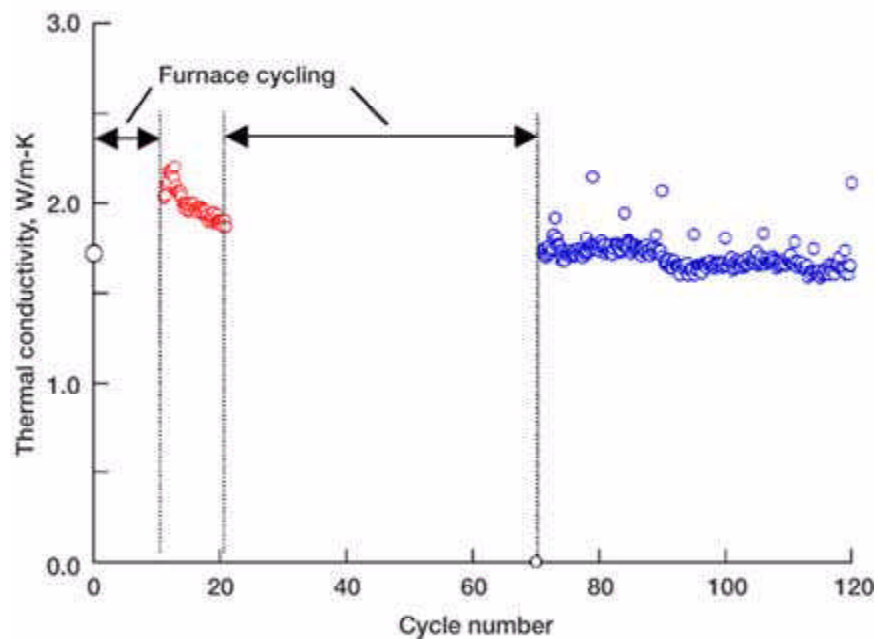
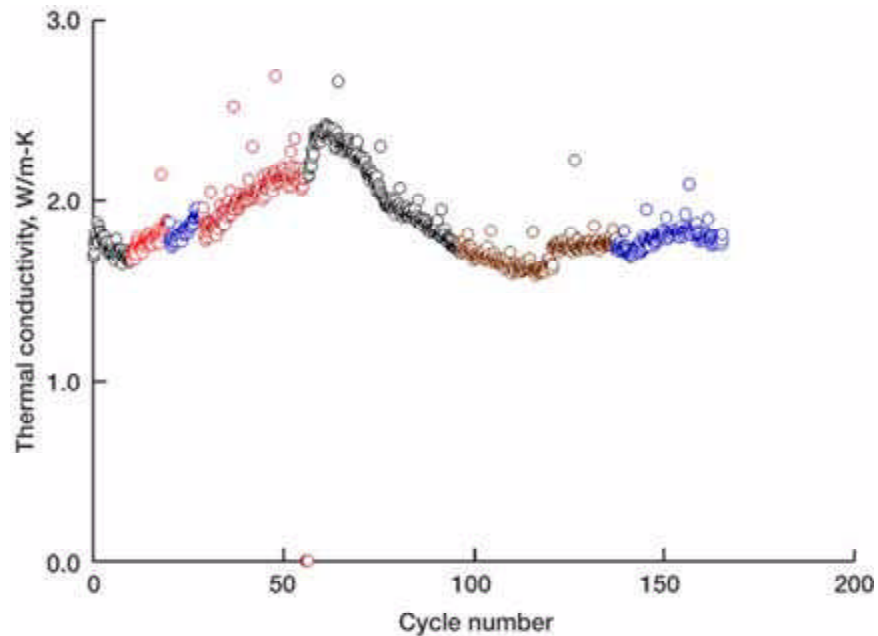


# Thermal Cyclic Behavior of Thermal and Environmental Barrier Coatings Investigated Under High-Heat-Flux Conditions

Environmental barrier coatings (EBC's) have been developed to protect silicon-carbide-(SiC) based ceramic components in gas turbine engines from high-temperature environmental attack (refs. 1 and 2). With continuously increasing demands for significantly higher engine operating temperature, future EBC systems must be designed for both thermal and environmental protection of the engine components in combustion gases. In particular, the thermal barrier functions of EBC's become a necessity for reducing the engine-component thermal loads and chemical reaction rates, thus maintaining the required mechanical properties and durability of these components. Advances in the development of thermal and environmental barrier coatings (TBC's and EBC's, respectively) will directly impact the successful use of ceramic components in advanced engines.

To develop high-performance coating systems, researchers must establish advanced test approaches. In this study, a laser high-heat-flux technique (ref. 3) was employed to investigate the thermal cyclic behavior of TBC's and EBC's on SiC-reinforced SiC ceramic matrix composite substrates (SiC/SiC) under high thermal gradient and thermal cycling conditions (refs. 4 and 5). Because the laser heat flux test approach can monitor the coating's real-time thermal conductivity variations at high temperature, the coating thermal insulation performance, sintering, and delamination can all be obtained during thermal cycling tests.

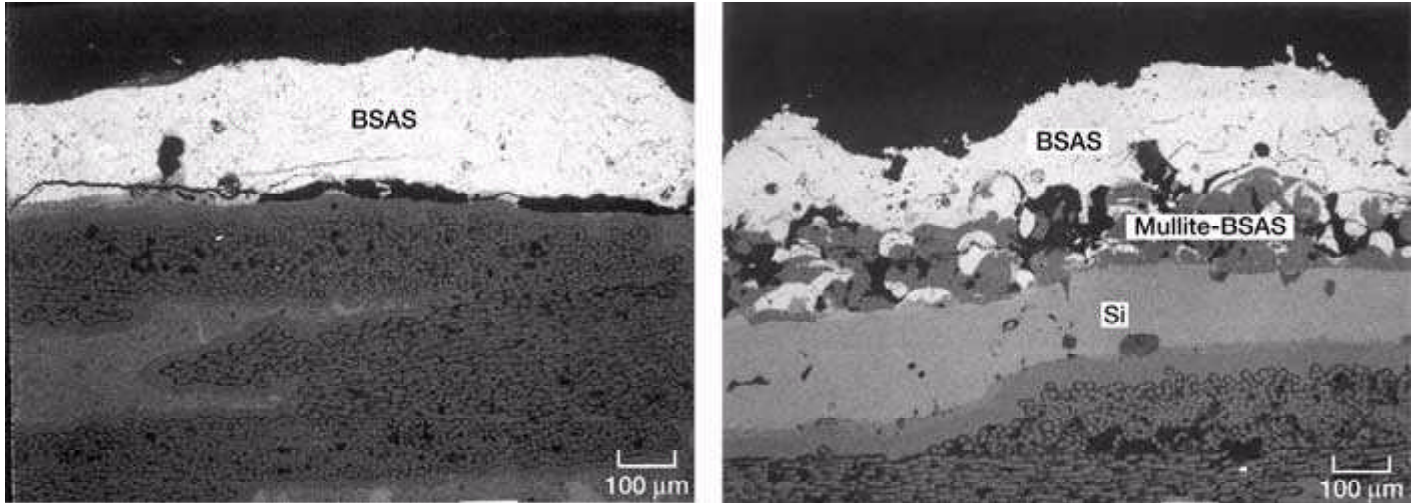
Plasma-sprayed yttria-stabilized zirconia ( $ZrO_2$ -8 wt%  $Y_2O_3$ ) thermal barrier and barium strontium aluminosilicate-based environmental barrier coatings (BSAS/BSAS+mullite/Si) on SiC/SiC ceramic matrix composites were investigated in this study. These coatings were laser tested in air under thermal gradients (the surface and interface temperatures were approximately 1482 and 1300 °C, respectively). Some coating specimens were also subject to alternating furnace cycling (in a 90-percent water vapor environment at 1300 °C) and laser thermal gradient cycling tests (in air), to investigate the water vapor effect. All cyclic tests were conducted using a 60-min hot-time temperature.



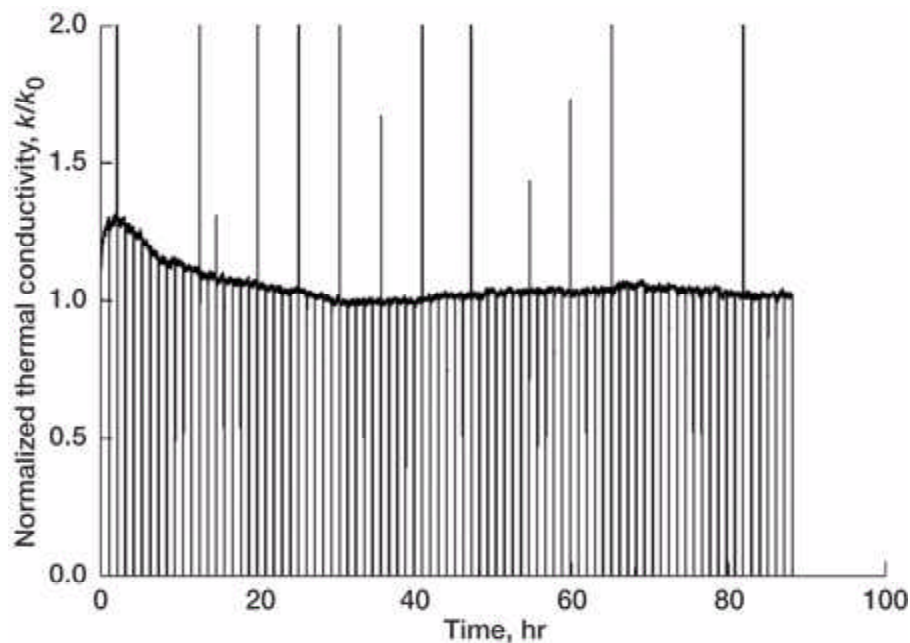
*Thermal conductivity changes of the BSAS/mullite-20 wt% BSAS coating systems as a function of the cycle number. Top: Laser thermal cycling testing. Surface temperature, 1482 °C; interface temperature, 1300 °C in air; total of 166 1-hr cycles. Bottom: Combined furnace water vapor and laser thermal cyclic testing. Total of 120 1-hr cycles.*

The preceding graphs show the thermal conductivity changes of 254- $\mu\text{m}$ -thick BSAS/mullite-20 wt% BSAS coating systems as a function of the cycle number. For both the laser and combined furnace-laser tested specimens, initial thermal conductivity increased considerably because of the coating sintering. However, the coating conductivity then decreased under further testing because of coating cracking and delamination. Coating sintering and delamination occurred faster under the combined furnace water

vapor and laser cyclic test conditions, indicating that water vapor has a detrimental effect on coating durability. Typical failure modes and cracking morphologies of the BSAS and BSAS/mullite-20 wt% BSAS two-layer coatings under the combined furnace and water vapor cycles exposure are shown in the following photomicrographs. The coating failure was accelerated by the interface pore formation in the water vapor environments and by subsequent coating delamination under laser thermal gradient cyclic testing.

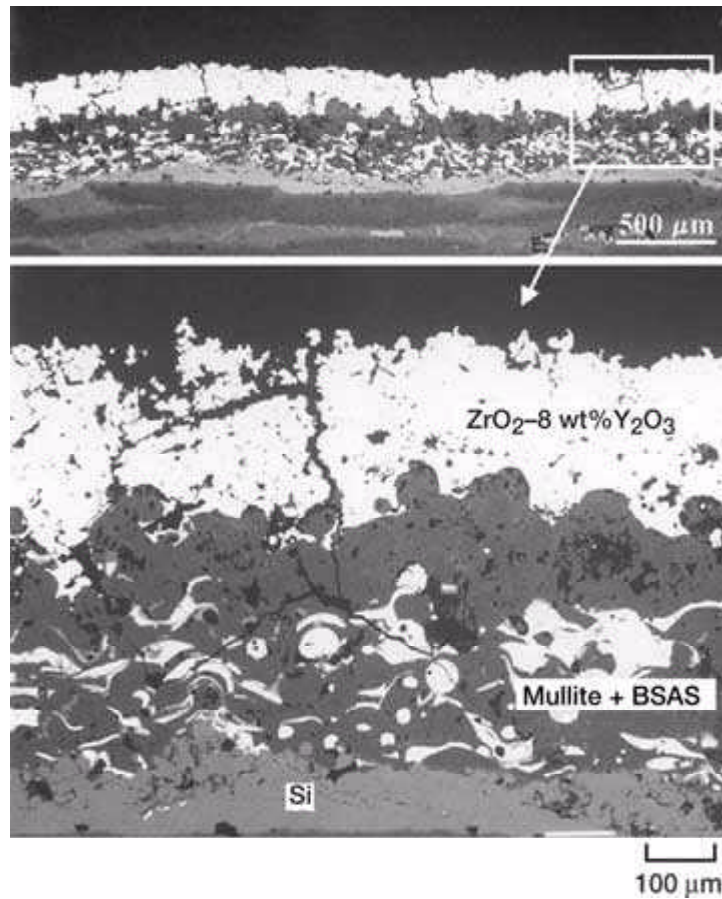


*Photomicrographs of cross sections of BSAS and BSAS/mullite-20 wt% BSAS coatings after combined laser and furnace water vapor cycle testing, showing the coating interface pore structures and coating cracking and delaminations after testing. Left: BSAS coating. Right: BSAS/mullite-20 wt% BSAS two-layer coating.*



*Normalized thermal conductivity of a 500-mm  $ZrO_2$ -8 wt%  $Y_2O_3$ /BSAS/ BSAS+mullite/Si multilayered coating system measured during the laser thermal gradient cyclic test. The coating conductivity first rapidly increased due to coating sintering, but later decreased due to coating cracking-delamination under further thermal cycling.*

For a  $\text{ZrO}_2$ -8 wt%  $\text{Y}_2\text{O}_3$ /BSAS/BSAS+mullite/Si multilayered coating system tested under thermal gradient cyclic conditions, thermal conductivity showed a similar trend with the cycle numbers as observed for BSAS/mullite-20 wt% BSAS coating systems. The coating-sintering-induced initial conductivity increase and the subsequent coating cracking-delamination-induced conductivity decrease are clearly seen in the preceding graph. However, the combined effects of the thermal expansion mismatch between the different coating layers and the substrate, along with the sintering shrinkage of the ceramic coatings, resulted in substantial wedge-shape surface cracking and coating delaminations. The failure morphologies of the coating systems are shown in the following photomicrograph.



*Photomicrographs of cross sections of a  $\text{ZrO}_2$ -8 wt%  $\text{Y}_2\text{O}_3$ /BSAS/BSAS+mullite/Si multilayered coating showing the coating failure morphologies after the laser cyclic test. The wedge-shape surface cracking and the coating delaminations were extensively developed under the thermal gradient cyclic test conditions.*

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