MATERIALS DESIGN FOR THE NEXT GENERATION THERMAL BARRIER COATINGS

D.R. Clarke and C.G. Levi

Materials Department, College of Engineering, University of California, Santa Barbara, California 93106-5050; email: clarke@engineering.ucsb.edu

Key Words   zirconia, materials science, high temperature

■ **Abstract**   The emphasis in this short review is to describe the materials issues involved in the development of present thermal barrier coatings and the advances necessary for the next generation, higher temperature capability coatings.

INTRODUCTION

The development of today's gas turbine engines has been the result of continual improvements in a wide variety of engineering skills including turbine design, combustion, and materials. One measure of the substantial improvements over the past five decades is the increase in the maximum gas temperature at a turbine airfoil afforded by these improvements, as shown in Figure 1. The increase in airfoil temperature has been facilitated by three principal materials developments: dramatic advances in alloy design to produce alloy compositions that are both more creep resistant and oxidation resistant; advances in casting technology that have facilitated not only the casting of large single-crystal superalloy blades and vanes but also the intricate internal channels in the blades to facilitate cooling; and the development of a viable coating technology to deposit a conformal, thermally insulating coating on turbine components. The advances and developments in the first two areas have been reviewed extensively elsewhere (1). Less well known is the development of thermal barrier coatings (TBCs), even though in the last decade their use has enabled a dramatic increase in airfoil temperature, far greater than that enabled by the switch from cast alloy blades to single crystal blades over approximately 30 years.

As originally envisaged, the primary function of a TBC is to provide a low thermal conductivity barrier to heat transfer from the hot gas in the engine to the surface of the coated alloy component, whether in the combustor or the turbine (Figure 2). The TBC allows the turbine designer to increase the gas temperature, and thereby the engine efficiency, without increasing the surface temperature of the alloy. Subsequently, it has been recognized that a TBC also confers additional benefits, for instance, providing protection to rapid thermal transients such as occur
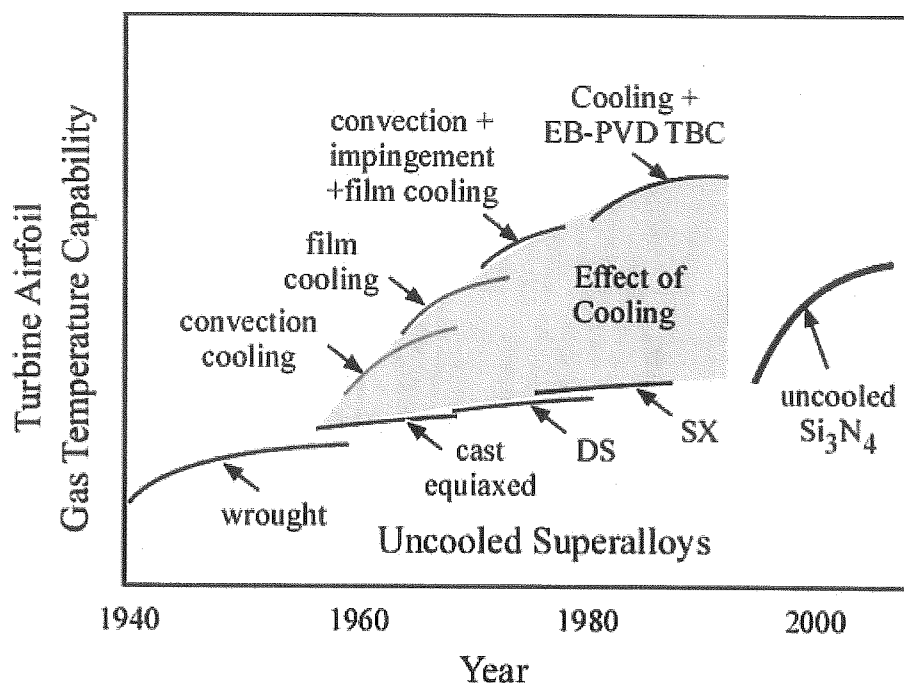
Figure 1   Increase in turbine airfoil temperature over the last six decades through combinations of materials advances and associated developments in cooling techniques. Since this diagram was constructed, the shaded region has extended to the present year, and the use of uncooled silicon nitride remains for the future.

due to flame out, and as a means to even out local temperature gradients. Indeed, in some cases, the use of a TBC has simplified the design of blades by minimizing thermal distortions of the blade. However, undoubtedly the biggest benefit of TBCs has been to extend the life of alloy components in the hottest sections in an engine by decreasing their surface temperatures.

Present day TBCs generally consist of a yttria-stabilized zirconia (YSZ) coating deposited onto an oxidation-resistant bond-coat alloy that is first applied to a nickel-based superalloy component (Figure 2). In diesel engine applications where the temperatures are usually lower, the YSZ coating is generally applied directly onto the alloy. Two main types of coating are in use. For relatively small components such as blades and vanes in aerospace turbines, the coatings can be applied by electron-beam physical vapor deposition (EB-PVD). For larger components such as the combustion chambers and the blades and vanes of power generation, stationary turbines, the coatings are usually applied by plasma-spraying (PS). In many respects, the choice of materials and their production represent a mature materials technology. While improvements in their capabilities continue, there is a growing realization that new TBC systems will be required for the next generation turbines presently being designed. To set the stage for coming developments, we first review the selection of materials used in present YSZ coatings, some of the new insights that have been gained in understanding how YSZ coatings
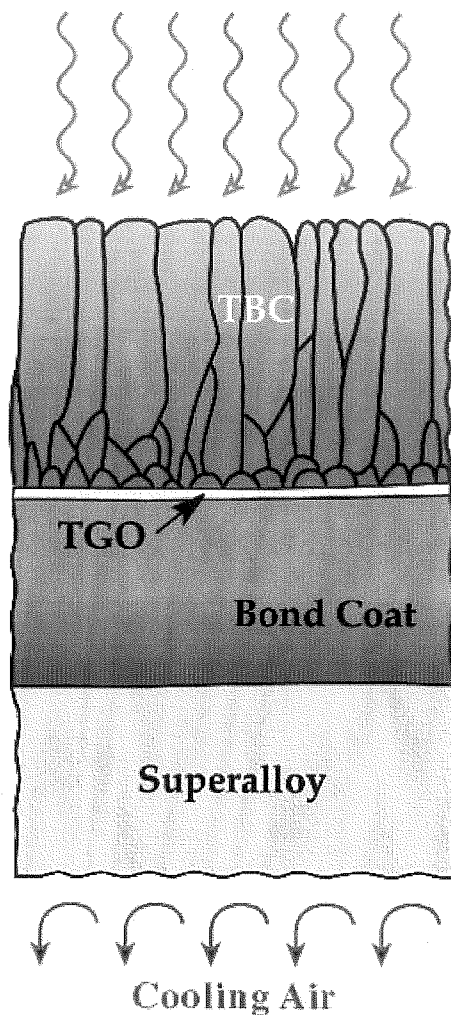
Figure 2 Schematic illustration of a TBC and the associated bond-coat on a superalloy in a thermal gradient.

fail, and then describe approaches to the development of the next generation TBC systems.

PRINCIPAL REQUIREMENTS OF A THERMAL BARRIER COATING

The turbine designers' primary requirement of a TBC is that it have a low thermal conductivity and, for rotating components, preferably also a low density to minimize centrifugal loads. At the materials design level this translates into three additional requirements. First, the material must have strain compliance so as to withstand the strains associated with thermal expansion mismatch between the coating and the underlying alloy on thermal cycling. The use cycle, both the maximum temperature and the times at temperature, of course, varies between aircraft and power generation turbines, but nevertheless the coating must accommodate the large strains associated with thermal cycling. The need for strain compliance is illustrated in Figure 3, where the thermal expansion coefficients of zirconia,
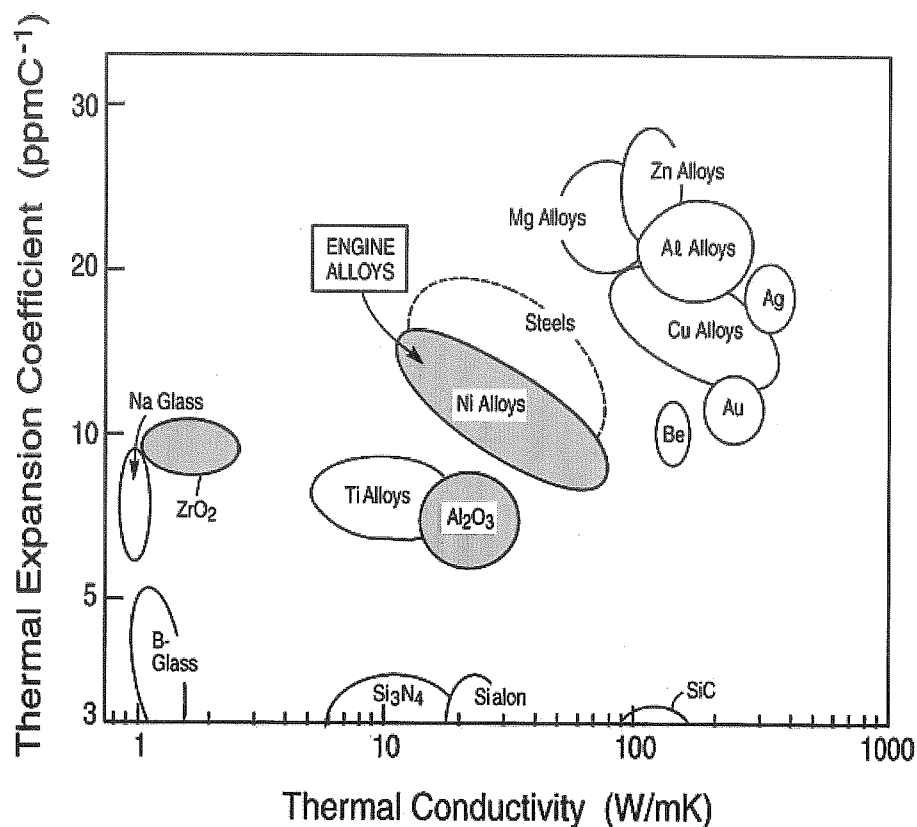
Figure 3 The thermal expansion coefficients and thermal conductivity of a range of materials illustrating the differences in thermal expansion and conductivity of the principal components in TBC systems.

alumina, and a number of alloys including nickel-based superalloys are cross-plotted against thermal conductivity. In the absence of any strain compliance, for instance due to a decreased elastic modulus, the large elastic mismatch would generate very large stresses and lead to spontaneous failure on cooling. Second, the coating material must exhibit thermodynamic compatibility with the oxide, usually aluminum oxide, formed on the bond-coat alloy at high temperatures. Third, with the continual quest to run engines at higher temperatures and the increasing difficulty of increasing the metal temperature, it is increasingly likely that designers will seek "prime reliant" coatings, namely ones that can be used with assurance that they will not fail. Prime reliant thermal coatings are ones that are necessary to prevent the temperature of the metal from exceeding its maximum temperature, much in the same way that the tiles on the space shuttle prevent the underlying aluminum airframe from being exposed to temperatures in excess of their melting temperature on re-entry.

Because weight is at a premium in aircraft engines, thin coatings with the lowest possible thermal conductivity are required. In contrast, in stationary, ground-based engines where weight is less of a consideration, a desired temperature drop can be

achieved through simply increasing the TBC thickness. In practice, in components in both types of engine, the thickness of the TBC usually is varied from place to place to provide the desired thermal insulation.

Erosion of the coating by both ingested particles, such as sand, from the operating environment and particles that come loose from the combustor liners as it degrades is a perennial source of concern, especially when the particles are large enough to cause impact damage of the coating. In some cases, inborn fine particles, primarily dust and sand, melt into the coating as a wetting silicate while it is hot and can degrade the coating. These silicates, usually variants of Si-Al-Mg-Ca oxides that are the principal elements in sands, are often referred to collectively as CMAS.

A recently recognized requirement of many materials exposed to high temperatures in gas turbines is a long-term stability in the presence of steam. This is partly a direct result of the generation of water during the combustion process, but in a number of designs it is a consequence of the use of steam injection to enhance turbine efficiency. Little is known about the effects of long-term exposure to steam on turbine materials. However, tests have revealed that many silicon-based compounds, including SiC, are unstable to the formation of volatile SiO, which results in the slow retraction of the material as evidenced by the reduction in thickness of components over long operating periods. This active oxidation and evaporation phenomenon precludes the use of silicon compounds in coatings unless protected by another coating.

More difficult to design against are the effects of corrosion, especially airborne species and those, such as sulfur and vanadium, in the fuel itself. The majority of land-based turbines operate on natural gas, but there is increasing interest in using alternative fuels, such as coal gas, that are much dirtier. The consequences of using such alternative fuels and their effects on coatings are only now beginning to be investigated.

THE THERMAL BARRIER COATING SYSTEM

From a materials engineering perspective, it is necessary to consider the TBC as an integrated materials system rather than simply a thermally insulating material coating on a structural alloy component. A representative cross-section of a commercial coating, shown in Figure 4, illustrates the multilayered nature of a coating after high-temperature exposure. There are three principal layers in addition to the superalloy and the low-conductivity coating. Between the alloy and the coating is the bond-coat, so called because in the initial development stages in producing a viable coating, it was found that the superalloy had to be first covered with a bond-coat to ensure that the YSZ coating remained adherent upon oxidation. Between the bond-coat and the YSZ coating—sometimes referred to as the overcoat—is the oxide formed during high-temperature exposure. Finally, during the formation of the bond-coat and the YSZ coating as well as subsequently during use, a reaction layer forms as a result of inter-diffusion between the bond-coat and the superalloy.

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS
Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS
Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS
Sync your system to PACER to automate legal marketing.