Surface Coatings Technology For Turbine Engine Applications

By Dorothy M. Comassar

The role of coatings in aircraft gas turbine applications is increasingly important. Higher engine operating temperatures, new alloys and component life requirements all drive the need for more durable systems. More and more, the engine component designer is using new coatings systems to help provide the environmental protection needed for these increasingly stringent demands. This article briefly reviews the historical use of coating systems in aircraft turbine engine applications. Typical coating systems by engine section (fan, compressor and turbine) are described by material, coating process and environmental challenges for each area. A state-of-the-art process—Thermal Barrier Coating (TBC)—describes coating process development challenges that typify future applications.

A look at typical coating applications in turbine engines over the past few decades shows increasing use as well as complexity In the 1960s, typical coatings were simple anodized aluminum, aluminum lacquer and ceramic coatings.

As operating temperatures increased in the 1970s, more component protection was required. Additionally, corrosion-resistant coatings were essential on more components, such as disks, blades, and vanes. Plasma-sprayed, wear-resistant coatings were also applied on compressor blade dovetails.

Throughout the 1980s, a typical engine profile would include coatings in every section of the engine. The broad range of coating systems addresses environmental conditions across the operating spectrum of the engine.

Design Changes

Turbine airfoil design has evolved to allow increasing temperature capability. (See example in Fig. 1.) The higher temperature environment has put increasing demands on airfoil materials, as well as protective coating systems.

Improved cooling provided by the impingement/film-cooled designs increase cooling capability; all aspects, however—design, materials, and manufacturing—are being pushed to meet higher temperature demands.

As shown in Fig. 2, alloy development has progressed significantly, providing additional temperature capability.

Coating systems provide the additional protection required to satisfy total design life. Simple aluminides satisfied early needs. Overlay coatings have been added over the last 10 years for further environmental protection. State-of-the-art systems, such as Thermal Barrier Coatings (TBC), are being implemented today. Strategies for coating technologies are shown in Fig. 3.

Evolution in Design & Coatings

1960—J79 (Fighter Engine)

Simple
- Solid turbine blade era
- 1500 °F (+) (822 °C) turbine temp

Coatings:

Anodized al
Ceramic coated stainless steel alloy combustors
Ceramic coated afterburner cases
Al-lacquer, heat-resistant compres sor case

1970—J79 (Fighter Engine)
- Expanded use of coatings
- Convection-cooled turbine blade era
- 1800 °F (+) (990 °C) turbine temp

Coatings:

Corrosion-resistant coating for blades & vanes
Aluminum corrosion-resistant paint on casings
Co-dep on vanes, blades
Corrosion-resistant coatings on disks
Corrosion-resistant paint on shaft
Plasma-sprayed, wear-resistant coating (bearing load on shaft)

1980—CF6 (Commercial Engine)
- Coatings in every section of the engine
- All types of coatings
- Impingement/film cooled turbine blade era
- 2150 °F (+) (1186 °C) turbine temp

Coatings:

Fan & compressor rub liners
Thermal barrier coatings
Hot gas path seals
Dovetail & mid-span wear coatings
Compressor erosion-resistant coatings
Oxidation & corrosion-resistant coatings
Labryinth seals

Historical perspective on design and coatings evolution over the past 30 years.

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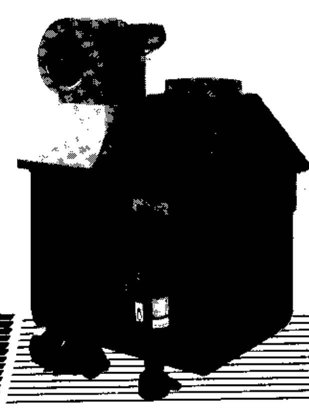

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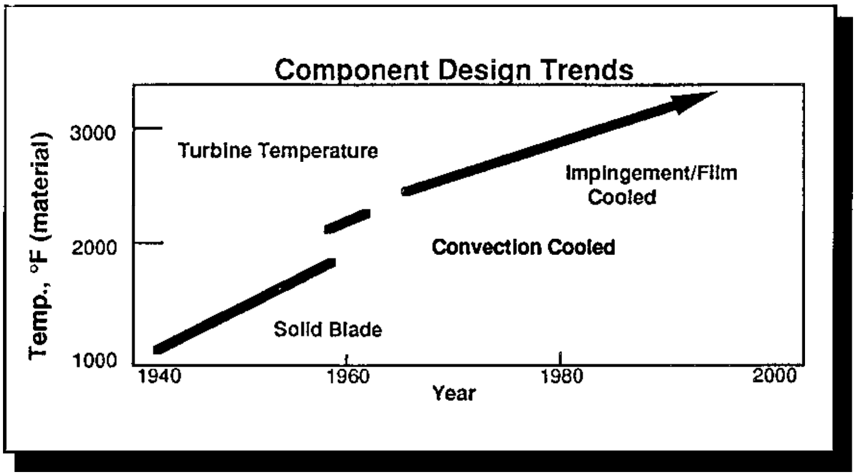


Fig. 1—Turbine technology trends.

Engine Section Profile Of Coating Systems

Coating systems are tailored to the environmental conditions to which they are subjected. Engine operating temperature increases dramatically from the fan to the turbine sections. Therefore, the profile of coatings axially within the engine accommodates the changing environment.

Fan Section

In the fan section of the engine, fan blades are coated at high-wear areas, principally the dovetail and mid-span damper (Fig. 4). Fan rub liners also provide a rub surface for the fan blade tips; therefore, they usually contain soft, abradable coatings. The selection of lightweight, high-strength materials, such as titanium-based alloys for the fan blades and disks, necessitates accommodation of titanium's poor-wear capabilities. The fan blade attachment surfaces, therefore, are clad with materials such as CuNiIn to prevent galling and fretting. Vibration dampener struts are coated with a strong, hard, wear-resistant coating, WC-Co, to prevent wear and fatigue resulting from the continuous loading and unloading during engine operation.

The shroud is an abradable material structure designed to wear away during contact with the fan blade. It also may be configured to act as a component of the noise attenuation system.

Compressor Section

The compressor section of the modern gas turbine is a labyrinth of structures that compresses the incoming air for combustion. The environmental temperatures range from about 300 °F to 1200 °F. To achieve the most efficient compressor, leakage into the sump and around the blade tips must be minimized. The airfoils are designed with specific contours to maximize pumping capability with a minimum of drag in as few compression steps as possible. Increasingly, the role of specialized coatings is to maintain the designed clearances and contours over the life of the engine. Ingested particulates erode the contours of the airfoils, causing a loss of efficiency by changing the airfoil contour, opening clearances at the blade tip, and reducing stall margins. Particulates raise the risk of fatigue

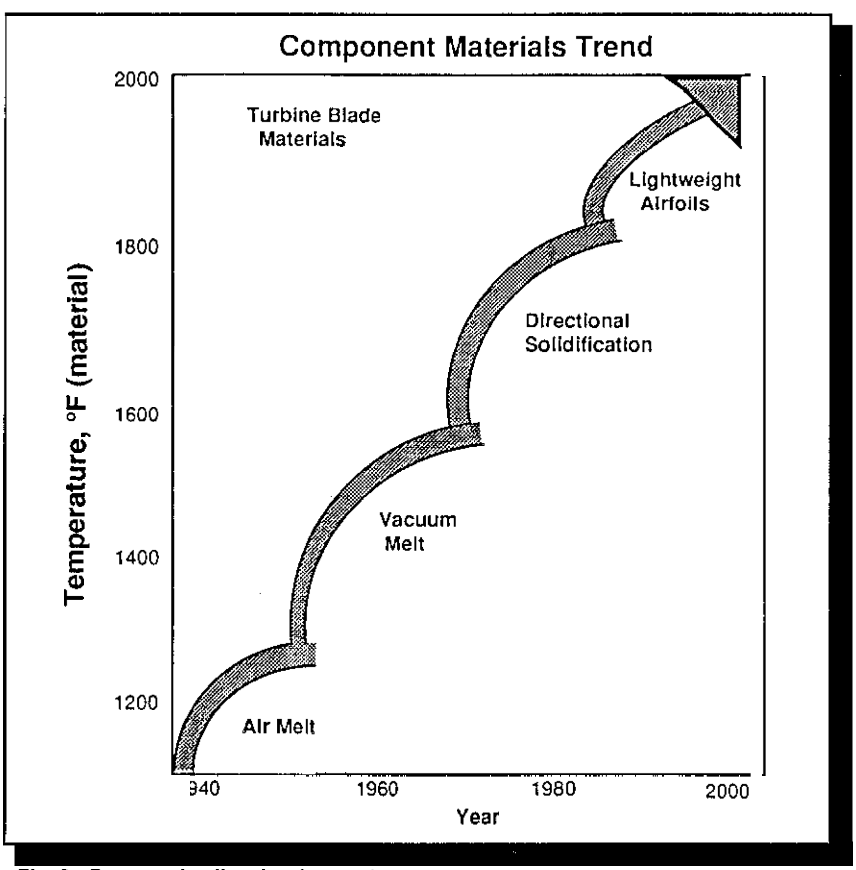


Fig. 2—Progress in alloy development.

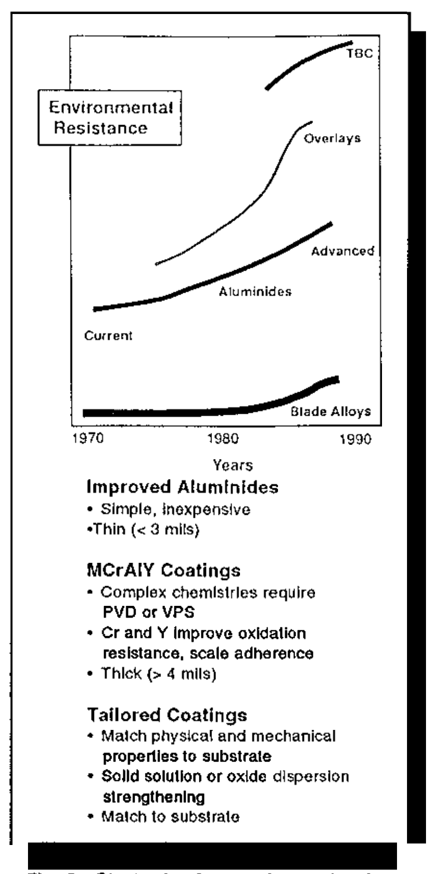


Fig. 3—Strategies for coating technologi

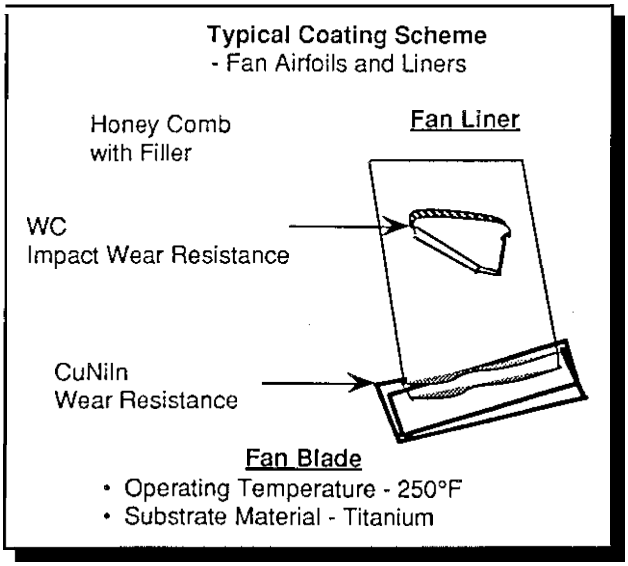


Fig. 4—Typical coating scheme for the fan section.

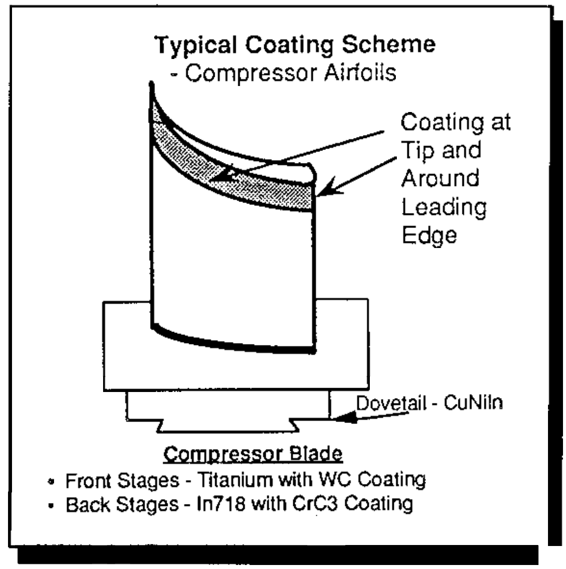


Fig. 5—Typical coating scheme for compressor section.

failure by reducing the blade cross-section and by defecting the highly stressed surfaces.

The degree of severity of such particulate damage is a function of the engine location, the use of the aircraft, and the locale where flown. As expected, helicopter engines, which are required to hover in their own dust storms, are prime victims, and have special centrifugal separators incorporated at the inlet to remove particulates. Commercial engines ingest particulates, especially when mounted in low-hanging nacelles.

Typical coating schemes in the compressor are illustrated in Fig. 5. The airfoils are protected from particulate damage by coating the pressure walls near the tip with tungsten carbide for lower temperature service, and with a chromium carbide-based coating in the higher temperature regions.

The seals for the blade tips are maintained with an abradable coating applied in segments, or directly to the casing, as dictated by the engine design. The materials are generally thermal-sprayed nickel graphite for lower temperature applications, and aluminum bronze-nickel graphite or NiCrAl bentonite for higher temperature needs. Each material is designed to wear preferentially with respect to the blade tips.

The rotors are coated with Al_2O_3 beneath the case mounted vanes to prevent wear of the rotor surface by the vanes. The blade mounts are coated with CuNiIn and a solid film lubricant, and mate against the same coating combination of knife-edge surfaces coated with Al_2O_3 to wear into filled and unfilled stationary surfaces.

Turbine Section

The turbine section represents the most challenging environment for the engine designer. Temperatures up to 2150 °F require both substrate materials and coating systems to be highly oxidation- and corrosion-resistant. To emphasize again, new turbine airfoil alloys have grown in temperature capability, but still require the added benefits provided by a coating system. Turbine airfoil coating systems include several processes that provide corrosion and oxidation resistance (see table). As can be seen from Fig. 6, there is an increasing use of more advanced coating processes. There is a strong trend toward complex coating systems (Fig. 7), each of which may contain several of the advanced processes.

Turbine Airfoil Coating Systems

Codeposition	• Simple aluminide Pack Cementation • External surfaces
Chemical Vapor Deposition (CVD)	• Simple aluminide positive flow gaseous system • Internal and external surfaces
Physical Vapor Deposition (PVD)	• Electron beam PVD • External surfaces
Vacuum Plasma Spray (VPS)	• Plasma spray inside an inert gas chamber under low-pressure environment
Ceramic Plasma Spray	• Air plasma deposition of ceramic
Ceramic PVD	• Complex ceramic gaseous system • Direct evaporation of ceramic (reactive evaporation) under partial pressure

Current Coating Processes

The following is a brief description of some of the current coating processes in use today.

Chemical Vapor Deposition (CVD)

Classic chemical vapor deposition uses an external generator to supply a reactor with the reactive aluminum halide. Internal and external surfaces are coated by CVD method. CVD allows the uniform coating of complex geometric parts (not limited to line-of-sight).

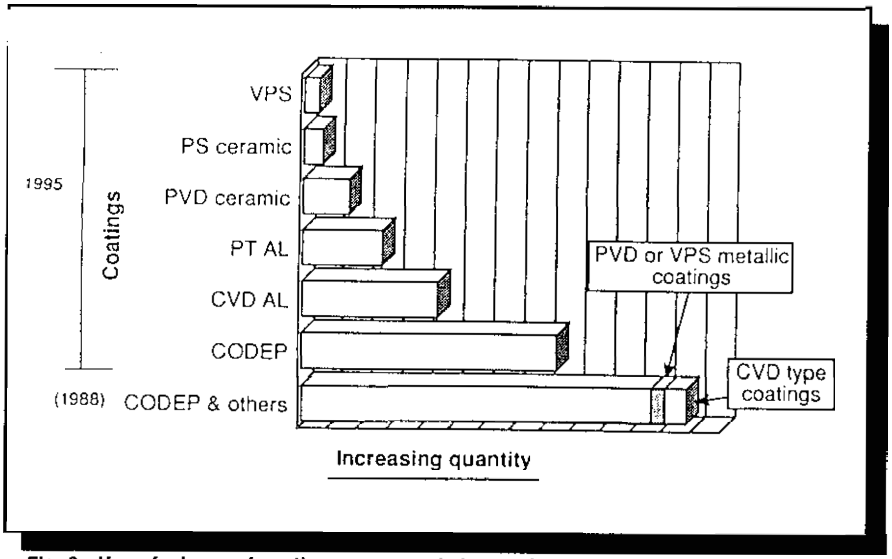


Fig. 6—Use of advanced coating processes is increasing.

Thermal Spray Processes
These are bulk coating deposition technologies. A raw material is heated to its melting point, using a plasma. Material is deposited in the form of molten droplets onto a relatively cool substrate. Thermal spray allows multi-component alloy deposition; involves both oxide and metallic systems.

Physical Vapor Deposition (PVD)
Heated raw material is evaporated from a source and condensed onto the workpiece. The system features:

1. High deposition rate
2. Generally high workpiece temperatures during deposition
3. Usually high vacuum environment
4. Provides precision deposition and molecular deposition.

Of interest is the characteristically different microstructure (see Fig. 8) resulting from the two thermal barrier coating processes. This variation in microstructure provides design flexibility to accommodate changing environmental demands.

Operating experience indicates that not only the external surfaces of turbine airfoils require protection, but also the internal passages. The chemical vapor deposition process provides this overall protection. The key advantage of the gaseous system is that it allows simultaneous deposition of both the internal and external coating.

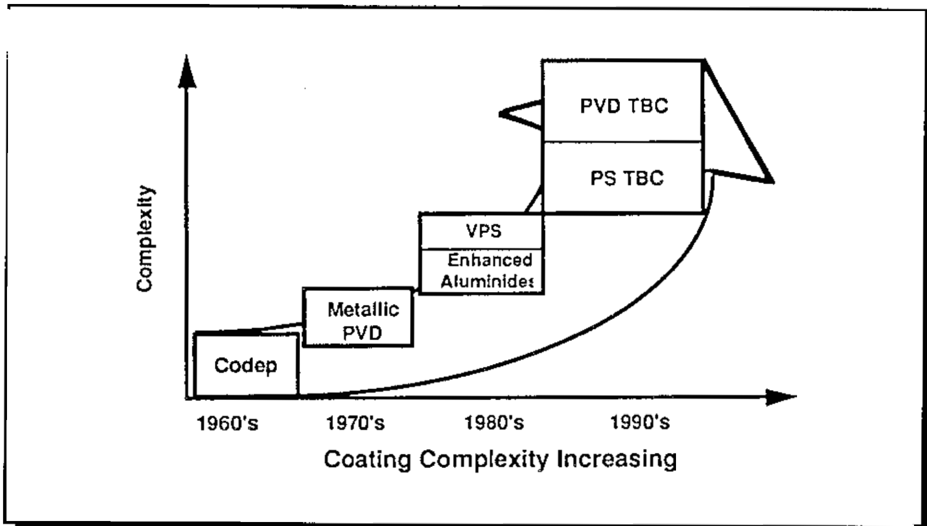
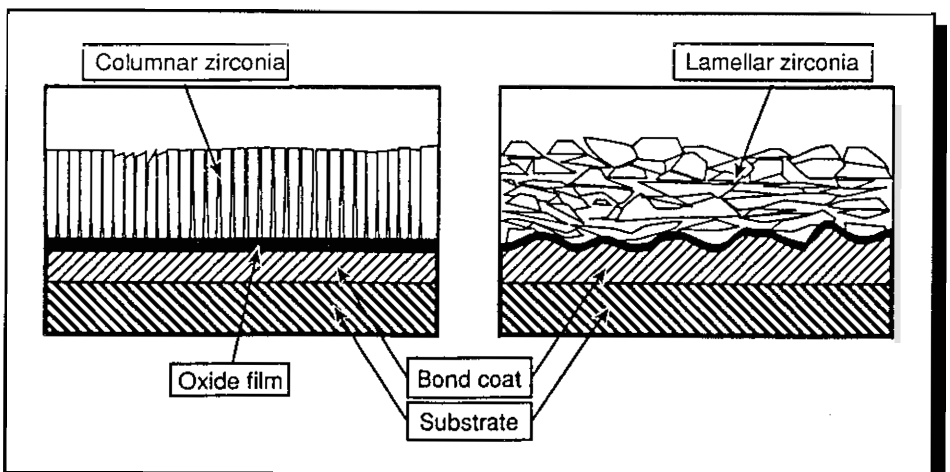


Fig. 7—There is a strong trend toward the use of complex coating systems.



ig. 8—Illustration of the different microstructure resulting from two thermal barrier coating p cesses, PVD (left) and plasma (right).

Coatings Enhance Engine Performance

The continuing drive for improved engine performance in terms of specific fuel consumption (SFC), has driven the need for thermal barrier coatings (TBCs). These coatings exhibit superior temperature capability and allow the needed growth in engine performance.

Characteristically, these coatings provide a thermal barrier to the substrate material, thereby enabling higher temperature capability with equivalent cooling air flow. The higher operating temperature results in improved SFC.

The importance of the TBC system becomes more evident as the material temperature limit is approached (Fig. 9). TBCs will extend the usefulness of this last generation of superalloys, and bridge the gap between superalloys and the next generation of materials.

Thermal barrier coatings present a number of challenges, from a process technology standpoint. The TBC example is representative of newer, more advanced coating systems, in that it speaks to certain challenges ahead, and how they must be approached from a process development standpoint.

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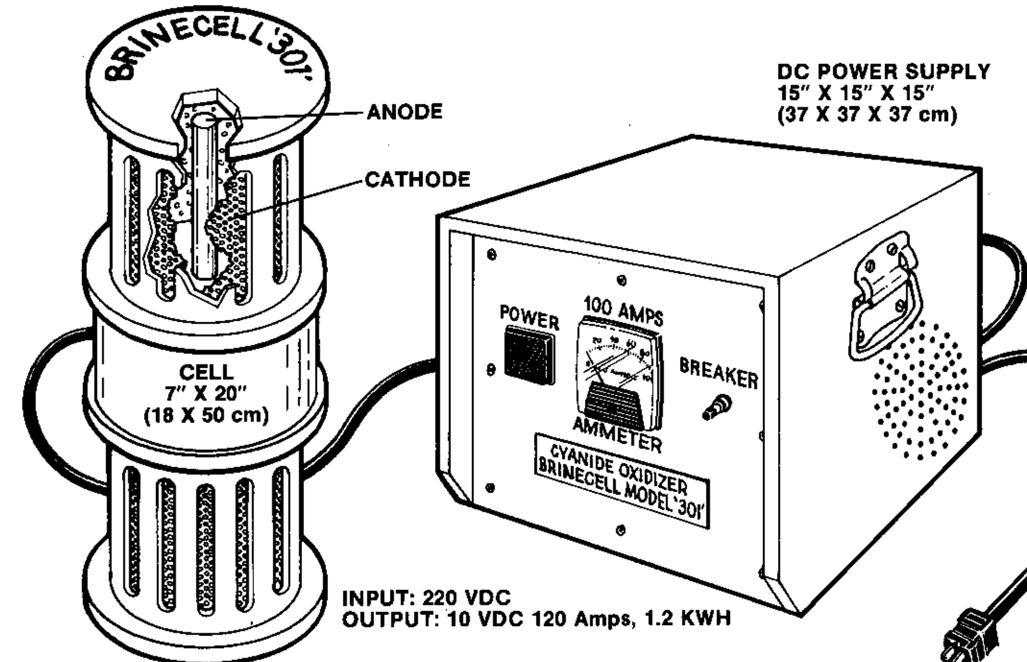

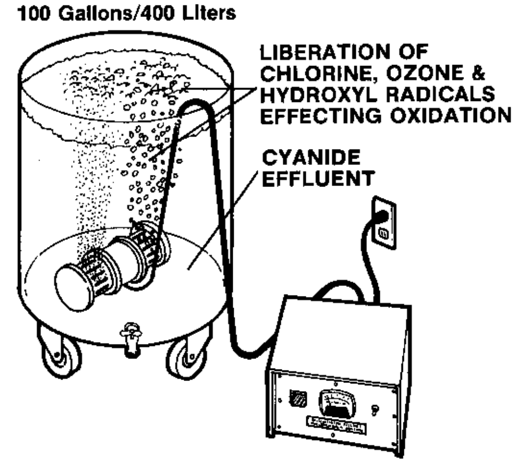

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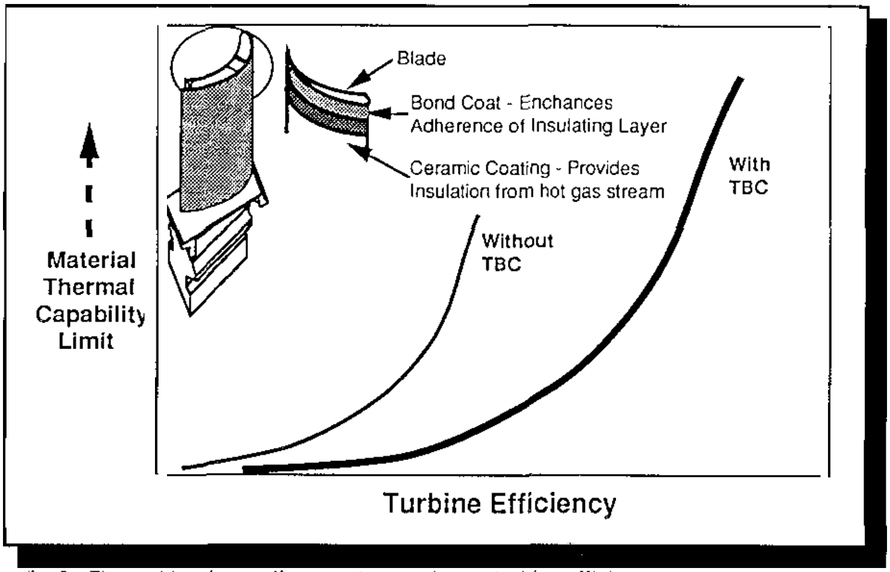


ig. 9—Thermal barrier coatings systems enhance turbine efficiency.

What About Tomorrow?

A look ahead to the engines of tomorrow shows that challenges abound, including:

- The increased use of nonmetallic materials
- Hybrid components fabricated from metals and ceramics
- Process technologies for construction of these hybrid components that require coated fibers, which are then shaped and formed into components
- In order to implement new coating processes, concurrent engineering must be addressed, so that design, manufacturing and process development are all in step, providing a better product in a shorter period of time.

All this translates into a host of new challenges across a broad spectrum. The coating process technologist will be faced with approaching process development in much the same way as with the TBC example. The task, however, will be much more difficult as new materials—with which there is little or no experience—must be addressed. The integration of product and process definition becomes imperative, because one is integral to the other in producing acceptably high-quality hardware (Fig. 10). Careful attention must be paid to our approach to process development today, to help in positioning for the challenges of tomorrow. ❑

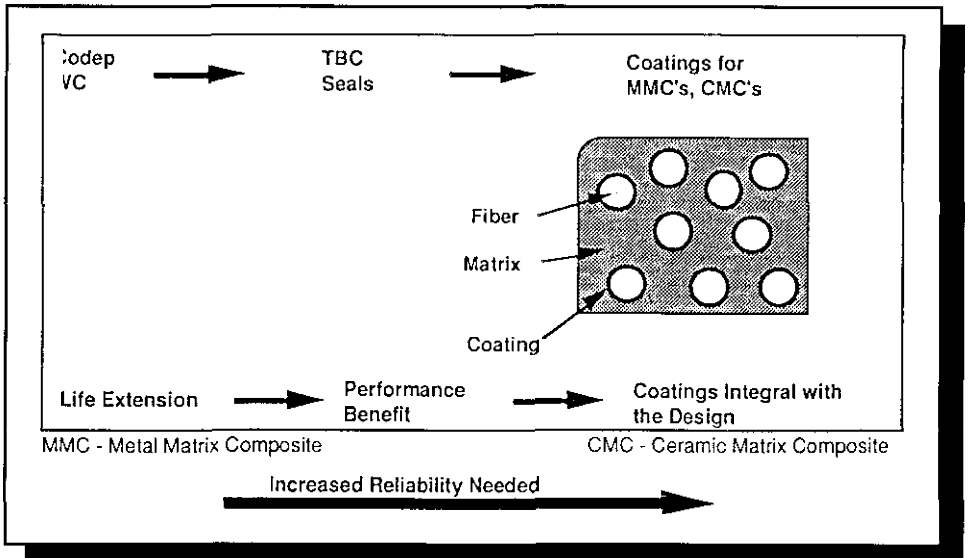


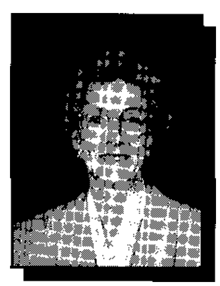
Fig. 10—Product and process definition are integral to the other in producing high-quality hardware.

Current applications of thermal barrier coatings are primarily ceramic coating materials over a metal substrate. Coating thickness may range from 0.050 in. for turbine shrouds, to 0.005 in. for turbine airfoils.

Applying the ceramic coating over metal-bond-coats and substrates creates significant technical challenges. Differences in coefficients of thermal expansion require a strain-tolerant ceramic to adhere during cyclic thermal shock in service. Sustained operation at elevated temperature requires a bond coat with superior oxidation resistance. In addition, stresses from the coating process must be understood and controlled to assure desired performance and durability in the engine.

Processing materials, notably the ceramic powder size and morphology, must be tightly controlled to achieve expected results. Finally, quality assurance tests, including nondestructive evaluation of coated hardware, must be developed for specific TBC applications. Current NDE techniques include eddy current for thickness measurement and thermography for detection of dis-bond areas.

The challenges of such a complex system require an increasingly disciplined approach to process development, more so than in the past. These more-advanced processes are less process-tolerant, and the process operating window must be carefully established. Study of the fundamental relationships between process parameters, material properties and product performance is imperative. The resultant process understanding will allow the required high yields to be obtained from a coating process that is in control.



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