N89 - 17331

THERMAL BARRIER COATING LIFE-PREDICTION MODEL DEVELOPMENT

T.E. Strangman, J.F. Neumann, and A. Liu
Garrett Turbine Engine Company (GTEC)*
Phoenix, Arizona

Thermal barrier coatings (TBCs) for high-performance engine turbine airfoils represent advanced materials technology with both performance and durability benefits. The greatest TBC benefit is the reduction of heat transferred into air-cooled components, allowing higher turbine operating temperatures and/or reduced component cooling for improved engine performance. Recognizing the benefits of TBCs, the Garrett Turbine Engine Company (GTEC) has developed mechanistic thermochemical and thermomechanical life models in this program to facilitate reliable exploitation of TBC benefits.

This program focuses on predicting the lives of two types of strain-tolerant and oxidation-resistant TBC systems that are produced by commercial coating suppliers to the gas turbine industry. The plasma-sprayed TBC system, composed of a low-pressure plasma spray (LPPS), or an argon-shrouded plasma spray (ASPS) applied oxidation-resistant NiCrAlY (or CoNiCrAlY) bond coating, and an air-plasma-sprayed (APS) yttria (8 percent) partially stabilized zirconia insulative layer (Figure 1), is applied by Chromalloy (Orangeburg, New York), Klock (Manchester, Connecticut), and Union Carbide (Indianapolis, Indiana). The second type of TBC is applied by the electron beam evaporation-physical vapor deposition (EB-PVD) process by Edwards-Temescal (Berkeley, California).

The primary objective of this program was to develop an operative TBC design model for life prediction. This objective was successfully accomplished with the development, calibration, and demonstration of a mechanistic thermochemical model, which rapidly predicts TBC life as a function of engine, mission, and materials system parameters (Figure 2). This thermochemical design model accounts for the three operative TBC damage modes (bond coating oxidation, zirconia toughness reduction, and molten salt film damage), which all contribute to spalling of the insulating zirconia layer. The model has been calibrated for three plasma-sprayed systems and one EB-PVD TBC system, which are applied by commercial sources. The GTEC preliminary design TBC life-prediction system has been demonstrated for three TFE731 turbofan engine cycles (business aircraft, maritime surveillance, and factory endurance test).

It should be noted that the preliminary TBC life model is primarily driven by the thermal analysis for the component and the anticipated mission usage of the aircraft. This feature permits the designer to economically consider the TBC early in the component design process, which facilitates full incorporation and exploitation of its benefits for turbine airfoil applications.

---

*Work performed under NASA Contract NAS3-23945.

In addition to achieving the primary objective, significant progress was achieved in the development of a thermomechanical stress-based, finite-element micromodel, which has the potential to more accurately model TBC spalling mechanisms for improved final design life predictions (Figure 3). As presently developed, the micromodel is capable of calculating localized stresses within the TBC system, which arise from ceramic-metal thermal expansion mismatch, thermal, and centrifugal strains. The micromodel is further designed to have sufficient flexibility for future incorporation of refinements, such as analysis of:

- Time- and temperature-dependent changes in local stresses arising from bond-coating oxidation
- Stress redistribution associated with bond-coating creep (stress relaxation)
- Zirconia sintering shrinkage
- Cyclic crack propagation in the zirconia

Substantial burner rig and mechanical properties data (Figures 2 and 4) have been obtained to facilitate development and calibration of these thermochemical and thermomechanical life prediction models. Interestingly, it was observed that the toughness of plasma-sprayed zirconia coatings remained stable during short exposures at high temperatures, but transitioned to lower values after longer exposures. Furthermore, the approximate transition time to the lower toughness value was similar to average spalling lives for the TBC system that were observed in burner rig tests in the 1100 to 1150 °C temperature range, where comparable data were obtained. Zirconia sintering densification ("mud-flat" cracking) and interfacial oxide scale growth (Union Carbide TBC specimens only) appeared to be associated with the reduced level of zirconia toughness.

Thermal conductivity is the critical design property of TBCs, which govern heat transfer into air-cooled turbine components. Component metal temperatures and thermal strains are dependent on the thermal conductivity of the zirconia layer. Consequently, thermal conductivity data were obtained for both plasma-sprayed and EB-PVD zirconia coatings. These data are presented in Figure 5 and are in excellent agreement with published data from other NASA-sponsored programs. They indicate that yttria-stabilized zirconia coatings have thermal conductivities that are lower by about a factor of 30 than typical superalloys.

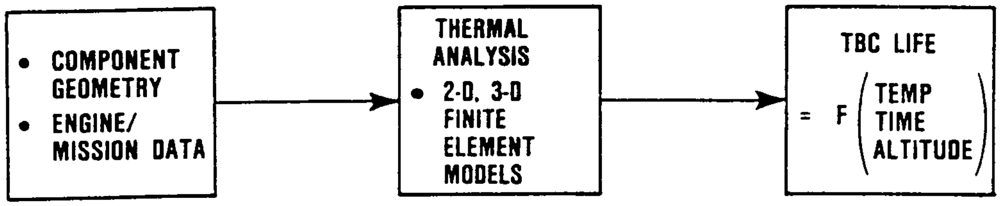
Finally, effective exploitation of TBCs requires that critical materials properties be verified. The insulative TBC system capability is dependent on thickness. Mechanical integrity of TBCs is dependent on the size of critical flaws. Therefore, feasibility of using nondestructive evaluation (NDE) to verify critical TBC properties (thickness and flaw size) was demonstrated. Eddy current analysis was verified to be a viable method for measuring zirconia thickness. High-frequency ultrasonics showed promise in detecting flaws at the ceramic-metal interface.

	PLASMA SPRAY	PLASMA SPRAY	ELECTRON BEAM — PHYSICAL VAPOR DEPOSITION
TBC	APS Y_2O_3 (8%) STABILIZED ZrO_2	APS Y_2O_3 (8%) STABILIZED ZrO_2	EB-PVD Y_2O_3 (20%) STABILIZED ZrO_2
BOND COAT	LPPS Ni-31Cr-11A1-0.5Y	ASPS Co-32Ni-21Cr-8A1-0.5Y	EB-PVD Ni-23Co-18Cr-12Al-0.3Y
SUBSTRATE	MAR-M 247 SUPERALLOY	MAR-M 247 SUPERALLOY	MAR-M 247 SUPERALLOY
SUPPLIER	• CHROMALLOY • KLOCK	• UNION CARBIDE	• TEMESCAL

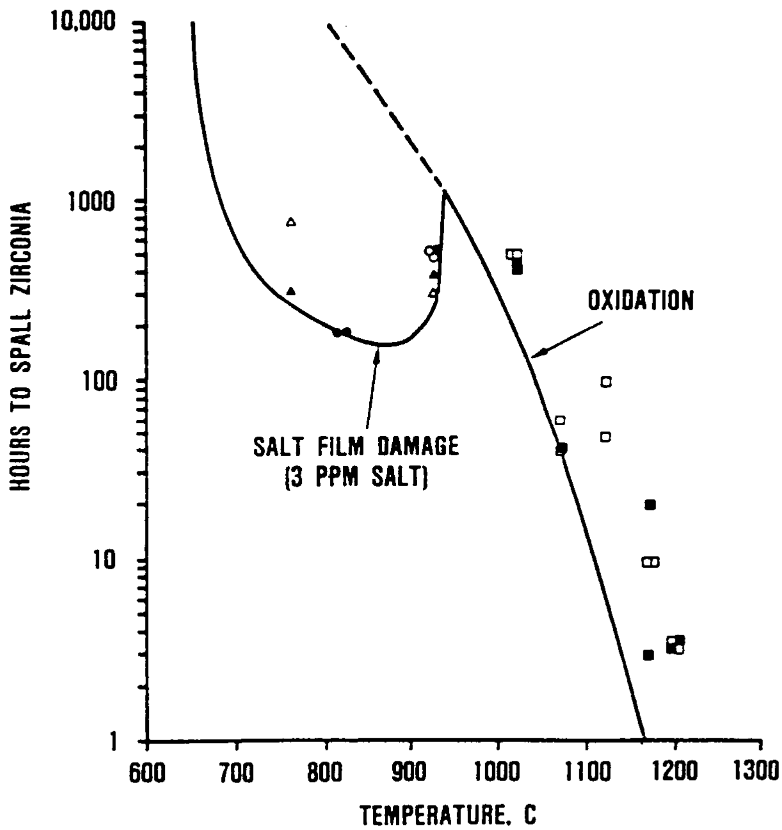
68-239-20

Figure 1. Life Prediction Models are Calibrated for Plasma-Sprayed and EB-PVD TBC Systems.

PRELIMINARY TBC LIFE ANALYSIS METHOD



THERMOCHEMICAL MODEL CALIBRATION



MISSION ANALYSIS PREDICTIVE CAPABILITY HAS BEEN DEMONSTRATED

TBC SYSTEM	BUSINESS JET	MARITIME SURVEILLANCE
PLASMA SPRAY		
CHROMALLOY	16,517 HOURS	9843 HOURS
UNION CARBIDE	6656 HOURS	5207 HOURS
KLOCK	49,644 HOURS	29,973 HOURS
EB-PVD		
TEMESCAL	55,607 HOURS	2106 HOURS

G7012-21

Figure 2. Inexpensive Design Analysis Iterations are Facilitated by Thermomechanical TBC Life Model.

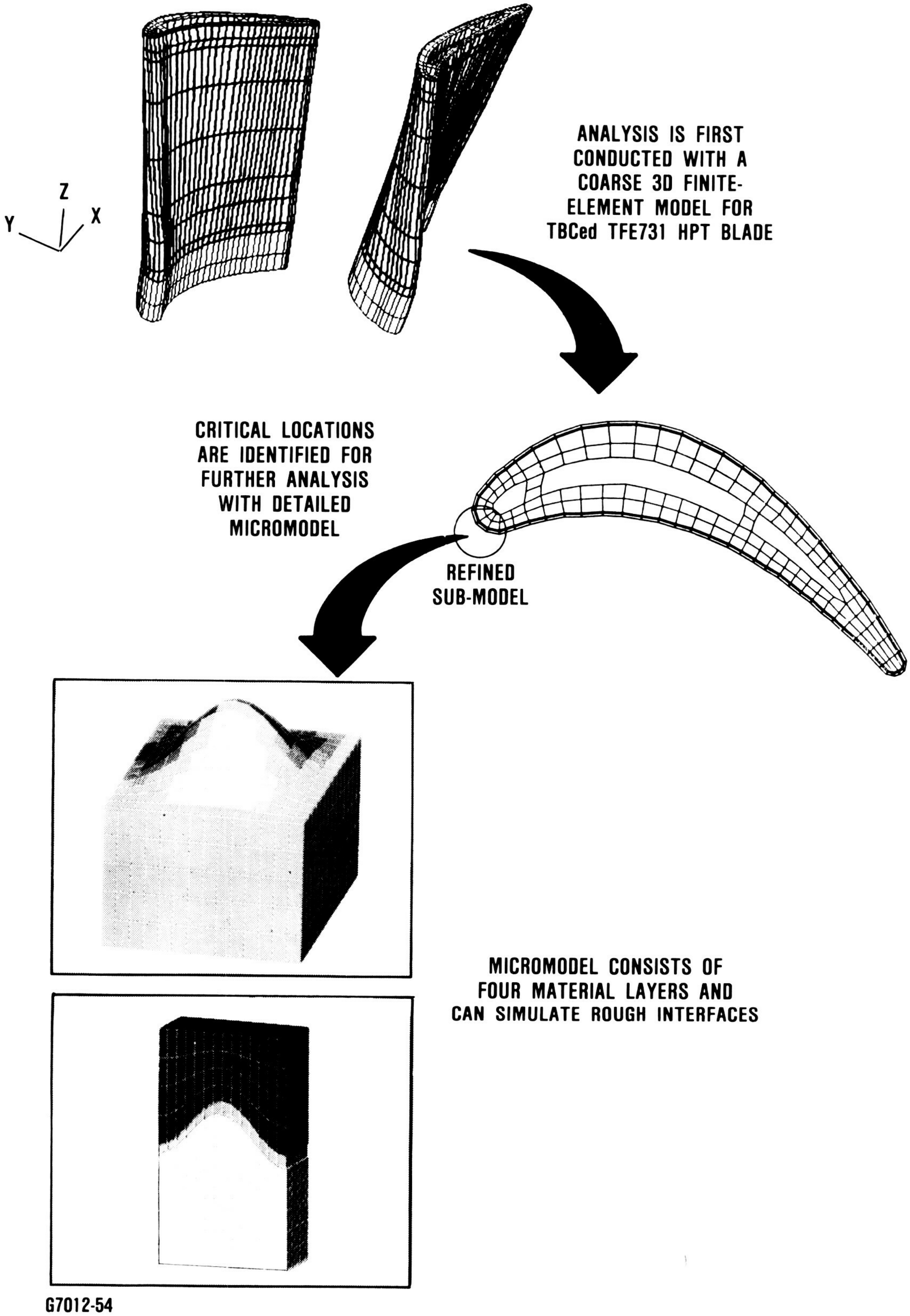


Figure 3. 3-D Finite-Element Thermomechanical Micromodel was Developed and Interfaced with a Design Grade Coarse Model.

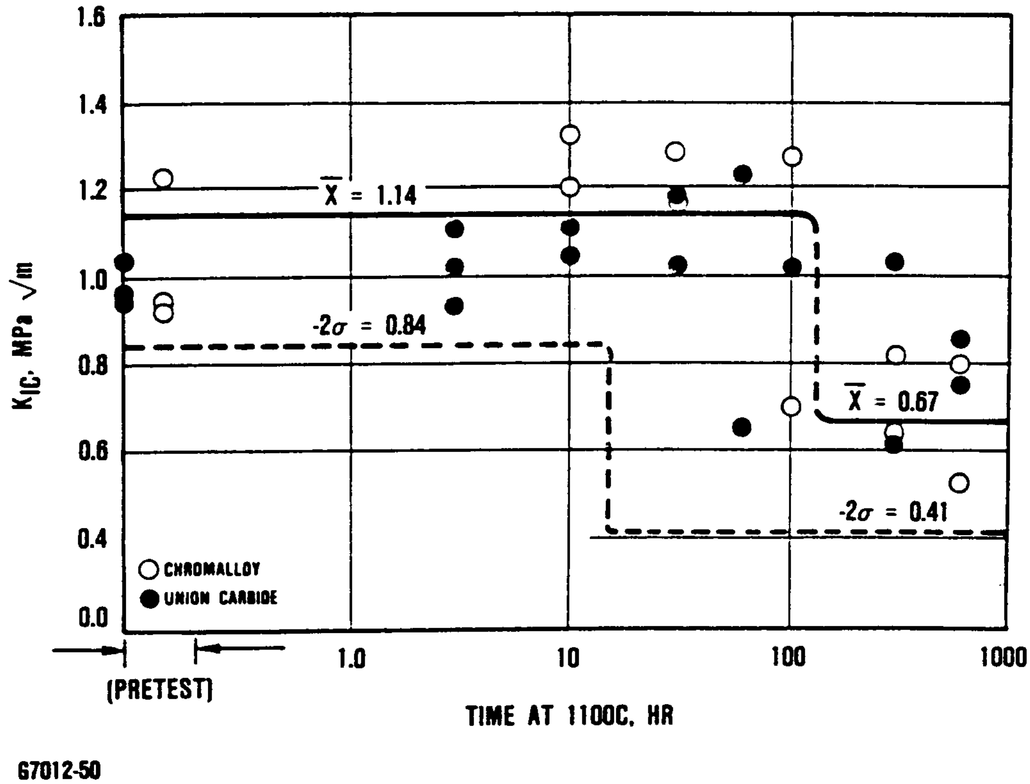


Figure 4. Fracture Toughness of Plasma-Sprayed, Yttria-Stabiliized Zirconia Coating is Reduced After Long Exposures at High Temperatures.

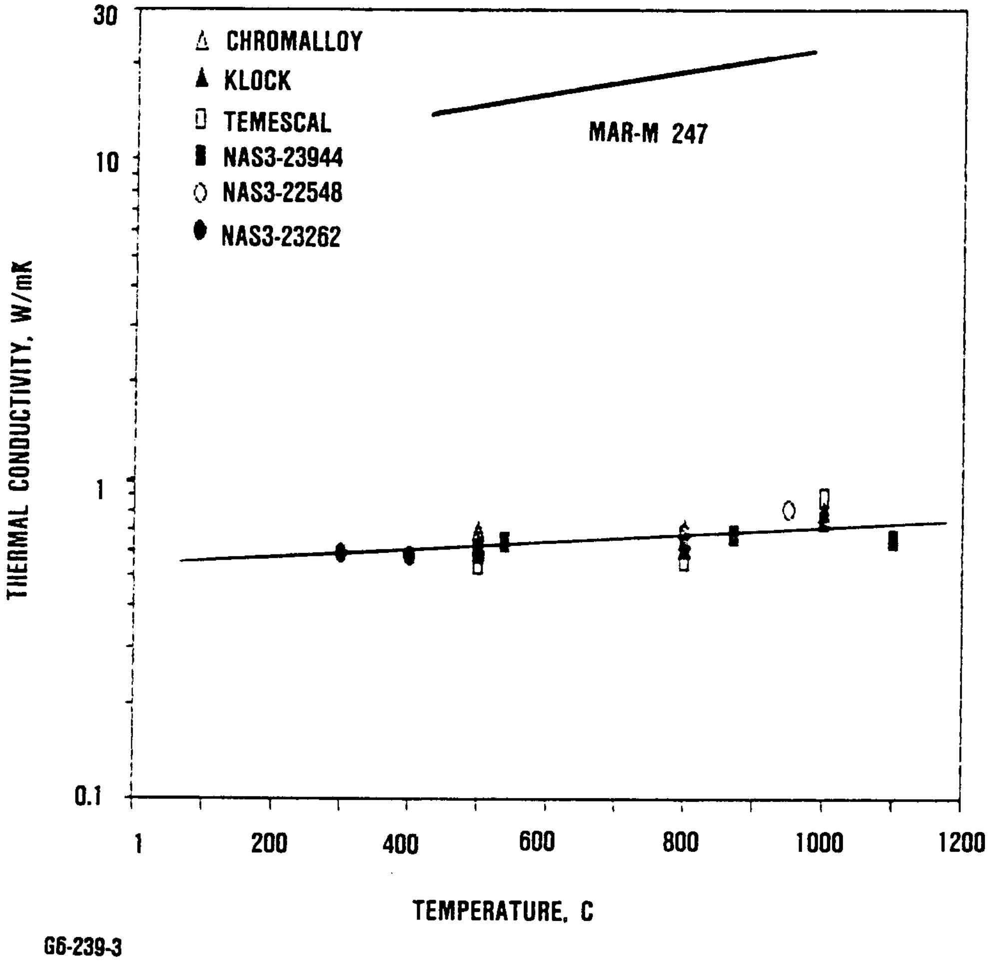


Figure 5. Plasma-Sprayed and EB-PVD TBCs Have Equivalent Thermal Conductivity