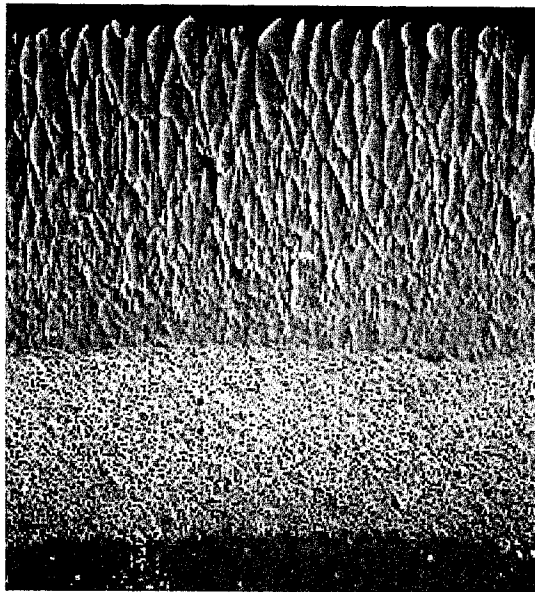


# Bond Strength and Stress Measurements in Thermal Barrier Coatings

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Thermal Barrier Coating Prepared by Electron Beam Physical Vapor Deposition

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# Executive Summary

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Thermal barrier coatings (TBCs) are required for Advanced Turbine Systems (ATS) engines to meet both the performance and durability goals of the ATS program. These coatings fail by spallation of the ceramic at the bond coat to thermally grown oxide interface or within the ceramic near the TGO to ceramic interface. There are dozens of materials and coatings processing variables that must be controlled to provide a TBC with good spallation resistance. At the start of this program, it was hypothesized that all these materials and processing variables may be related to two critical TBC system variables: the localized stress and the strength of the bond or interface at the spallation site. This program was designed to investigate techniques for the measurement of bond strength and stress and to determine whether any of these techniques had the potential for becoming a non-destructive evaluation (NDE) technique for assessing initial coating quality and coating life remaining for thermally cycled samples.

The program's industrial partners provided superalloy specimens coated with five different production TBCs: two of the ceramic coatings were deposited by electron beam physical vapor deposition (EB-PVD) and three of the ceramic coatings were deposited by air plasma spray (APS). In each case, the ceramic material was 6 to 8 wt. % yttria stabilized zirconia (YSZ). The specimens were thermally cycled to various life fractions, from room temperature to 1121°C (2050°F), with one-hour hold times, at the NASA-Lewis Research Center.

In Phase I, five techniques were evaluated for measuring bond stress and four techniques were evaluated for measuring bond strength. The five techniques for measuring bond stress included: (1) laser photoluminescence of stress in the TGO, (2) enhanced laboratory x-ray diffraction of the stress in the bond coat, (3) synchrotron x-ray diffraction, (4) neutron diffraction, and (5) AC potential drop. Following successful laboratory evaluation of the five techniques, laser photo luminescence was selected as the most promising technique for measuring TGO stress and exhibited the potential for becoming a low-cost NDE technique.

Four techniques were evaluated for measuring bond strength that included: (1) modified ASTM direct-pull test, (2) chevron notch fracture toughness test, (3) laser ultrasonic test, and (4) Hertzian ball indentation test. Favorable results were obtained using the first three test methods, and the modified ASTM direct-pull test was selected as the most promising technique for measuring bond strength.

In Phase II, the five production coatings were thermally cycled at NASA-Lewis to failure and to various life fractions. The two EB-PVD coatings exhibited the longest average

spallation lives compared to the three APS coatings, with the EB-PVD on a Pt-Al bond coat showing the longest average life. Of the APS coatings, the one with an MCrAlY on Mar-M509 showed the longest life. The EB-PVD coatings showed the greatest scatter in lives, suggesting that small variations in processing have a greater influence on life than for plasma spray coatings.

The laser photoluminescence technique involves the fluorescence of chromium ions in the TGO. The change in position of the spectra peak can be related to the biaxial compressive stress in the TGO. It has been demonstrated that each TBC has a characteristic as-coated value of compressive stress that can be explained, to a first approximation, by the thermal expansion mismatch stress. The compressive stresses in the TGO of the EB-PVD coatings are very high, varying from about 4.2 GPa for the Pt-Al bond coat and 2.5 GPa for the MCrAlY bond coat. This high localized stress in the TGO is the reason that spallation of all TBCs occurs at or near the TGO.

The stress in any given sample is highly reproducible and shows a normalized standard deviation of 5 to 7 percent. Furthermore, the stress in the TGO varies in a characteristic fashion with thermal cycling. The reproducibility of the stress measurement, the characteristic initial value and consistent variation with thermal cycling are all reasons that the laser fluorescence technique shows excellent potential for becoming a non-destructive inspection technique for TBCs.

To determine the strength of bonds/interfaces in the five TBCs, the modified ASTM direct pull test was employed on specimens tested to various life fractions. In all coatings, the fracture location in the direct-pull test matched that produced by laboratory and engine thermal cycling. For the EB-PVD coatings, the fracture was predominantly at the bond coat to TGO interface, and in the plasma sprayed coatings, the fracture was predominantly in the ceramic just above the TGO to ceramic interface. The as-coated bond strengths of the five TBCs varied from 4,000 to 11,000 psi, with the EB-PVD coatings having the greater strengths. This is consistent with the EB-PVD coatings having a chemical bond and the plasma coatings having a mechanical bond. With thermal cycling, the strengths of all the coatings continuously decreased until spallation failure. The spallation life of the five coatings could be related to the as-coated bond strength, with the TBCs having the strongest as-coated bonds exhibiting the longest lives.

Spallation mechanism studies were conducted for the five TBCs. For both EB-PVD coatings, damage initiation occurred at processing defects found on the bond coat surface. In the Pt-Al bond coat, the defect was a grain boundary ridge that formed on the surface of the bond coat during the deposition of Al in the chemical vapor deposition coater. Finite element analysis (FEA) showed large in-plane and out-of-plane tensile stresses as a result of the ridge. With thermal cycling, through thickness cracks are formed in the TGO and, as a result, oxygen is introduced at bond coat grain boundaries. Preferential grain boundary oxidation occurs and a sharp crack is formed in the grain boundary. With further thermal cycling, as a result of cyclic plastic deformation processes, the sharp grain boundary crack is transformed into a broad cavity, partially filled with oxide. Ultimate spallation of the ceramic occurs as the

localized interface stress increases with thickening of the TGO and as the interface strength weakens, perhaps as sulfur diffuses to the bond coat to TGO interface.

Since the ridges were the sites for damage initiation, specimens were prepared to assess the effect of ridges on thermal cyclic life. Seven specimens were bond coated at the same time. For five of the specimens, the ridges were removed by careful mechanical polishing and all seven specimens were ceramic coated and thermal cycled tested at the same time. The specimens with ridges removed showed a factor of three improvement in life.

For the EB-PVD coating on the MCrAlY-I bond coat, damage initiation occurs at the embedded oxide formed at the surface of the bond coat due to post-bond coat processing. The embedded oxides are sites for accelerated oxidation, and as for the Pt-Al bond coat, these linear defects are transformed into broad cavities partially filled with oxide as a result of thermal cycling. Final spallation occurs as a result of the increased interface stress associated with TGO thickening and the loss of interface strength due to formation of spinels and Ta, Ti, and W-rich oxides on the bond coat surface.

For the three plasma sprayed coatings, spallation occurs predominantly in the ceramic, just above the TGO to ceramic interface. In addition, there is some cracking observed at the bond coat to TGO interface, at the TGO to ceramic interface, and within the TGO itself. Localized debonding occurs at numerous sites at low fractions of life. Spallation occurs by micro-crack progression and link-up. The growth of the TGO and the formation of spinels and other oxides contribute to final spallation.

Finite element analyses were conducted using the actual geometries for the ridges and cavities of the EB-PVD on Pt-Al TBC. These analyses showed high in-plane and out-of-plane stresses at the ridge peaks. These regions of high tensile stress corresponded to locations where cracking was observed.