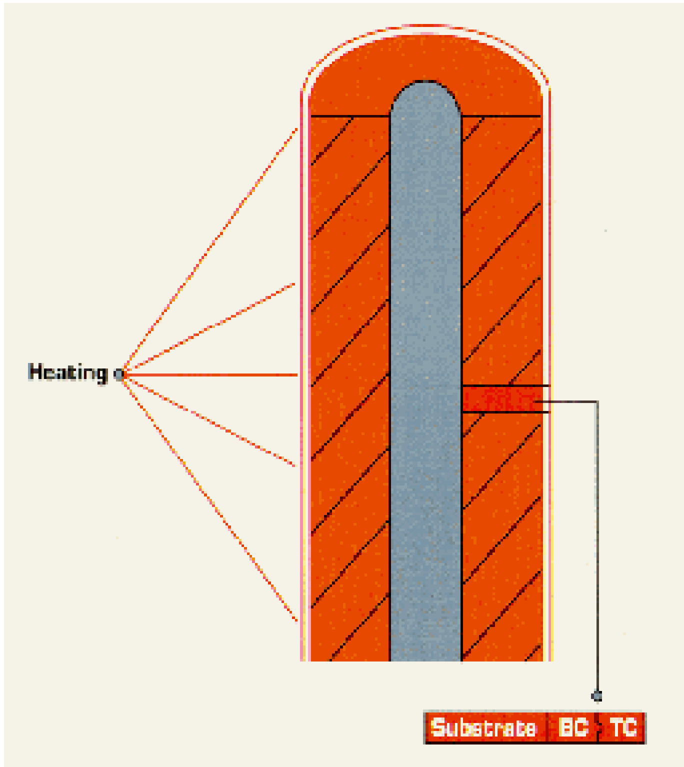
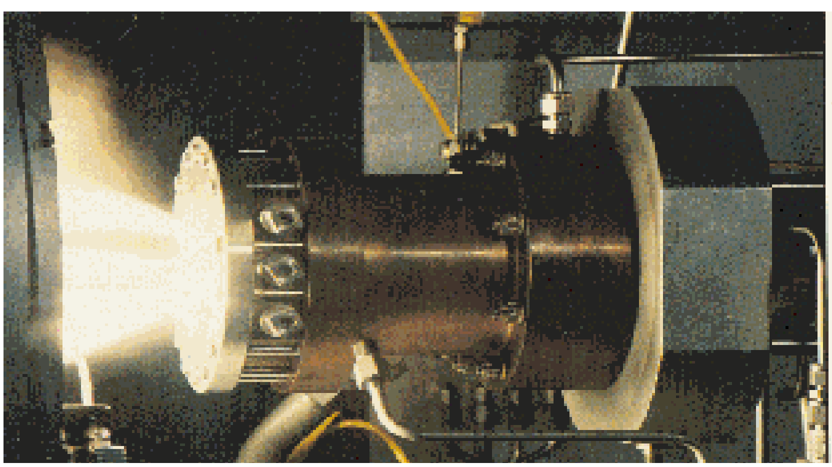
Modeling the Behavior of Thermal Barrier Coatings

DCT has been a leader in developing methods for the analysis and design of thermal barrier coatings using computer simulation. Under a NASA sponsored Small Business Innovation research (SBIR) Phase II program, DCT developed a finite element modeling technique, incorporating complex geometry and material property interactions. This technology aids in the design of ceramic coatings for high temperature components, and hepls to improve the efficiency of turbine and diesel engines by allowing increased operating temperatures.



TBC System showing bond coat and top coat ceramic on substrate

Thermal barrier coatings (TBC's) are typically evaluated using expensive "Burner Rig" tests, in which coated cylinders of varying configurations are subjected to a series of sequential heating and cooling cycles, usually within a temperature range of 30 - 1200 °C.



This modeling work provided the first fundamental description of the role of oxidation in TBC failure, as well as the first published statistical descriptors for

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For turbine engines in propulsion and power applications, improved engine efficiencies are achieved through higher combustion temperatures, which create more energy per volume of fuel consumed. However, the ability to operate an engine at higher temperatures is limited by the engine component material properties. Various methods for reducing engine component temperature have been developed, including the use of a thermal barrier coating (TBC). With development time for new TBC systems for non-rotating components typically being two years for aircraft engines and four years for land based turbines, continued reliance on empirical design methods is costly and necessitates the development of alternative design methods utilizing nondestructive evaluation and life prediction modeling. An innovative approach to TBC design has been developed by DCT within the framework of the commercial finite element software ABAQUS[1]. Based on finite element techniques, the approach models complex material behaviors, including oxidation effects, and is coupled with a simple optimization method to assess the relative effects of specific design criteria on predicted TBC performance. During a recently completed NASA Phase I SBIR, the following analysis methodologies were investigated for commercialization:

Coated Aircraft Gas Turbine Stator Vane

- Implement a Finite Element Thermal Barrier Coating Evaluation Technique into a Commercial Finite Element Code
- Incorporate a Design Optimization Technique into the System
- Investigate a Cracking/Failure Model for the TBC

The plasma sprayed TBC coatings modeled during Phase I incorporated a high level of material model sophistication, including bond coat oxidation behavior, multi-layer effects, material property evolution, thermal gradients induced via internal cooling, and TBC cracking behavior. The simplified optimization technique evaluated provides a means for assessment of specified TBC design variables such as interface

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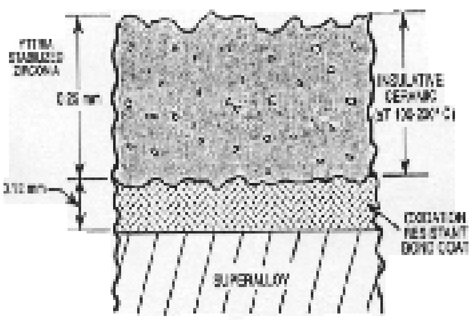
The two most prevalent methods for manufacturing thermal barrier coatings are vacuum plasma spray and electron beam – physical vapor deposition (EB-PVD). The different coating applications involved in these processes produces two completely distinct physical structures. In vacuum plasma spraying, the coating is applied through application of the material in a plasma "plume", creating a relatively uniform



(a)

Plasma Sprayed Coating Structure

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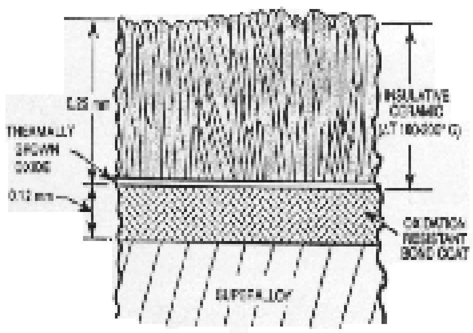

(b)

EB-PVD Coating Structure

microstructure with periodic undulations in roughness along the bond coat/ceramic interface. In contrast, EB-PVD processing produces a highly directional microstructure in which ceramic exhibits a columnar morphology parallel with the direction of application (i.e. normal to the interface). In addition, the interfaces in EB-PVD coated materials tend to exhibit a very low roughness.

In the continuously expanding field of thermal barrier coating research and development, the TBC design engineer needs to be able to assess a large array of potential designs, including the two main manufacturing techniques with their two distinct physical structures. New research into this area has begun to reveal differing failure mechanisms based on structure. EB-PVD cracking appears to be strongly influenced by physical grain anomalies along the interface, leading to intergranular fracture. Plasma sprayed coatings on the other hand appear to crack more in relation to stress fields created by the interaction of CTE mismatch, creep and oxidation in conjunction with the irregular

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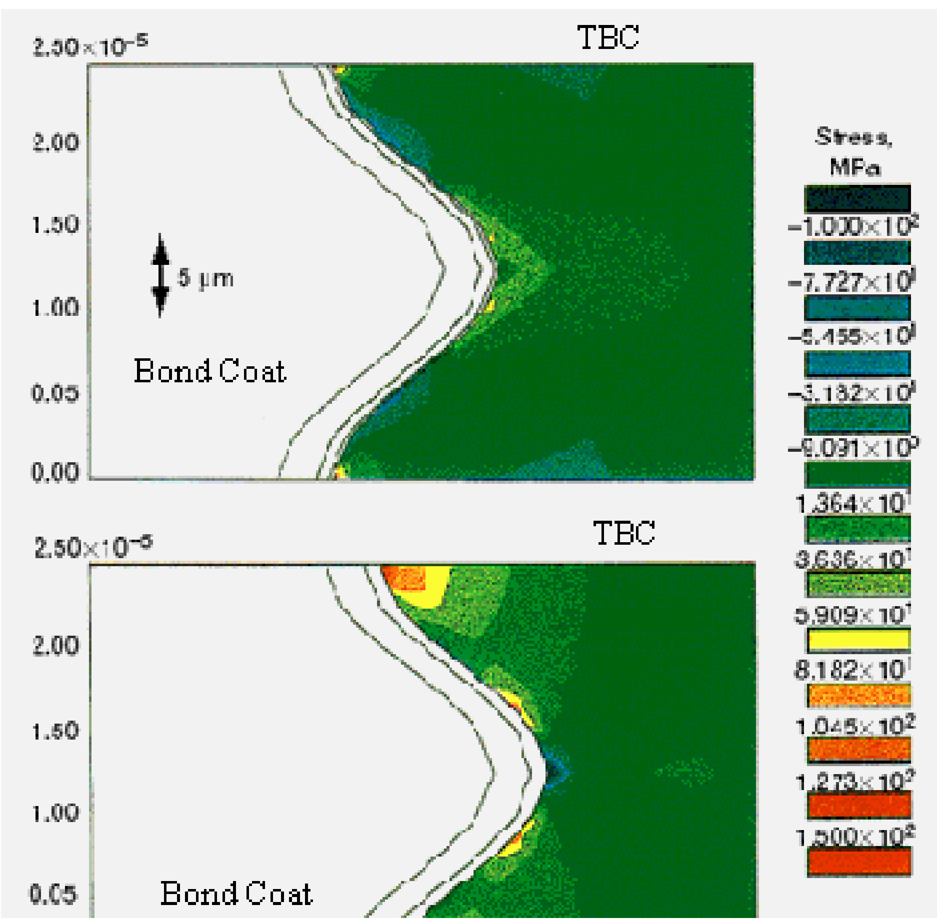
stress perpendicular to the interface. In plasma sprayed systems which typically exhibit a "wave-like" surface roughness, this effect is manifest in the form of tensile stresses at wave peaks, and compressive stresses at wave valleys.

interface
geometry. Modeling work at DCT has concentrated on plasma sprayed systems.

Although it is difficult to design an experiment to examine these factors unambiguously, it is possible to design a computer modeling "experiment" to examine the action and interaction of these factors, as well as to determine failure drivers for TBC's. Previous computer models have examined some of these factors separately to determine their effect on coating residual stresses, but none have examined all the factors concurrently. The purpose of this research, which was performed at DCT, Inc., in contract with the NASA Lewis Research Center, was to develop an inclusive finite element model to characterize the effects of oxidation on the residual stresses within the TBC system during thermal cycling as well as to examine the interaction of oxidation with the other factors affecting TBC life.



The plasma sprayed, two-layer thermal barrier coating that was modeled incorporated a superalloy substrate, a NiCrAlY bond coat, and a ZrO_2-8 wt % Y_2O_3 ceramic top coat. We examined the effect on stress