Overview of Thermal Barrier Coatings in Diesel Engines

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An understanding of delamination mechanisms in thermal barrier coatings (TBCs) has been developed for diesel engine applications through rig tests, structural analysis modeling, nondestructive evaluation, and engine evaluation of various TBCs. This knowledge has resulted in improved TBCs that survive severe cyclic fatigue tests in high-output diesel engines.

Although much conflicting literature now exists regarding the impact of TBCs on engine performance and fuel consumption, changes in fuel consumption appear to be less than a few percent and can be negative for state-of-the-art diesel engines. The ability of the TBC to improve fuel economy depends on a number of factors, including the fuel injection system, combustion chamber design, and initial engine fuel economy. Limited investigations on state-of-the-art diesel engines have indicated that surface-connected porosity and coating surface roughness may influence engine fuel economy.

Current research efforts on TBCs are primarily directed at reduction of in-cylinder heat rejection, thermal fatigue protection of underlying metal surfaces, and possible reduction of diesel engine emissions. Significant efforts are still required to improve the plasma spray processing capability and the economics for complex-geometry diesel engine components.

Keywords: diesel engine experience, failure behavior, mullite coating, thermal barrier coating

1. Background

Thermal barrier coatings (TBCs) were initially investigated for "adiabatic" diesel engines due to first law thermodynamic predictions of significant fuel economy improvements, reduction in heat rejection, and potential increased power density of the diesel engine. Cummins Engine Company, Inc., conducted an extensive evaluation of existing TBCs using the Cummins V903 diesel engine. These initial exploratory efforts used duplex coatings consisting of a NiCrAlY bond coating and a yttria-stabilized zirconia (YSZ) top layer. Total coating thickness was on the order of 1.5 mm, with a bond coating thickness of approximately 0.1 mm. These investigations, conducted in the early 1980s, revealed that the existing TBCs were insufficient to survive short-duration tests in a high-output diesel engine (1.38 MPa brake mean effective pressures, or BMEPs) (Ref 1). Extensive trial-and-error development efforts using plasma-sprayed zirconia coatings did not result in acceptable or reproducible coating lives.

Efforts sponsored by the Department of Energy/National Aeronautics and Space Administration (DOE/NASA), U.S. Army Tank Automotive Command (TACOM), and Cummins internal funds in the mid-1980s focused on understanding the stresses in the TBCs with a goal of significantly improving the life of coatings in diesel engines. Improvements in TBC life of approximately two orders of magnitude were necessary for utilization of the coatings in advanced diesel engines.

An objective of the DOE/NASA program (Ref 2) was to develop zirconia-based TBCs with a thermal conductance of 410 W/m²K that could survive 100 h of operation in a research single-cylinder engine. The engine chosen for this program was the Cummins V903 direct-injection diesel engine with a 140 mm bore and 120 mm stroke. The V-8 engine was rated at 360 kW at 2100 rev/min for the turbocharged configuration. The geometric compression ratio chosen for this work was 13.5:1, and the peak cylinder pressure was limited to a maximum of 13.8 MPa.

Extensive diesel engine cycle simulation and finite-element analysis of the coatings were conducted to understand the effects of a coating on diesel engine performance and the stress state in the coating and underlying metal substructure. The TACOM programs (Ref 3) expanded the effort initiated with DOE to develop improved TBCs that could survive the high cylinder pressures and thermal loads projected for military applications.

An engineered coatings approach was taken in the DOE program, using existing databases augmented where necessary by collecting additional data, modeling stresses in the coatings by finite-element techniques, and performing extensive rig and engine tests. Cummins and United Technologies Research Center (UTRC) cooperated on this program to modify thick TBCs developed for turbine tip seals for diesel applications.

2. Coating Development for Diesel Engines

2.1 Modeling

Diesel engine performance modeling projected that the maximum benefits of TBCs were obtained by applying the coatings to piston and cylinder head surfaces. The effects of the coatings on valves and cylinder liners were not projected to result in significant fuel economy improvements. Therefore, research efforts in the DOE/NASA and TACOM programs concentrated on cylinder head and piston coating development. With the insulation levels defined by the coating thermal conductance, diesel
engine performance models predicted that the in-cylinder heat rejection would be reduced by 38% and that the fuel economy would be improved by 2% for a turbocharged engine and by 3% for a turbocompound version of the engine.

United Technologies Research Center used one-dimensional thermal-structural modeling to select preferred coating systems for spray fabrication trials and rig tests. A one-dimensional thermal-structural model was established to predict both the temperature gradients across layer interfaces of candidate coating systems and overall coating state-of-stress at maximum operating conditions. Predicted temperatures from the thermal analysis were used to predict stresses within the coating systems under maximum operating conditions of a diesel engine. The modeling indicated that single-layer coating systems were in compression at the top of the coating and in tension at the bond/substrate interface (Ref 4). Previous single-layer coatings have been shown to delaminate in the zirconia coating in this tensile region above the bond coating.

It was determined that multilayer coatings, consisting of multiple layers of ceramic metal mixtures with a top coating of ceramic, reduce in-plane tensile stresses in the ceramic top layers. Figure 1 shows that the thermal stresses were significantly less than the measured coating strength. The coating was in compression at the top surface, which was 2.5 mm from the bond coating/ceramic coating interface. Metal substrates were also analyzed, and it was determined that substrate yielding should not be expected. Additionally, thermal modeling indicated that the metal temperatures were insufficient to result in bond coating oxidation in the short time that engine coating delamination was experienced in previous engine tests.

Two-dimensional finite-element modeling using the cycle average boundary conditions also suggested that a multilayer TBC could survive engine conditions. Efforts concentrated on understanding the performance of a 2.5 mm multilayer coating. This coating consisted of mechanical mixtures of CoCrAlY and zirconia fully stabilized by yttria. The 2.5 mm coating consisted of 0.5 mm layer of 40% zirconia and 60% CoCrAlY, followed by a 0.5 mm layer of 85% zirconia and 15% CoCrAlY, followed by a 1.5 mm thick 100% zirconia layer. The zirconia layer was approximately 85% dense. Processing conditions were developed to generate residual stresses in the TBCs by controlling the substrate temperature during the deposition process.

It is also important to consider thermal transients when designing with ceramic materials. The low thermal diffusivity of ceramics causes their temperatures to respond quickly to changes in operating environment, whereas the temperatures of the base materials respond much more slowly. This thermal response behavior causes significantly different temperature and thermal stress profiles to be encountered under transient operation than those observed at steady-state conditions.

The first thermal transient considered was a sudden cooling of the combustion face. Calculations were made at steady-state for conditions representative of full-load operation at rated speed. At time zero, the in-cylinder conditions were suddenly changed to those representative of no-load conditions. The resulting transient spatial thermal response within the coating is summarized in Fig. 2, where the surface temperature drops rapidly while the interior temperature reacts more slowly. With increasing time, the coating temperature decreases. The predicted thermal stresses in the coating are shown in Fig. 3. The trend shows a relaxation of the compressive stress at the surface with increasing time. This relaxation results in a slight reduction in the tensile stress experienced in the bond coat adjacent to the substrate. Cycle-to-cycle transients and rapid heating of the coating were also modeled.

It was determined through transient analysis using a simple finite-element model that:

- Temperature and stress profiles under transient conditions were found to be significantly different from those at steady-state conditions.
- Engine load changes, although resulting in a change in stress profiles, were not predicted to result in coating failure for the cases considered.
- Firing-cycle transients resulted in a predicted surface temperature swing of 225 °C and increased compressive stresses in the surface layers of the coating. These compressive stresses were predicted to be less than 0.13 mm into the coating.

### 2.2 Spray Fabrication and Rig Tests

United Technologies Research Center developed a spray fabrication technique to define material properties most representative of actual coating material. Flat-plate substrates were attached to a rotating holding fixture in areas representing the piston crown diameter. Heat was applied to the panels through the use of small propane torches mounted on a ring that surrounded the base plate. A thermocouple placed on the backside of the substrates provided the processing temperature and allowed for manual adjustment of the propane to maintain the desired prestress temperature through the spray run. The actual robot motion control and spray processing parameters used to coat the piston crowns were used to coat the substrates. Test specimens were fabricated from the substrates in locations indicative of the crown rim and center dome areas of the piston.