THERMAL BARRIER COATINGS FOR SUPERALLOYS

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Ceramic thermal barrier coatings offer a potential near-term means to dramatically increase gas turbine inlet temperatures beyond those possible with metallic coated superalloys. Alternatively, such coatings may make it possible to increase component durability and corrosion resistance. Current efforts are underway to develop such coatings to withstand conditions encountered in aircraft and stationary gas turbines.

INTRODUCTION

The performance and efficiency of gas turbine engines are directly related to the temperatures at which the engines are operated. However, the reliability and durability of engine components are inversely related to temperature. Increases in permissible engine operating temperatures are generally dependent on improvements in alloys and coating materials and on advances in cooling technology. A significant further increase in operating temperatures is possible in the relatively near future through the use of a new class of coatings on air-cooled components. These are insulating, ceramic coatings called thermal barrier coatings. This type of coating is now used in the combustor section of some advanced gas turbine engines. However, current thermal barrier coatings have not yet been introduced into the turbine section of any commercial engine . The goal of present research in thermal barrier coatings is to provide the technology base for their eventual engine demonstration and incorporation into the engine bill-of-materials. Through the use of such coatings, turbine inlet temperatures could be increased, cooling air flow rates could be decreased, or cooling schemes could be simplified. Alternatively, existing gas temperatures and cooling schemes could be maintained and the components could be operated at lower metal temperatures. In this latter instance, increased component durability and reliability would result.

Thermal barrier coating systems consist of a ceramic, insulating layer applied over an intermediate, metallic, bond coat layer. An alternative to this two layer or duplex coating system is a graded coating system in which there is a gradual transition from bond coat to ceramic. Materials used for the ceramic layer should have low thermal conductivity, relatively high thermal expansion, thermodynamic stability in the gas turbine environment, and mechanical stability towards thermal cycling.

Both the ceramic and the metallic bond coat layers are generally applied by the plasma spray process from powdered starting materials. The powders are fed into a high temperature, high velocity plasma arc gas where the powder particles are melted as they are propelled at high velocity towards the substrate. A typical cross-sectional micrograph of a duplex coating system produced by the process is shown in Figure 1.

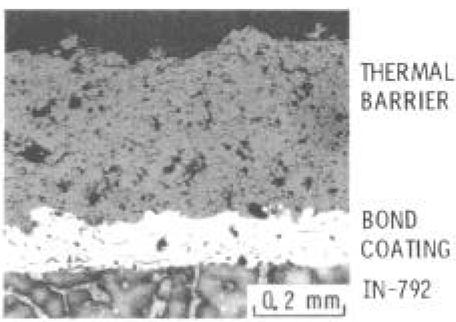

Fig. 1. Photomicrograph of Thermal Barrier Coating System

This figure illustrates that the metallic bond coat is rough and irregular which aids in the attachment and retention of the ceramic. The ceramic layer is highly porous and microcracked. The inherent stability of plasma-sprayed ceramics towards thermal shock arises from this porous microstructure and the stable microcrack network which develops. However, because the porosity is interconnected, the metallic bond coats are not completely protected from oxidation and hot corrosion. Thus, bond coat materials must be environmentally resistant.

EARLY DEVELOPMENT OF THERMAL BARRIER COATINGS

The current optimistic outlook for thermal barrier coatings for protection of turbine airfoil components began with the publication of the burner rig test results on a duplex ZrO_2-12% Y_2O_3/Ni-16% Cr-6% Al-0.6% Y (in weight percent, w/o) coating system (1,2). This type of duplex coating system has proven to be superior to graded coating systems for high temperature, aircraft-oriented usage. A major milestone in the demonstration of the potential of this coating was the successful test of coated turbine blades in a J-75 research engine (3). This early coating system (0.04 cm ceramic and 0.01 cm bond coat) survived 500 two-minute cycles between full power and flame out. At full power the turbine inlet temperature of the engine was 1370^oC. The coating surface temperature reached as high as 1080^oC and the blade metal temperature was as high as 930^oC.

This coating was subsequently evaluated on the first stage blades of a Pratt & Whitney Aircraft JT9D-7 research engine (4). The turbine inlet temperature in this test reached 1430^oC. After 39 hours (327 cycles) of testing, spalling occurred at the center of the leading edge. After an additional 225 hours (1097 cycles) more of the ceramic coating spalled from part of the pressure surface of the blade in the 70% span, trailing edge region. A heat transfer analysis was conducted to provide insight into conditions which led to the observed spalling. The calculated temperature distributions for the blades at the 70% span are presented in Figure 2 which is adapted from Reference 4. The heat transfer analysis showed that the 0.02 cm (7 mil) ceramic coating lowered the average blade metal temperature by 54^oC and lowered the maximum metal temperature by 67^oC. The calculted gradients were 464^oC/mm in the ceramic compared with 40^oC/mm in the metal. Coating failure was correlated with regions of high compressive stress and high temperature. Over the remainder of the blade, the coating was intact. It was concluded in this study that the thermal barrier coating concept is viable and that these coatings have the potential to significantly reduce blade average and maximum metal temperatures and strain range.

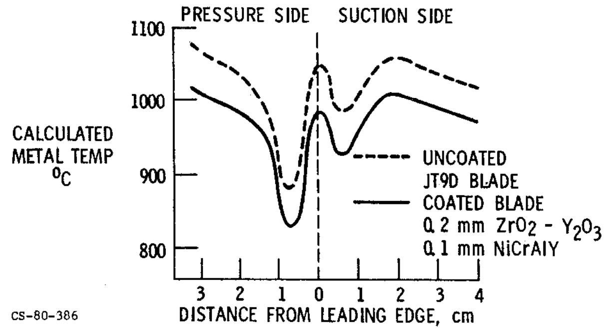

Fig. 2. Effect of Thermal Barrier Coating System on Blade Metal Temperature

IMPROVED THERMAL BARRIER COATING SYSTEMS

The first step directed toward improving the early ZrO_2-12% Y_2O_3/Ni-16% Cr-6% Al-0.6% Y system involved a systematic investigation of the Y_2O_3 level in the ceramic and the Y level in the bond coat. The testing involved coated specimens subjected to one hour cycles at high temperature in rapid response furnaces, natural gas torch rigs, and Mach 1 burner rigs (5).

Figure 3, adapted from reference 5 (6), shows the results of torch rig tests on coated solid specimens.

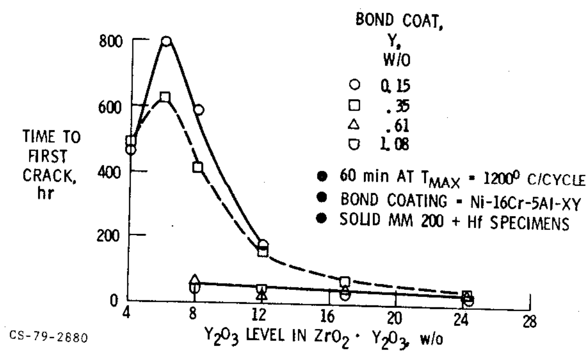

Fig. 3. Cyclic Natural Gas Torch Test Data

The result for the early coating system is given by the point representing 0.6% Y at 12% Y_2O_3. Improvements on coating life of over an order of magnitude resulted from decreasing both the level of Y_2O_3 in the ceramic and Y in the bond coat. Recently, further improvements in the durability of thermal barrier coatings were obtained by adjusting the levels of Cr and Al in the NiCrAlY (7). In burner rig tests (5) air-cooled turbine blades coated with ZrO_2-8% Y_2O_3/Ni-17% Cr-5% Al-0.35% Y survived 2000 hours without failure at a surface temperature of 1450°C and a substrate temperature of 920°C. The early ZrO_2-12% Y_2O_3 based system failed after 800 hours at somewhat lower temperatures.

Work is continuing towards further optimization of the coating systems through variations in materials and processing parameters and through analytical design work. A contract in place with General Electric is aimed at exploring the methodology needed to tailor thermal barrier coatings to aircraft engine components (second stage turbine blade for an automated CF-6 engine) by integrally designing the component and the coating. Low pressure plasma spraying of the metallic bond coat is also being investigated under this contract. In another contract, a closed-loop automated plasma spray system is being developed by TRW under NASA sponsorship (8). Such a device would be required for eventual routine processing of turbine hardware. An electron beam-physical vapor deposition process is being evaluated as an alternative to the plasma spray process under the NASA-Engine Component Improvement Program (9). In addition, basic research on thermal barrier coatings is also being conducted and supported. Such efforts will help provide a fundamental understanding of coating behavior and guide future coating improvements.

DEVELOPMENT OF AIR/FUEL IMPURITY TOLERANT THERMAL BARRIER COATINGS

Another phase of research into thermal barrier coatings involves the evaluation of these coatings under hot corrosion conditions where inorganic salt condensates are present. These activities relate primarily to the operation of land-based gas turbine engines for the production of electric power where there are strong incentives to burn lower grade but more corrosive fuels. They also relate to aircraft gas turbine engine operation under certain conditions, especially those where sea-salt ingestion is possible. Some relaxation of the quality of aircraft gas turbine fuels may also occur in the future.

Currently the in-house research at NASA-Lewis in this area is being conducted under both NASA and DOE sponsorship. Concurrent contractural work, managed by NASA-Lewis, is under DOE and EPRI sponsorship. The research programs are in an early phase, but significant progress has already been made towards identifying some of the associated problems and demonstrating the potential for their solution.

The initial results showed that the early ZrO_2-12% Y_2O_3 based thermal barrier coating system was not durable in the presence of Na_2SO_4 and other salt condensates (10,11,12). These failures result from infiltration of liquid-phase deposits into the pores and microcracks of the ceramic coating, thereby causing a decrease in the ability of the coating to withstand thermal shock. The conditions under which liquid deposits are stable are defined by the thermodynamic dew points and melting points of the condensates (13). In preliminary tests, several new coatings systems were identified which had a significantly improved tolerance to Na-, V-, and S-doped combustion gases (12). Improvements in life by factors of about five, eight, and twelve times were obtained for new systems based on ZrO_2-8% Y_2O_3, $2CaO \cdot SiO_2$, and a MgO-NiCrAlY cermet, respectively.

Several zirconia based thermal barrier coating systems and a calcium silicate based system, are being evaluated under an EPRI-sponsored contract at Westinghouse (14). The coatings are being tested in burner rigs fired both on relatively clean No. 2 gas turbine fuel and on doped fuels. Most of the tests have been conducted at relatively low substrate temperature of 800°C which is appropriate for present day electric utility turbines. Recent unpublished results have been very encouraging. The results of several preliminary tests have shown that a graded ZrO_2-8% Y_2O_3/Ni-20% Cr-11% Al-0.4% Y coating system can survive at least 500 hours in the presence of 50 ppm V plus other fuel contaminants and additives. Encouraging results have also been obtained with the calcium silicate coating system. Recent work on this contract has affirmed that duplex coating systems are more durable than graded systems at higher temperatures.

Work is continuing at NASA to further improve existing coating systems and to identify new materials and concepts. Two NASA-managed DOE sponsored contracts with Westinghouse (14) and Solar (15) , respectively, are also aimed at identifying new thermal barrier coatings. The results of the three contracts and the in-house work will provide the technology base for assessing the potential of ceramic coatings for electric utility gas turbines.

CONCLUDING REMARKS

The potential benefits of thermal barrier coatings include improved efficiency, durability, reliability, and fuel flexibility for aircraft and land based gas turbine engines. Considerable progress has been made towards improving these coatings and further efforts, with the goal of demonstrating engine readiness, continue.

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