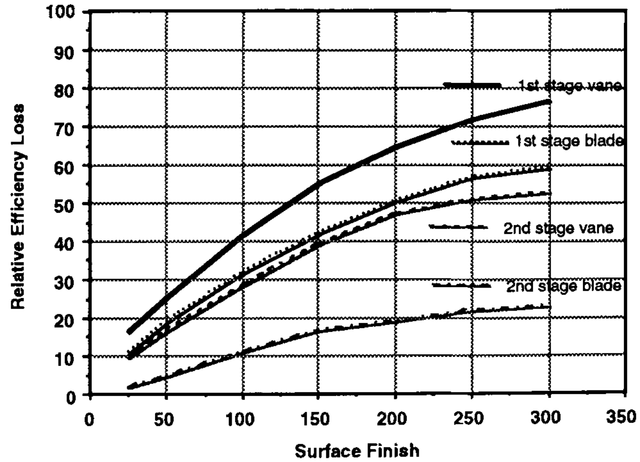

Fig. 1 Effects of surface roughness on loss of efficiency. The aerodynamic efficiency of the stage 1 and 2 high-pressure turbine vanes and the stage 1 high-pressure turbine blades is very sensitive to the surface roughness of the suction wall surface finish.

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coating. Coatings produced by PVD taper very rapidly at the opening of the cooling hole (Fig. 2). Plasma spray coatings, however, have a greater tendency to build up coating at the hole opening. The sticking and buildup of the molten plasma-sprayed particles can close over small cooling holes. Several approaches have been attempted to circumvent this problem, including drilling holes after coating, filling holes with wires during spraying, and oversizing holes, but none has proved universally acceptable.

Application of plasma spray TBCs is generally less expensive than PVD, due in large part to lower capital costs. However, other issues can make PVD coatings less expensive. For example, small parts favor PVD because many can be coated simultaneously. On the other hand, some applications where only one surface is being coated may allow a full ring of parts to be plasma spray coated at the same time. For PVD the same space in the coater is taken up whether all surfaces or only one surface is being coated. The overall assessment is that both plasma and PVD TBCs will continue to have applications in aircraft engines. Many issues determine which process is best for a given part. The balance of this paper deals with issues related to PVD processing of TBCs.

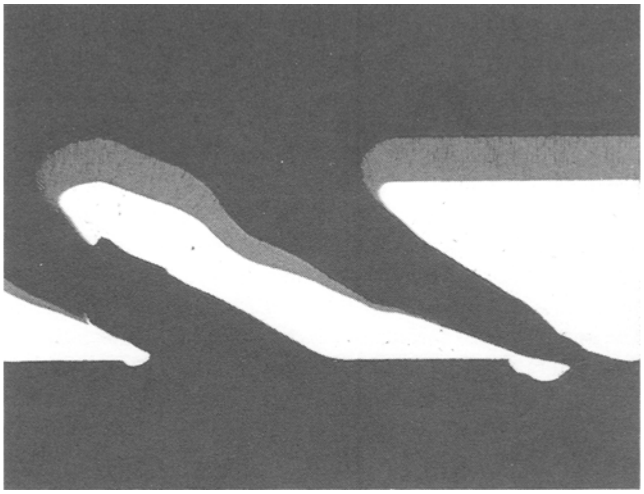


Fig. 2 Component showing PVD coating in region of cooling holes. Deposit is approximately 350 µm (0.014 in.) thick. The atomistic nature of the PVD coating process results in a rapidly, smoothly tapered coating at the hole entrance. Laser drilling usually results in the throat of the hole (the narrowest dimension) to be located near the interior end of the hole.

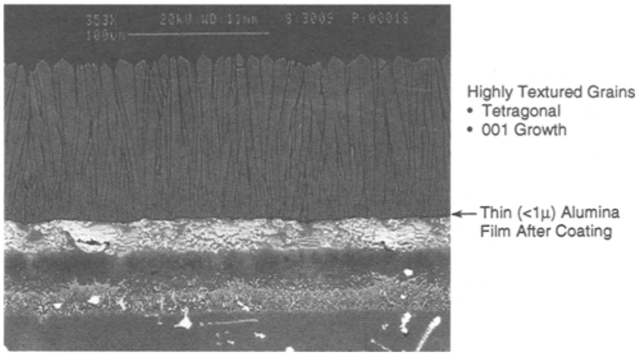


Fig. 3 Cross section of TBC characterizing PVD YSZ deposit. A thin alumina film chemically bonds the YSZ to the bond coat. High-modulus, oriented columnar grains are characteristic of PVD coatings. Low modulus in surface plane results in the ability to withstand high strain rates.

3. General Considerations for PVD Coatings

Adherence and durability as well as producibility and productivity are key issues for TBCs. Loss of the TBC will result in increased metal temperatures (at least in the area of TBC loss) and potentially shorter part lives. Initially, a very thin alumina scale exists between the bond coat and the zirconia (Fig. 3). This alumina scale is formed by oxidation of the surface during preheat and the initial moments during deposition of the zirconia in the coating chamber. In service, growth of the alumina scale occurs through oxygen transport through the zirconia. The dense alumina scale will be under high compressive loads when cooled to room temperature due to the lower thermal expansion of the alumina scale compared to the metallic substrate. Ideally, the open columnar structure of the zirconia will not contribute additional compressive stresses. Eventually, thickening of the alumina scale produces sufficient compressive force such that the scale will buckle, carrying both the alumina and the overlying zirconia with it (Fig. 4). This failure should occur after a relatively long and predictable time, permitting the designer to use the TBC capability in the design life consideration for the part. Unfortunately, very short lives can occur if the bond coat surface is not properly prepared or if the deposition process parameters are not well controlled or are sensitive to process variations beyond the control capability.

An important aspect of PVD TBC development is selection of process parameters to provide a reliable, reproducible coating. Although much effort has been expended toward this goal

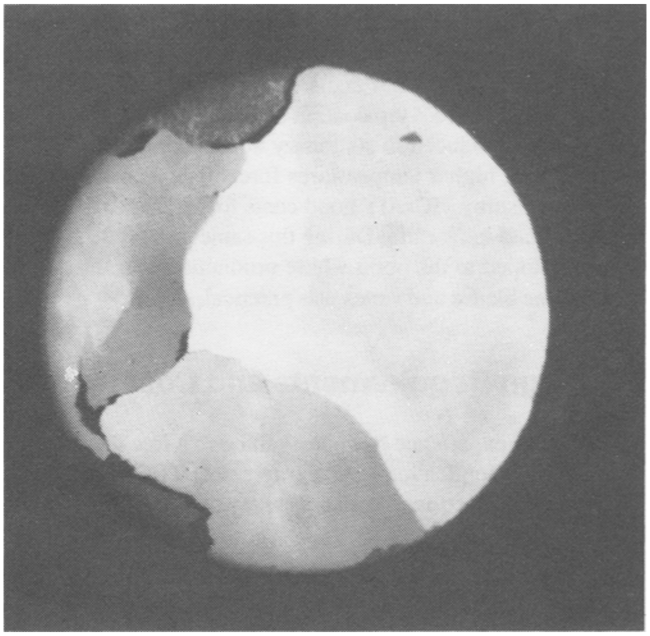


Fig. 4 PVD TBC-coated button at end of cyclic test. Button shows that oxidation growth causes compressive loading on Al_2O_3 and results in lifting of both Al_2O_3 and thermal barrier.

by several sources, very little has been published and this remains an area of competitive development. Experience with different equipment designs has shown that results obtained in process development are closely linked to the equipment. In the following sections, some of the process development experiences at GEAE are discussed.

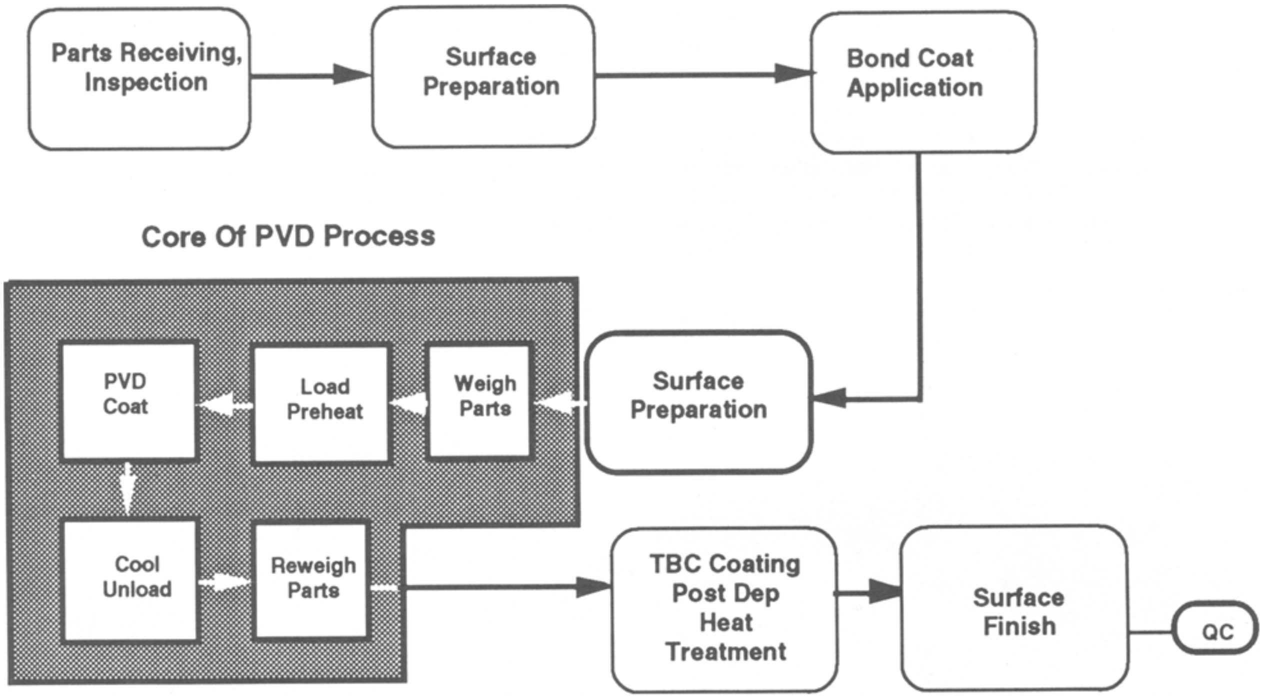
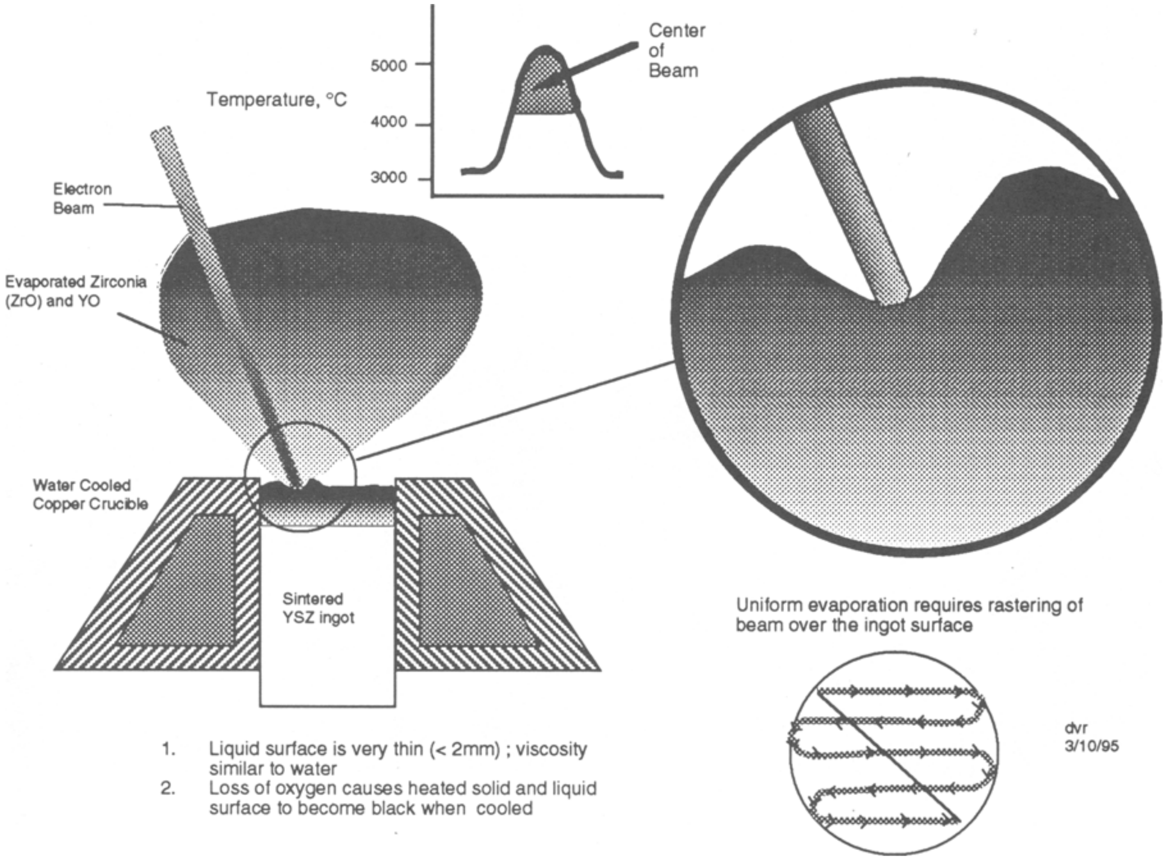


Fig. 5 Schematic of PVD TBC process sequence



Uniform evaporation requires rastering of beam over the ingot surface

1. Liquid surface is very thin (< 2mm) ; viscosity similar to water
2. Loss of oxygen causes heated solid and liquid surface to become black when cooled

Fig. 6 Schematic illustrating evaporation from ceramic pool. Evaporation takes place when liquid being directly impinged by electrons is superheated. In the YSZ system, the liquid pool is only 2 to 3 mm (0.08 to 0.12 in.) deep.

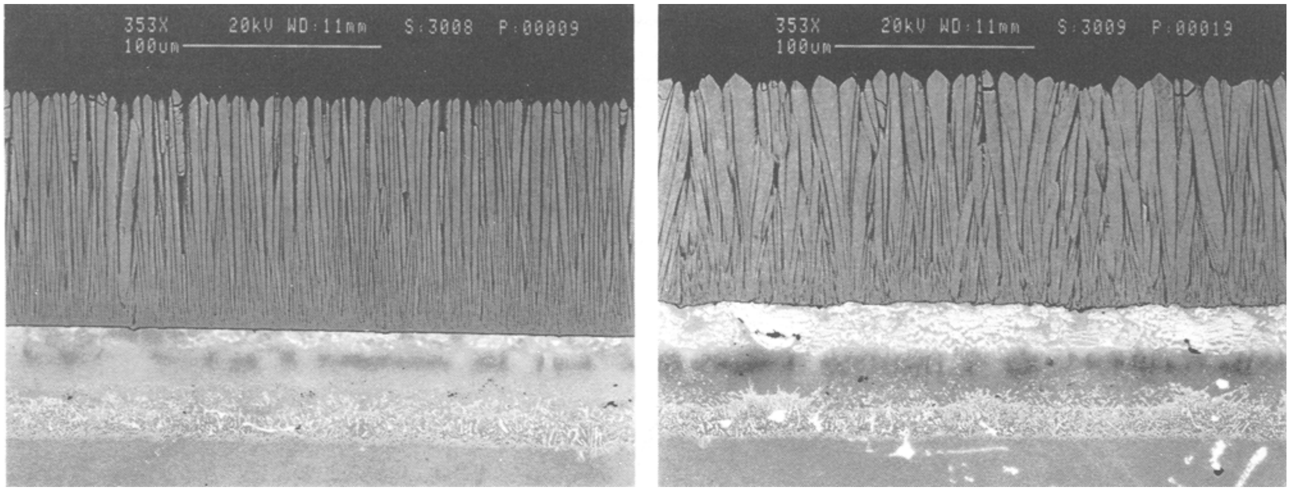
4. Processing of PVD TBCs

The PVD TBC system requires a multistep coating sequence (Fig. 5). The development of a highly reliable PVD TBC requires precise process controls on all process steps.

In the PVD process, the coating material is heated to vaporization temperatures through kinetic energy exchange between the electron beam (EB) (≈38 kV) and the coating material. The process is unique in that large amounts of energy can be focused in a small area. Evaporation from large areas can be achieved by sweeping the beam over the surface of the material. Ceramic materials such as $ZrO_2 \cdot 7Y_2O_3$ have very high melting points (≈3200 °C, or 5800 °F) and very low thermal conductivities. It is estimated that the temperature at the point of EB impact is greater than 4000 °C (7230 °F) (Fig. 6). The coating material evaporates atomistically (or molecularly) and condenses onto the part. The condensed atoms can move on the surface for short distances, and then form nuclei and begin grain growth. Columnar growth is the norm; however, grain orientation may be affected by processing temperature, surface morphology, and so on.

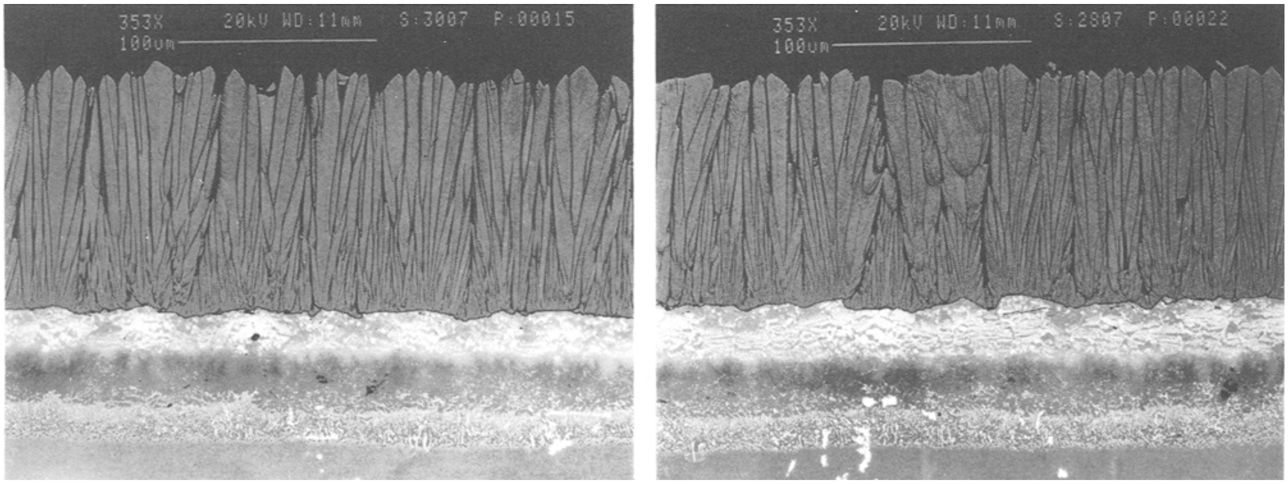
To achieve good PVD TBCs, parts must be processed at elevated temperatures. Coating morphology is a function of the melting point of the coating material and the temperature of the substrate being coated (Ref 3-5). The closer the part temperature is to the melting point of the coating material, the greater the surface mobility of the condensed atoms and the denser the coating. The coating temperature limit for nickel-base alloys is about 1100 to 1150 °C (2010 to 2100 °F), owing to the melting point of the substrate and the stability of the bond coat/substrate system.

A generalized process sequence used to apply ceramic coatings is described in the sections that follow.



(a) Polished

(b) 220 Grit



(c) 80 Grit

(d) 54 Grit

Fig. 7 Influence of bond coat surface texture on ceramic top coat microstructure. (a) Polished surface, resulting in deposition of a uniform, dense columnar structure. (b) to (d) Gradations of greater porosity and nodularization from grit-blasted surfaces

4.1 *Surface Preparation*

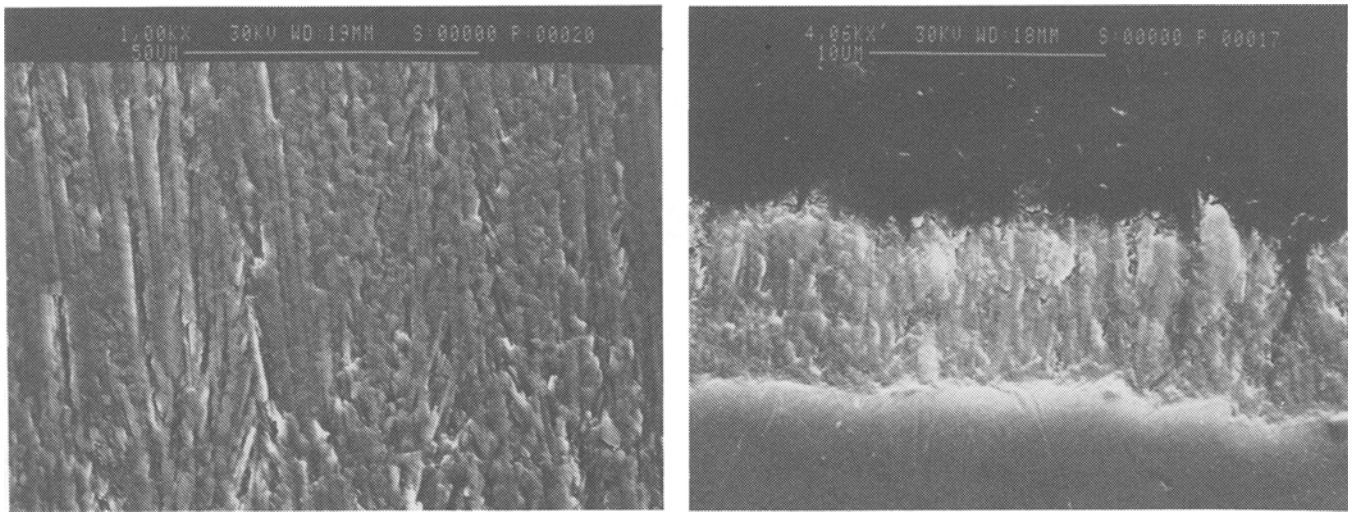
Proper engineering of the bond-coated surface for subsequent coating is critical to any successful coating process. For PVD TBC coatings, the surface preparation serves to normalize the chemical and physical natures of the part such that a predictable coating can be applied. Examples of the effect of different surface textures on a subsequent ceramic top coat microstructure are shown in Fig. 7 for different coarseness of media: polished and 220, 80, and 54 mesh.

4.2 *Loading and Preheat*

After cleaning and surface preparation, parts are weighed and fitted into mask/holders. Weighing the parts before and after the coating process has been found to be a rapid, precise technique to nondestructively determine the thickness of the coating deposited. The weight gain during coating is compared against data from metallographic examinations in prior runs. Parts are loaded into a load lock, evacuated to a low pressure, and then moved into a separate preheat chamber.

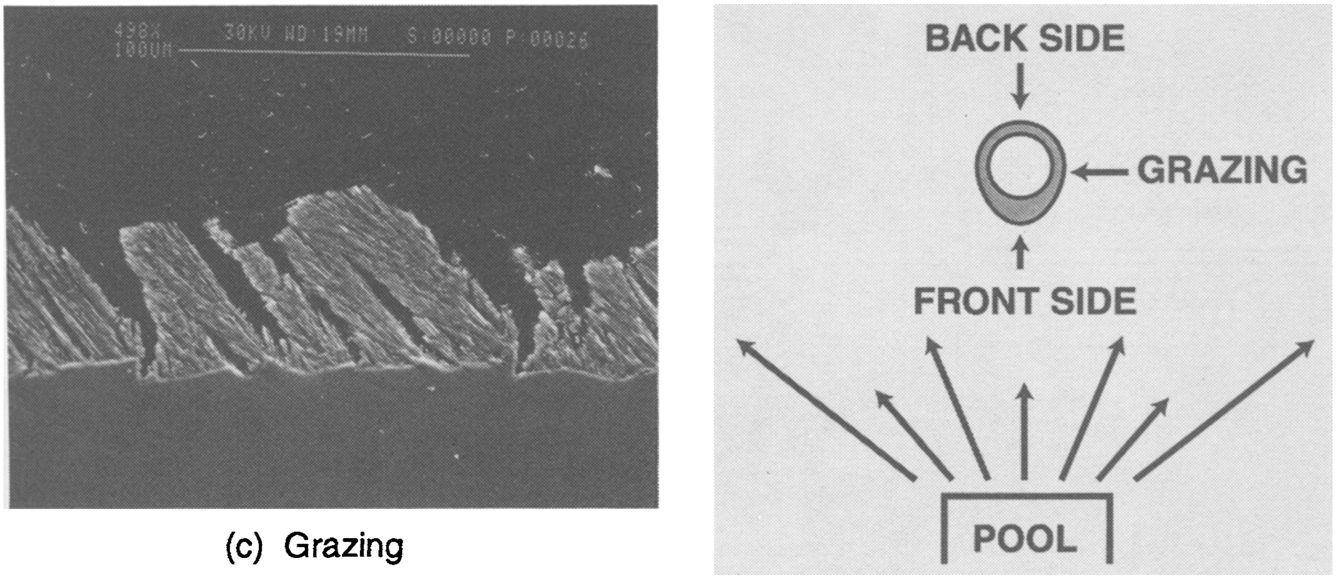
4.3 *Coating*

The microstructure of the coating is a complex function of many variables: material, deposition rate, pressure, part rotation rate, geometric attitude, temperature, and so on. The substrate temperature is one of the most important parameters affecting coating microstructure and life, and the temperature must be maintained within a defined envelope during coating deposition. The parts to be coated are heated by several different



(a) Front Side

(b) Back Side



(c) Grazing

Fig. 8 Coating structures deposited on stationary cylinder. (a) Thin, fine-grained columnar film deposited by gas-scattering on part facing away from source. (b) Open, feathery deposit at tangency point on cylinder of vapor flux from pool. (c) Thick, dense structure deposited on surface facing pool sources during coating, including heat of condensation, radiation from the hot pool, and heat from impingement of electrons reflected from the melt. If the thermal input from these sources is insufficient, additional heating must be provided by reflection (insulation), an auxiliary EB source, or other means. Unlike metallic systems, ceramic materials such as $ZrO_2{\cdot}8Y_2O_3$ dissociate during evaporation and require addition of oxygen to compensate for gas pumped out of the chamber.

4.4 *Removal and Postcoating Processing*

After coating, the parts are returned to the load lock, where they are cooled and the lock vented. The parts are then removed and reweighed. Satisfactory comparison with weight gain envelopes derived from sectioned blades qualifies the parts for the next evaluation steps and further processing.

5. Line-of-Sight and Rotation Effects on PVD TBC Microstructure

The effects of line-of-sight deposition were studied by coating a stationary cylinder with a grit-blasted surface finish over a single source. The thickness and structure show a very thin (<12.5 μm, or 0.5 mil) fine-grained coating deposited on the backside of the cylinder (Fig. 8). A thicker, porous (open grain) coating is deposited at the tangency (grazing) point of the vapor. On the other hand, at the static/head-on position, the coating is much denser and thicker (>230 μm, or 9 mils). If a part is to be coated uniformly, it must be rotated or rotated and tilted. Most production coaters use a numerical control system to control orientation and rotation (Fig. 9). Others may use complex tooling and fixturing concepts to achieve similar results (Fig. 10).

The substructure of the coating crystals is significantly altered by the effects of rotation. Figure 11 shows different substructures generated by the rotation of a simulated part over the coating source. The two micrographs show a view of the growth of C-shaped structures formed during each revolution within the main crystal at two different rotation rates. The character of each is the same. The relationship of these structures is a function of rotation rate and the vapor flux at the surface (evaporation rate and distance from the source). The fine structured grains were deposited onto a surface rotating at approximately 6 rev/min; the coarser structure was grown on a surface rotating at about 0.4 rev/min.

6. Practical Experience with PVD Equipment

The use of TBCs for performance benefit depends on a high degree of confidence in the life of the product. As part of the development effort to produce this improved TBC, a pilot production-scale PVD coater was purchased by GEAE in 1989 and installed in 1992. The coater was designed with a full production-scale evaporation chamber, but only one parts-handling chamber. Although this reduced the throughput, added space was available for process monitors and controls for development work (Fig. 12).

The coater is equipped with two 200 kW evaporation EB guns that evaporate from two ceramic sources and one over-source heating EB gun. The coater can coat 10 CF6-80C2 stage 1 HPT blades simultaneously in a uniform 140 by 420 mm (5.5 by 16.5 in.) coating zone. Three minicomputers allow programming and control of the processing conditions and continuous logging of more than 90 process and equipment variables. Coating pressure, rotation, rate, lateral and tilt position, EB parameters and adjustments, cooling water temperature, and time since oil change (pumps) are examples of logged items.

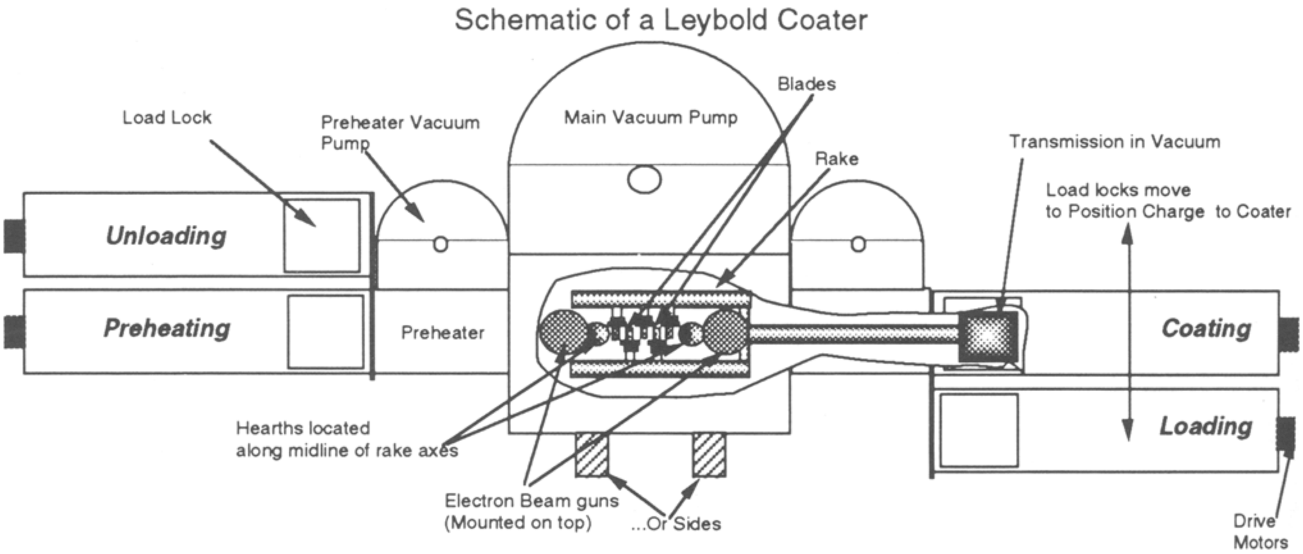


Fig. 9 Schematic of generic Leybold-design PVD coater. Coater uses multiple pools to generate a large vapor cloud. These pools may be heated from above the pools or, using magnetics to assist in directing the electron beams, from sources aimed from the side. Parts are oriented over the pools on numerically controlled gear-driven holders on shafts to allow multiple part coating. The parts can be tilted to coat platforms and other surfaces. Multiple shafts allow nearly continuous coating of parts by timing the major process events in a four lock system: (1) loading of parts, (2) preheating parts to coating temperature, (3) coating deposition, and (4) cooling and unloading.

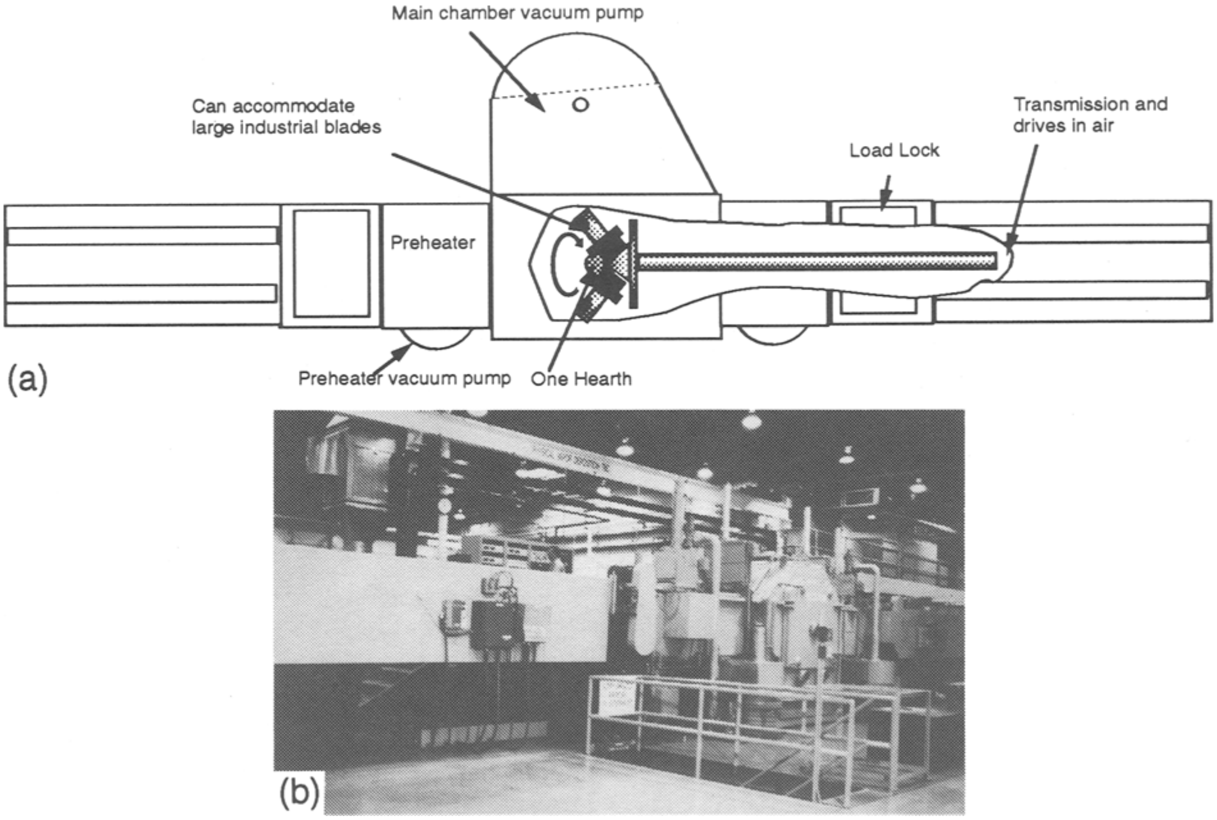
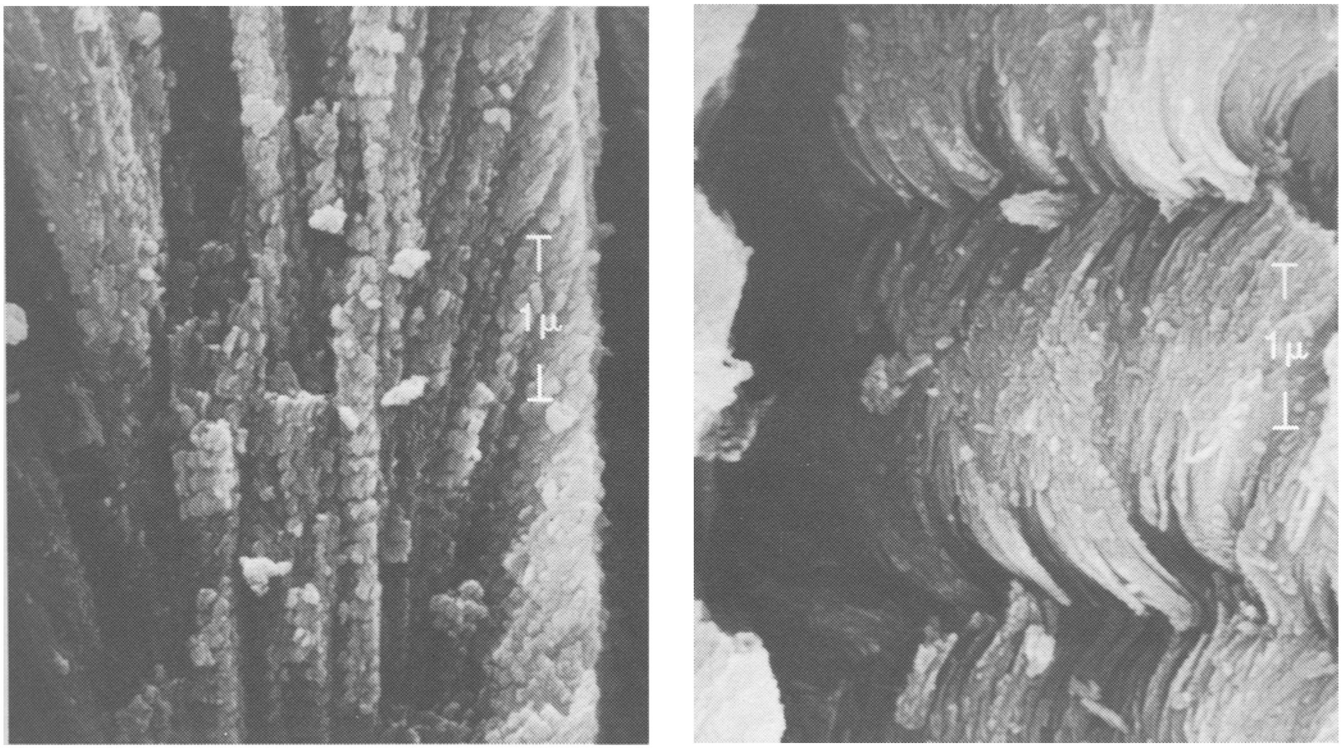


Fig. 10 Large coater made by Temescal. Coater uses complex tooling and large weight-carrying capability of shaft to achieve simultaneous coating of many parts. Weight-carrying capability and size allow large industrial turbine components (>10 kg, or 22 lb) to be coated. Opposed load locks and shafts allow efficient use of coater evaporation time. Note operator just behind coater



(a) (b)

Fig. 11 Photomicrographs showing grain substructures resulting from rotation effects. (a) 0.18 μm/rev. (b) 2.6 μm/rev

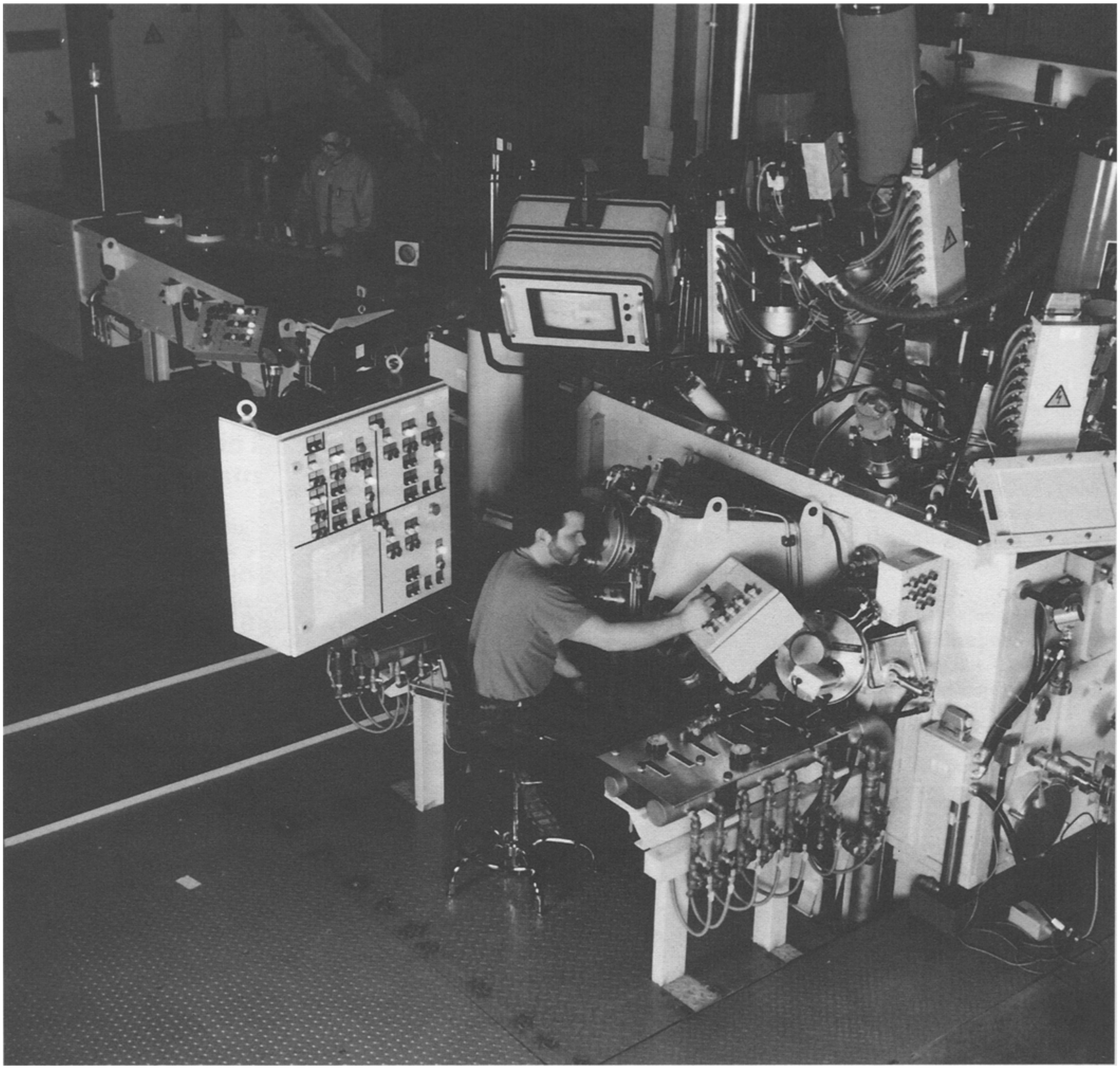


Fig. 12 General Electric prototype EB-PVD coater. Coating chamber is production scale, as is the loading chamber.

Initial development efforts at GEAE concentrated on producing a coating equivalent to the industry standard (i.e., that which is available on the commercial market). A designed experiment was conducted to evaluate significant parameters, including:

- Part temperature during preheat
- Part temperature during coating
- Pressure in the coating chamber
- Oxygen partial pressure in the coating chamber
- Part rotation rate during coating

As part of the experiment, bond-coated alloy button specimens were prepared. The primary evaluation method was exposure in a furnace cycle test (FCT) at 1093 and 1135 °C (2000 and 2075 °F). Each cycle consisted of 45 min at temperature and 20 min heating and cooling. The number of cycles to ≥10% spall of the ceramic coating constituted coating life. All the parameters exhibited acceptable furnace cycle lives and compared favorably to concurrent and past cyclic test results obtained from specimens prepared at commercial sources, showing that the overall process is robust, at least with regard to these parameters. Three parameters were determined to have a significant effect on spallation life: preheat temperature, coating temperature, and part rotation rate. Preheat and coating temperature were shown to be the most significant pairings necessary to produce consistent performances in the FCT.

The initial result of the program was the establishment of a baseline TBC coating, which is currently being applied on a pilot scale. The objectives of operating the pilot line are to provide parts for field evaluation, gain operating experience with the coater systems, and assess the continuing constancy of the TBC process. As part of the pilot line, two lots of bond-coated René N5 buttons were coated along with pilot production hardware over a period of more than 18 months. The results of the FCT is shown in Fig. 13. The data exhibit zero infant mortality. On the other hand, scatter increased in both bond coat lots after about 6 months into the sequence, and the 3σ value of the data rose from about 36% of the mean to ±66% of the mean (over all the data). At this point, the causes for these variations have not been ascertained. Some of the variations have been attributed to piece-to-piece variation in bond coat application, surface treatment, and run-to-run variations in the ceramic deposition. Data are being gathered on the durability and reliability of the mechanical and electronic systems that make up the coater.

7. Concluding Remarks

Development activities are continuing and clearly must focus on several process aspects of the TBC system: the bond coats; surface preparation and cleanliness; and PVD process parameters, monitors, and controls. Additional engine testing and feedback concerning the performance of coated hardware from field exposures will provide additional insight into the performance capabilities of the TBC. The continued use of the coater for pilot production is complementary to the project. Quality issues observed in producing coated hardware within the same coater can be addressed by modifying the development plans. Likewise, the production experience helps maintain a focus toward development of a producible TBC process.

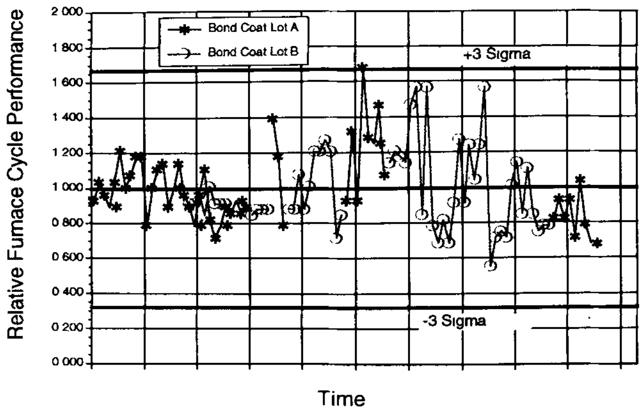


Fig. 13 Relative furnace cycle tests performed on specimens coated during pilot production operations in the GE prototype coater over an 18 month period

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