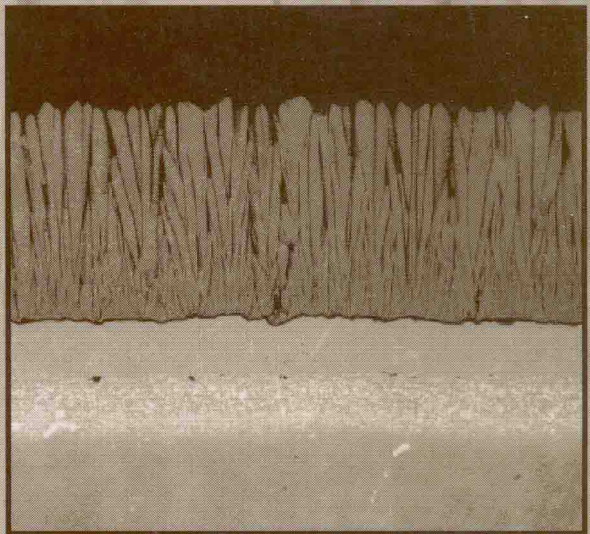
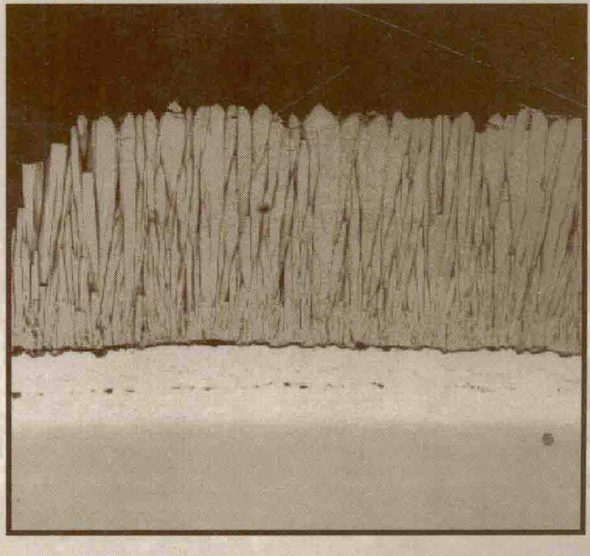
# Coatings for High-Temperature Structural Materials

## Trends and Opportunities





NATIONAL RESEARCH COUNCIL

# Coatings for High-Temperature Structural Materials

## Trends and Opportunities

Committee on Coatings for High-Temperature Structural Materials

National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council



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# Abstract

This report assesses coatings materials and processes for gas-turbine blades and vanes; determines potential applications of coatings in high-temperature environments; identifies needs for improved coatings for performance enhancements, design considerations, and fabrication processes; assesses durability of advanced coating systems in potential service environments; and discusses required inspection, repair, and maintenance methods. Promising areas for research and development of materials and processes for improved coating systems and approaches for increased standardization of coatings are identified, with an emphasis on materials and processes with the potential for either improving performance, quality, or reproducibility or significantly reducing manufacturing costs.

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The committee is grateful to those people who took time to brief the committee on the latest developments in coatings for high-temperature structural materials. The information and ideas from these briefings were essential to the study. Briefings were presented by Steve Balsone, Wright-Patterson Air Force Base; Andy Culbertson, Naval Air Warfare Center Trenton; Jack Devan, Oak Ridge National Laboratory; Dick Novak, Engineered Coatings; Randy Sands, Naval Air Warfare Center; Fred Soechting, Pratt & Whitney; Joseph Stephens, NASA Lewis Research Center; and Sharon Vukelich, Wright-Patterson Air Force Base.

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The chair of the committee thanks the members for their dedication and patience during the course of this study. This report could never have been completed without the diligence and goodwill of the members.

The committee thanks the staff of the National Materials Advisory Board, almost all of whom seemed to have been involved in the study at one time or another. Three program officers helped guide the study. In particular, the committee thanks Robert Ehrenreich for finishing the study. Tom Munns initiated the project and deserves thanks. Jill Wilson's support and guidance during the course of the study is greatly appreciated by the committee, as is Robert Sprague's, whose ideas as a consultant helped shape the report. Charles Hach and Jack Hughes were invaluable in the latter stages of the report. The committee also thanks Robert Schafrik for his support and direction along the way. Finally, the committee gratefully acknowledges the support of Aida C. Neel, senior project assistant.

# Preface

The U.S. Department of Defense and the National Aeronautics and Space Administration requested that the National Research Council conduct a study and provide recommendations on future research and development needs for high-temperature coatings systems. This report represents the work of the Committee on Coatings for High-Temperature Structural Materials, established by the National Research Council for this purpose.

Performance improvements in high-temperature mechanical systems have resulted in increasingly severe operating environments for high-temperature structural materials, particularly in gas turbines. This has sparked an increased demand for more reliable coatings that possess predictable failure mechanisms, improve the performance of structural materials, and extend the operating range of applications. With this background, the following objectives were outlined for this study:

- assess the state of the art of coatings materials and processes
- identify potential applications for coatings in high-temperature environments
- identify needs for improved coatings for performance enhancements, design considerations, and fabrication processes
- assess durability of advanced coating systems in expected service environments
- identify required inspection, repair, and maintenance methods
- recommend promising areas for materials and process research and development for improved coating systems and identify approaches to increased coating standardization

To address these objectives, the committee considered (1) propulsion systems for commercial and military aircraft and their marine and industrial derivatives and (2) land-based turbines for power generation and mechanical drives (excluding automotive, diesel engines, and space applications). The committee directed its efforts toward the hot section (combustor and turbine) of these gas-turbine systems, because this represents the most significant materials and coating challenges. To focus the study further, the committee considered a wide range of application and technology areas that might be covered under this broad charter and identified those that would be reviewed in detail. The intent was to concentrate on the materials systems and degradation modes in the hottest section of the identified power-generation systems and to consider the technology and application implications for coatings systems under these most severe conditions. A primary focus was on the needs for advanced machines under development by the U.S. Department of Energy, the U.S. Department of Defense, and the National Aeronautics and Space Administration sponsorship. This deliberation resulted in the list shown in table P-1, which defines the study focus, the areas not considered, and the areas that were only referenced by association with the primary focus.

Through a series of briefings from industry and government experts, the committee reviewed current coating systems, newly developed coating systems, and their implementation in products over the next five to eight years. To evaluate coating needs beyond this time frame, the committee reviewed the substrate materials (e.g., ceramics and intermetallics) being considered for future engine designs. The committee recognized that defining needs for many future systems would currently lack clarity, but a need was perceived to anticipate any fundamental changes that may demand longer-range research, process development, or manufacturing innovations.

This report reviews the state of the art for coating systems based on the following approach. First, the application needs were identified and a description of the domain of use was developed. Second, the environment that currently exists and the substrate materials that are now used in the hot section of gas-turbine engines were examined. This, in turn, led to a more complete definition of the coatings systems required. Third, the application processes, the industrial base, and the repair and overhaul requirements were discussed and the support capabilities (e.g., modeling, testing, and nondestructive evaluation) were assessed. This review provided a baseline for discussion of future trends and indicated how U.S. industry, government, and academia are planning to address the requirements of advanced propulsion systems.

To determine materials and coatings needs, advanced systems were assessed. The assessments on these advanced systems were obtained through presentations and information provided by the program managers for three major

TABLE P-1 Committee Focus

| Focus | Associated/Referenced | Excluded |
|---|---|---|
| Industrial, marine, power generation, aircraft engine | Land-based systems | Auto, diesel engines, space |
| Structural materials<br>superalloys (Ni, Co)<br>intermetallics<br>composites (IMC, CMC)<br>monolithic ceramics | Refractories | Titanium alloys |
| 700°C + temperatures (to capture Type II hot corrosion) | | |
| Oxidation, corrosion, erosion | Seal systems degradation caused by the service environment | Tribological wear |
| Gas-path coatings and clearance coatings | Gas-path seals | |
| Combustor, transition piece, high-pressure turbine, power turbine | Off-line combustion | Compressor, fan |
| Diffusion coatings, overlays, TBC, surface modifications | Functionally graded materials, claddings, vitreous coatings | Low observable coatings, fiber coatings |
| Thermal spray, CVD, PVD, advanced processes | Plating,C/S/N/O-resistant coatings | |
| Operating environment (air, fuel, water, particulates) | Combustion, emissions | |
| Environmental impact: manufacturing, service, overhaul | | |
| Repair considerations | Lower-temperature coatings affected (e.g., impact-resistant coatings) | Repairs involving brazing, welding, etc. |
| Nondestructive evaluation (NDE) | | |
| Standards and standardization | | |
| Databases, modeling, engine condition sensors | Controls, intelligent processing of materials | |
| Systems design (coating/substrate integration): advanced concepts | Material systems that might reduce or eliminate need for high-temperature coatings (e.g., Lamalloy) | |
| Customer—DOD, DOE, NASA, original equipment manufacturers, suppliers | Airframe manufacturers, airlines, utilities | |

TABLE P-2 Primary Performance Goals for Advanced Engine Systems

| Advanced Engine System | Requirements |
| --- | --- |
| Integrated High-Performance Turbine Engine Technology (IHPTET) | Cold section (fan and compressor):<br>2–3 times specific strength for materials<br>650–1000°C operating temperature<br>Hot section (the focus of this report; includes the combustor, turbine, augmenter, and nozzle subsystems):<br>3–5 times specific strength for materials<br>1650–2200°C with advanced cooling<br>1550°C uncooled<br>Nonstructural (bearing and lubes):<br>up to 825°C |
| High-Speed Civil Transport (HSCT) | Range: 2 times greater than the Concorde<br>Payload: 3 times greater than the Concorde<br>Economics: 8 times greater than the Concorde<br>Environmental emissions: 8 times lower than the Concorde<br>Noise: 3 times quieter than the Concorde |
| Advanced Turbine Systems (ATS) | High efficiency, clean gas-turbine systems initially based on natural gas; adaptable to coal- or biomass-derived fuels<br>Power generation: >60% system efficiency<br>Industrial systems: >15% improvement<br>Environmental: 8 ppm $NO_X$ emissions; CO and HC < 20 ppm<br>Cost competitive: 10% reduction in busbar cost of electricity |

government-sponsored materials efforts representing future military, commercial, and power-generation needs:

- Integrated High-Performance Turbine Engine Technology—advanced military systems
- High-Speed Civil Transport—aimed at the advanced supersonic commercial market
- Advanced Turbine Systems—advanced utility and industrial power generation

Table P-2 summarizes the primary performance goals for each of these advanced systems. For each case, the committee obtained information on mission profile; systems needs; and specifics on time, temperature, and environmental requirements for materials in the propulsion system. This provided a perspective on what were the ultimate materials needs for propulsion systems reaching maturity early in the next century. In all cases, the goals underscored the demand for materials that can withstand significantly higher operating temperatures and service life than today's state-of-the-art devices. The reviews also provided information on significant changes that might be required as a result of new regulatory requirements, such as those that might stipulate permissible emissions from future propulsion systems. In addition, these reviews showed those areas common to aircraft engines and power-generation machines and changes to this commonality that might be demanded by derivative machines as, for example, the increased use of air to combat $NO_X$ in the combustor of land-based electric utility turbines. Some fundamental differences exist between aircraft and land-based systems that might cause a divergence in materials (and coatings) technologies. For instance, land-based systems are less affected by weight and can be supplemented with auxiliary systems, such as air supplies, steam supplies, or heat exchangers. The potential use of alternative fuels in nonaircraft systems might be another divergence affecting coatings type. Both aircraft and land-based gas turbines are moving toward higher temperatures and longer service-time requirements; this trend is causing increased emphasis on coatings needs. Finally, the committee heard presentations on the design requirements for coating systems and the engineered materials efforts that may have a bearing on the development and application of advanced coating systems.

In reviewing these briefings, the committee considered the following key questions:

- Can the goals for the advanced systems be achieved simply by an evolution from today's materials?
- Are programs and efforts in place to address the key potential barriers?

- Are there additional recommendations that can be made to enhance the chances for success in any of the key areas?

The committee then considered future opportunities for developing improved coatings by virtue of evolutionary development and by way of innovative concepts. The committee developed several innovative concepts for advanced coating systems and suggested how a wide variety of ideas could be integrated into coatings development and application advances. The members of the committee continually posed several key questions during their considerations of innovative approaches:

- Are there concepts that have not been explored or that should be re-evaluated in light of recent knowledge?
- Are there ideas or knowledge bases in other industries that can revolutionize thinking in the gas-turbine engine coating industry?
- Are there ideas that can shorten the development cycle of existing efforts and thereby enhance the chance for success?
- What are the latest developments in modeling, intelligent process manufacturing, and smart materials, and can these technologies be focused in the coatings area?
- Are there new testing techniques that would be required and will new industry standards and procedures have to be defined?

Finally, the committee provides its conclusions and recommendations for the future as well as a bibliography of cited references and available texts.

Robert V. Hillery, chair
Committee on Coatings for High-Temperature Structural Materials

# List of Figures and Tables

FIGURES



TABLES

# Acronyms

| | |
|---|---|
| AISI | American Iron and Steel Institute |
| ASM | American Society for Materials |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| ATS | Advanced Turbine Systems |
| CTE | coefficient of thermal expansion |
| CVD | chemical vapor deposition |
| DOD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| EB-PVD | electron-beam physical vapor deposition |
| FGM | functionally graded materials |
| HSCT | High-Speed Civil Transport |
| HVAF | high-velocity air fuel |
| HVOF | high-velocity oxy fuel |
| IHPTET | Integrated High-Performance Turbine Engine Technology program |
| ISO | International Standards Organization |
| LPPS | low-pressure plasma spraying |
| NASA | National Aeronautics and Space Administration |
| NDE | nondestructive evaluation |
| PVD | physical vapor deposition |
| SNECMA | Société National d'Etude et de Construcion de Moteurs d'Aviation |
| STEP | Standard for the Exchange of Product |
| SVPA | SNECMA vapor phase aluminizing |
| TBC | thermal barrier coating |

# Contents

# Executive Summary

Traditionally, coatings and substrates have developed independently. Coatings have also traditionally done an excellent job of doing what they were designed to do: prolong the life of turbine engines by protecting component parts from oxidation and corrosion, erosion by particulate debris, and other potential hazards. Engineers now face a challenge, however. With new technologies creating a broad range of heat-resistant materials, turbines now operate at temperatures that are significantly higher than a decade ago. The new demands on turbine coatings and substrates make it imperative that the two be designed *interdependently*; each must go hand-in-hand into the regime of ever-increasing temperatures. In this harsh environment, a failure in one quickly leads to a failure in the other. Indeed, in some proposed designs, the coating and substrate form a continuum, literally blurring the boundary between the surface deposit and the material it coats.

In future years, turbine engines will have the potential to reach new heights of efficiency and service life. But to keep pace, coating technologists will have to continue moving away from the traditional way of designing coatings. The bottom line is that coatings must be integrated into the total component design taking into full consideration the alloy composition, casting process, and cooling scheme.

The efficiency of gas turbines, whether for industrial power generation, marine applications, or aircraft propulsion, has steadily improved for years. These advances have come about, in large part, because the means have been found to operate the gas-generator portion of the engine at increasingly higher temperatures. The need for greater performance from advanced turbine engines will continue, requiring even higher operating efficiencies, longer operating lifetimes, and reduced emissions. A large share of these improved operating efficiencies will result from still higher operating temperatures. Better engine durability would normally require lower operating temperatures, more cooling of the hot structure, or structural materials possessing inherently greater temperature performance. Since the first two options cause a penalty in operating efficiency, the last approach is preferred. Achieving greater temperature performance has made imperative the use of surface protection to extend component life and the concurrent development of the advanced structural materials and the coatings that protect the structure from environmental degradation.

This report assesses the state of the art of turbine coatings, identifies applications for coated high-temperature structures, identifies needs for improved coating technologies, assesses durability of coatings in expected service environments, identifies coating life-cycle considerations, suggests innovative directions for coating systems, and presents recommendations for coating technologies. *The report concludes that coatings have become an enabling technology for advanced engines; the development of coatings and their processes must keep pace with the broader materials and systems requirements.*

## TRENDS

### High-Temperature Coatings Design

In the past, high-temperature coatings were selected predominantly after the component design was finalized. Current designs require that the substrate (typically a nickel-base superalloy) have sufficient inherent resistance to the degradation mechanisms to prevent catastrophic reduction in service lifetime in the event of coating failure. Since the materials considered for future substrates may possess less inherent environmental resistance at higher temperatures, the importance of coatings in achieving performance will continue to grow. In future turbine designs, coatings will be increasingly viewed as an integral portion of the design process to meet the high demands for system performance.

### High-Temperature Coating Types

Although many types of high-temperature coatings are currently in use, they generally fall into one of three types: aluminide, chromide, and MCrAlY.[1] The family of coatings that insulate the substrate from the heat of the gas path (i.e., thermal barrier coatings [TBCs]) is increasing in importance as they begin to be used for performance benefits. TBCs are

[1] MCrAlY is a type of metallic coating in which M is a metal, usually cobalt, nickel, or a combination of the two; Cr is chromium; Al is aluminum; and Y is yttrium.

ceramic coatings (e.g., partially stabilized zirconia) that are applied to an oxidation-resistant bondcoat, typically a MCrAlY or aluminide.

## Processes for Applying Coatings

A wide variety of processes are used to apply coatings, although they rely on one of three general methods: physical vapor deposition, chemical vapor deposition, and thermal spray. These processes deposit a wide range of coatings between the extremes of diffusion coatings (i.e., the deposited elements are interdiffused with the substrate during the coating process) and overlay coatings (i.e., the deposited elements have limited interdiffusion with the substrate). Diffusion coatings are well bonded to the substrate but have limited compositional flexibility; their usefulness is strongly dependent on substrate chemistry. Overlay coatings are typically well bonded and have broad compositional flexibility; however, they are more expensive and thicker than diffusion coatings. TBCs are overlay coatings and as such can be deposited on a variety of substrates. The main difficulty with TBCs is that the abrupt change in composition and properties at the interface tends to promote ceramic layer spallation.

Electron-beam physical vapor deposition is often favored over plasma deposition for TBCs on turbine airfoils since it applies a smooth surface of better aerodynamic quality with less interference to cooling holes. However, the widely used plasma-spray process has benefits, including a lower application cost, an ability to coat a greater diversity of components with a wider composition range, and a large installed equipment base.

*Coating developers must not only find a suitable coating for an application but must also develop the necessary application processes with on-line control so that the resultant composition and microstructure of the coating is highly reproducible and within the performance limits needed for the service requirements. Developing the relationship of the process-to-product performance must also be a priority, near-term endeavor for advanced coating systems.*

## Degradation Modes

A primary consideration in selecting a coating system is determining if it provides adequate protection against the active, in-service, environmentally induced degradation mechanism(s) experienced by the component. These degradation modes are a function of the operating conditions and the component base materials. The degradation modes common to superalloy hot-section components include—to varying degrees—low-cycle thermomechanical fatigue, foreign object damage, high-cycle fatigue, high-temperature oxidation, hot corrosion, and creep.

Because of the use of thin walls and compositional design for highest strength, aircraft turbine blades with internal cooling passages have historically had insufficient high-temperature oxidation resistance to meet required lifetimes without the use of a coating. Coatings have been used in these circumstances to extend overhaul limits and useful life of the component. Although the latest generation of single-crystal blades has excellent oxidation resistance compared with conventionally cast industrial engine blades and aircraft gas-turbine blades with moderate to high chromium contents, the blades have less tolerance for hot corrosion once the coating has been breached. Industrial gas-turbine blades, which use thick walls and lower-strength alloys with higher corrosion resistance, generally have significant service life after the coating is breached.

During service, coatings degrade at two fronts: the coating/gas-path interface and the coating/substrate interface. Deterioration of the coating surface at the coating/gas-path interface is a consequence of environmental degradation mechanisms. Solid-state diffusion at the coating/substrate interface occurs at high temperatures, causing compositional changes at this internal interface that can compromise substrate properties and deplete the coating of critical species. In the worst case, interdiffusion leading to the precipitation of brittle phases can cause a severe loss of fatigue resistance.

## Engineering Considerations

Given that a coating system is required and that one has been identified that provides environmental protection, six significant engineering factors must be evaluated.

1. Chemical (metallurgical) compatibility. The coating must be relatively stable with respect to the substrate material to avoid excessive interdiffusion and chemical reactions during the service lifetime. An unstable coating can lead to premature degradation of both the coating and the substrate through lower melting temperatures, lower creep resistance, embrittlement, etc.

2. Coating process compatibility. The coating material may be completely compatible with the component, but the coating process may not be compatible. This would usually occur when process conditions require high temperatures or special pre-coating surface treatments.

3. Mechanical compatibility. Coatings resistant to oxidation and corrosion maintain their protectiveness only if they remain adherent and free from through-thickness cracks. Important considerations include close match of the coefficient of thermal expansion (CTE) of the coating with the substrate,