

An Investigation of Metal and Ceramic Thermal Barrier Coatings in a Spark-Ignition Engine

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ABSTRACT

Surface temperature and heat flux were measured in a single cylinder SI engine piston when uncoated and with two different surface coatings: a metal TBC and YSZ. Average heat flux into the piston substrate was 33 % higher with the metal TBC and unchanged with the YSZ relative to the uncoated surface. The increase with the metal TBC was attributed to its surface roughness. However, the metal TBC and YSZ reduced peak heat flux into the substrate surface by 69 % and 77 %, respectively.

INTRODUCTION

Extensive research has been performed on the use of Thermal Barrier Coatings (TBCs) in diesel engines to reduce heat loss. A literature survey by Jaichandar and Tamilporai [1] found that most of the experimental studies observed that TBCs improved diesel engine performance. Considerably less research has been performed on insulated Spark-Ignition (SI) engines, largely due to concerns that elevated surface temperatures would cause excessive knock. However, if used sparingly to moderately increase surface temperatures, TBCs may have beneficial applications for SI engines.

Moderately elevated wall temperatures have been shown to reduce accumulation of knock-promoting carbonaceous deposits. Nakic and co-workers [2] observed that increasing piston surface temperatures reduced deposit accumulation, and no deposits were observed when surface temperatures were above 320°C and premium gasoline was used. In SI engines, the build-up of deposits over time causes an Octane Requirement Increase (ORI) [3]. Therefore, if peak wall temperatures can be raised enough to reduce deposit build-up but not so much to induce auto-ignition, a TBC could reduce ORI. Furthermore, as heat is transferred from the wall to the

gas during parts of the intake and compression stroke, a thin TBC with low thermal inertia may not decrease volumetric efficiency [4].

Spark-ignition engine performance improvements have been demonstrated experimentally with thin ceramic coatings. Assanis and Mathur [5] tested an SI engine with the combustion chamber coated with a 0.10 to 0.27 mm thick ceramic, and found the coating improved power and fuel efficiency and increased exhaust gas temperatures without increasing knock occurrence. At low speeds (1600 RPM), the coated engine achieved 18 % higher brake power and 10 % reduced brake specific fuel consumption compared to the engine uncoated. Mendera [6] found that a 0.2 to 0.4 mm thick ceramic coating on an SI engine piston improved fuel consumption by 2 % to 6 %, depending on operating conditions.

In two-stroke SI engines, TBCs have been shown to improve fuel evaporation and combustion, thereby reducing carbon monoxide (CO) and hydrocarbon (HC) emissions [7,8]. Furthermore, two-stroke engines typically run rich and elevated wall temperatures allow for leaner operation to further improve fuel efficiency and reduce emissions.

Thermal barrier coatings can also protect against thermal fatigue by reducing the magnitude of cyclic temperature swings at the substrate surface. Coating application could be targeted to components that are particularly susceptible to thermal fatigue.

The objective of this study was to test two TBCs in an SI engine on the surface of an aluminum piston. The first TBC was metal-based and applied by wire-arc thermal spraying. In this process, two metallic electrode wires with opposing polarity are melted at their tips by an electric arc inside of a

Table 1. Thermal barrier coating properties

	Metal-based TBC	YSZ
Application method	Wire arc thermal spray	Plasma spray
Thickness (mm)	0.4	0.2
Average roughness - Ra (μm)	12-20	7-12
Thermal conductivity ($\text{W/m}\cdot\text{K}$)	5.0	1.2 [9]
Density (kg/m^3)	6400	4950 [9]
Specific heat capacity ($\text{J/kg}\cdot\text{K}$)	430	490 [9]
Thermal diffusivity (m^2/s)	1.8E-6	0.49E-6 [9]
Porosity (%)	8.9	10.0 [9]
Coefficient of Thermal Expansion (K^{-1})	15E-6	9.8E-6 [1]

spray gun. Compressed air is used to atomize the molten material and accelerate it onto the workpiece to form the coating. The process is maintained by continuously feeding the wires. Cored wires for wire-arc spraying are continuous electrodes composed of a stainless steel sheath formed around a core containing metal powders. The powder composition can be varied to adjust the resulting coating chemistry and properties. In this case, the wires were a cored stainless steel containing a nanostructured iron-based refractory powder. From the dimensions of the wire, it is estimated that the coating composition was approximately 50 % stainless steel and 50 % iron-based powder. The second TBC was plasma sprayed Yttria-Stabilized Zirconia (YSZ), which is a typical TBC ceramic material. The approximate properties of the coatings are listed in [Table 1](#).

While YSZ is the better insulator of the two coatings, the metal TBC may be more durable on metal engine components because of its higher coefficient of thermal expansion and greater ductility. Durability is essential for engine use, and a lack of durability is one of the primary reasons ceramic TBCs have not been widely adopted in engines [10].

This study included preliminary modeling to obtain rough predictions of TBC performance. In the engine tests, the piston was instrumented with surface and “in-depth” thermocouples to measure heat flux.

PRELIMINARY HEAT FLUX MODELING

Simple Finite Element Analysis (FEA) modeling was performed to obtain rough predictions for the effect of the TBCs on heat flux. The model geometry and boundary conditions used for the analysis are shown in [Figure 1](#). The convective heat flux boundary condition inputs were in-cylinder gas temperatures and a heat transfer coefficient. Gas temperatures were taken from previous SI engine work by

Enomoto and Furuhashi [11], and the heat transfer coefficient was calculated with the Woschni equation [12] using temperature and pressure data from Enomoto and Furuhashi. The model was run with both TBCs, using the thicknesses and properties listed in [Table 1](#) and it was also run uncoated with the TBC layer removed. The boundary conditions were the same for all runs; the model ignored the effects of surface temperature and roughness on the heat transfer coefficient, gas temperature and the lower aluminum boundary condition temperature. In reality, these parameters would change and, in particular, the heat transfer coefficient would be affected by surface roughness and temperature. After experiments with a piston polished to a mirror finish, Tsutsumi et al. [13] calculated from piston temperature and fuel consumption data that the polishing treatment reduced heat loss by 6 %. Multiple researchers, including Furuhashi and Enomoto [14], have found that elevating engine component surface temperatures can increase the heat transfer coefficient enough to offset the reduction in temperature difference between the surface and gas. The only changing variables were the thickness and thermal properties of the TBC layer.

[Figure 2](#) shows the FEA computed TBC and uncoated surface temperatures, and [Figure 3](#) shows heat flux into the aluminum substrate behind the TBC. [Figure 3](#) shows that both coatings are predicted to be similarly effective at reducing peak heat flux into the substrate. The effect of the coatings on average heat flux, however, is not as substantial. Average heat flux into the substrate, calculated by averaging the curves in [Figure 3](#), is only 1.9 % and 3.6 % lower with the metal TBC and YSZ, respectively, than average heat flux into the uncoated surface. Thicker coatings could be used to further reduce average heat flux, but these would increase the likelihood of knock problems and negatively affect volumetric efficiency.

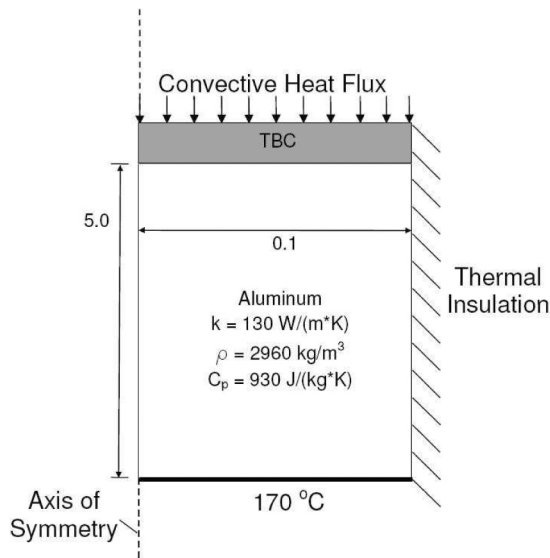


Figure 1. Model geometry and boundary conditions (all dimensions in mm, not to scale)

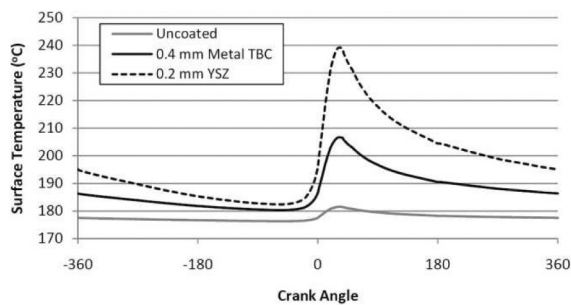


Figure 2. FEA predicted surface temperatures

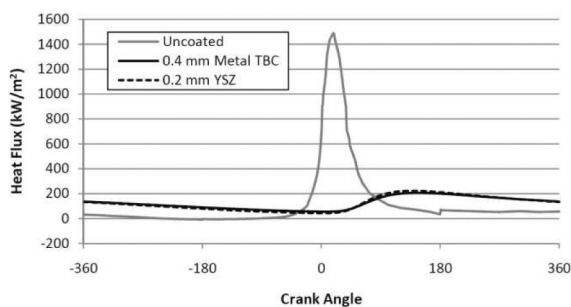


Figure 3. FEA predicted heat flux into substrate surface

EXPERIMENTAL SETUP AND METHODOLOGY

This section describes the experimental setup and methodology used for the engine tests. This section includes a description of the engine, the thermocouples and instrumentation of the piston, and the test procedure.

ENGINE

All tests were performed with a gasoline-fueled Cooperative Fuels Research (CFR) engine. Important engine specifications are listed in Table 2, and further information can be found in the ASTM Manual of Engine Test Methods for Rating Fuels [15]. All tests were run with a stoichiometric air-fuel mixture using regular pump gasoline with the average of the research and motor octane numbers being 87.

Table 2. CFR engine specifications

Number of cylinders	1
Bore	8.255 cm
Stroke	11.43 cm
Displacement volume	612 cm ³
Compression ratio	Variable (set at 8.7:1)
Spark timing	Variable
Fuel metering	Carburetor
Load control	DC dynamometer
Cooling system	Evaporative with water-cooled condenser
Coolant	Water

PISTON THERMOCOUPLES

A primary objective of this investigation was to measure piston substrate surface temperatures and instantaneous heat flux into the crown. Instantaneous heat flux can be calculated from the one-dimensional heat conduction equation below.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

According to Borman and Nishiwaki [16], the one-dimensional assumption is reasonable for the transient component of the heat flux, as temperature gradients into the surface are greater than those parallel to the surface. This assumption is less valid for the steady component of the heat flux. Many authors, including Borman and Nishiwaki [16], have shown that the solution to the one-dimensional heat conduction equation by Fourier analysis yields the equation below to calculate instantaneous heat flux into a surface.

$$\dot{q}_s(t) = \frac{k}{l}(T_{s,m} - T_i) + k \sum_{n=1}^N \sqrt{\frac{n\omega}{2\alpha}} [(A_n + B_n)\cos(n\omega t) + (A_n - B_n)\sin(n\omega t)]$$

In equation above, $T_{s,m}$ is the mean surface temperature, T_i is the temperature at a depth l where cyclic temperature fluctuations are negligible. A_n and B_n are the Fourier coefficients from the Fourier series representation of the instantaneous surface temperature, N is the number of harmonics, k is the thermal conductivity and ω is the frequency of the engine cycle. The heat flux equation

therefore requires surface and “in-depth” temperature data to calculate heat flux. The following sub-sections describe the surface and in-depth thermocouples used to measure these temperatures in the piston.

Surface Thermocouple

A new thermocouple was developed to measure temperatures at the surface of the aluminum piston crown (under the TBCs). This new thermocouple was developed because existing coaxial and eroding designs measure higher average temperatures and larger temperature swings than are actually occurring at the aluminum surface [17,18]. This inaccuracy is due to a mismatch in thermal properties between the thermocouple and the aluminum. A brief description of the new thermocouple is presented in this section. Full details on the development of this thermocouple, including FEA modeling and engine testing, have been published in a separate paper [19].

Figure 4 illustrates the surface thermocouple as it would be installed in a typical aluminum component. A 0.25 mm diameter constantan wire with Teflon insulation (Omega product no. TFCI-010-XX) is fixed in a 0.57 mm diameter hole through the aluminum with ceramic cement (Omega product no. CC HIGH TEMP). The constantan wire is the first thermocouple element and the aluminum component serves as the second element. A copper layer is applied to the surface by wire arc thermal spraying to form the electrical connection at the hot junction. The copper layer can be machined to the desired thickness. The TBCs would be applied on top of the copper. Constantan-aluminum is not a standard thermocouple metal combination, and therefore temperature-voltage calibration is required.

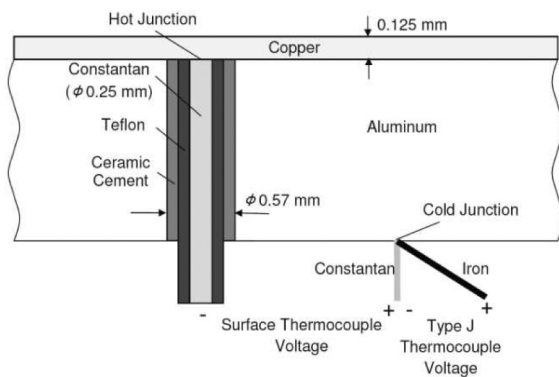


Figure 4. Surface thermocouple schematic

The cold junction is formed by pressing a second constantan wire into contact with the aluminum at any location that is convenient. To allow for measurement of cold junction temperatures, the tip of an iron wire is pressed into the aluminum directly beside the cold junction. As iron and constantan form a type J thermocouple, the cold junction

temperature can be calculated from the voltage across these wires.

In addition to forming the hot junction, the copper also provides a path for heat conduction between the constantan wire tip and the aluminum surface to allow for temperature equalization. If the copper layer were not present, the hot junction would measure higher average temperatures and larger temperature swings than would be actually occurring at the aluminum surface because the thermocouple materials have lower thermal conductivity and diffusivity than aluminum. The copper layer counteracts this material property difference by providing a highly conductive path for heat transfer.

Finite element analysis was used to optimize the thickness of the copper layer for accuracy. Figure 5 shows the FEA computed hot junction temperatures for a range of copper thicknesses with no TBC. The True curve represents the temperature profile at the aluminum surface if the thermocouple were not installed. The 10 and 400 micron curves illustrate the measurement errors associated with making the copper layer too thin or too thick. The optimum thickness was found to be between 100 and 125 μm . In this range, the thermocouple is capable of measuring average temperatures within 0.20°C and temperature swings within 6 % under typical engine heat flux conditions. The drawback of the copper layer is that it introduces a response delay. According to the FEA, this delay would be less than 5°C (Crank Angle) with a 125 μm thick copper layer.

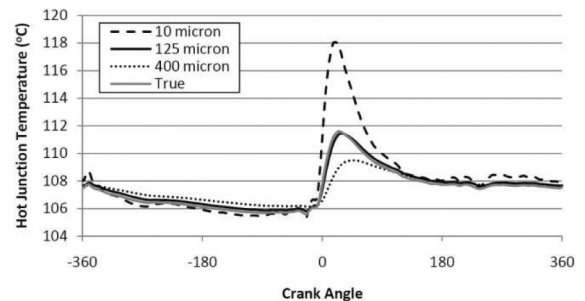


Figure 5. FEA computed hot junction temperatures with different copper thicknesses with no TBC

When measuring temperatures behind a TBC, the thickness of the copper layer is less important as the TBC damps temperature swings at the piston substrate surface. When thermocouple is used behind a TBC, a copper layer thickness in the range 125 to 400 μm will allow for accurate measurement.

In-Depth Thermocouple

Figure 6 illustrates the in-depth thermocouple that was developed for the piston. To fabricate the thermocouple, a hole is drilled mid way through the crown from the backside