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Temperature and thermal stress analyses of a ceramic-coated aluminum alloy piston used in a diesel engine

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ABSTRACT

The goal of this paper is to determine both temperature and thermal stress distributions in a plasma-sprayed magnesia-stabilized zirconia coating on an aluminum piston crown to improve the performance of a diesel engine. Effects of the coating thickness on temperature and thermal stress distributions are investigated, including comparisons with results from an uncoated piston by means of the finite element method. Temperature and thermal stress analyses are performed for various coating thicknesses from 0.2 to 1.6 mm excluding the bond coat layer. Temperature at the coated surface is significantly higher than that of the uncoated piston. It is observed that the coating surface temperature increases with coating thickness by decreasing rate. Increase in the maximum temperature according to the uncoated piston is 64.3% for 1.0 mm thick coating. The higher combustion chamber temperature provided by means of coating results in the better thermal efficiency of the engine. It also provides for a reduction in the substrate surface temperature. The normal stress on the coated surface decreases with increasing coating thickness. Maximum normal stress occurs on the bond coat surface. Its value is approximately two and three times greater than substrate and coating surfaces respectively. Maximum shear stress occurs on the bond coat surface and its magnitude is nearly double that of the substrate surface.

1. Introduction

Thermal barrier coatings (TBCs) are commonly applied to substrates to insulate them thermally so as to allow for higher operating temperature. The desire to increase thermal efficiency or reduce fuel consumption of engines makes it tempting to adopt higher compression ratios, in particular for diesel engines, and reduced in-cylinder heat rejection [1]. Coating of the diesel engine pistons is one engineering application of TBCs among others. TBCs are applied to insulate combustion chamber components or selected surfaces like the piston crown. Heat rejection is then reduced in the cylinder and the metallic surfaces are protected from thermal fatigue, especially from power and exhaust strokes of the diesel engine cycles. The coating is a ceramic-based material that has low thermal conductivity and good strength is capable of enduring higher temperatures than metals. One of the widely used materials is zirconia, which is applied by a plasma-spraying technique. The main purpose of this is to raise the temperature of the piston crown's surface during the expansion stroke, thereby decreasing the temperature difference between the wall and the gas to reduce heat transfer. Some of the additional heat energy in the cylinder can be converted and used to increase power and efficiency [1–6]. Additional benefits include protection of metallic combustion chamber components from thermal stresses and reduction of cooling requirements. A simpler cooling system will reduce the weight and cost of the engine while improving reliability. There are many potential advantages of low heat rejection (LHR) for engine concepts such as reducing fuel consumption and emissions as well as more durable pistons and exhaust valves [7–10].

The bond coat layer is used between the TBC and the metal substrate. The bond coat material is an intermetallic alloy that provides oxidation resistance at high temperatures and aids in the adhesion of the TBC layer to the substrate. The bond coat plays an important role in reducing the internal stresses which may arise between the substrate and the ceramic coating because of thermal shock. The coefficient of thermal expansion (CTE) of the bond coat should be between that of the TBC and the metal substrate [1–5].

The coating thickness has a significant effect on the combustion temperature, the temperature gradient and the stress distribution in both coating and interfacial stresses. The thermal shock resistance of a ceramic coating depends on its elastic modulus, thermal expansion coefficient and thermal conductivity [11–15]. It is known that thicker coating can provide better insulation, but residual thermal stress leads to spallation of thicker coatings. Therefore,

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determining the proper thickness of the TBC plays an important role not only in the accurate assessment of the temperature drop, but also in the resulting performance of the coated system. Although many factors affect the overall performance of the coatings, two of them are more important: oxidation of the bond coat and thermal mismatch between the substrate (SUBS) and the top coating (TC), which affect the lifetime of the coating system [2–4]. Thermal mismatch causes high stress value at the interface. On the other hand, the lifetime of the TBCs can be limited by stresses owed to changing thermal loads during the operation which lead to crack nucleation and propagation in a parallel direction to the ceramic-bond coat interface, leading in turn to delamination of coating. Arising from normal stress, the other typical TBC failure occurs through spalling of the ceramic top coat from the bond coat (BC) [1,16].

Modeling of the piston temperature distribution is very important for keeping the thermal stresses within acceptable levels at the interfaces (BC/TC and SUBS/BC). Computer simulations of thermal stress analyses are very useful and economically viable for reducing the time and cost at the design stage of a piston in diesel engines before the first prototype is constructed [17–21]. There are many research papers on the calculation of the temperature distribution [3,4,10,19,20], but thermal stress analyses are limited [2,14].

The aim of this paper is to investigate the aluminum piston temperature and stress distribution by using various thicknesses of the coating materials to achieve higher diesel engine performance. As shown in Fig. 1a, the aluminum piston model used in the simulation is a diesel engine piston. Thermal stress analyses have been carried out by means of the finite element technique, which is a powerful numerical tool. A quarter of the piston model and thickness of the coatings are shown in Fig. 1b. Analyses have been performed for various conditions: an uncoated piston crown and a ceramic-coated piston crown with a ceramic top coat ranging in thickness from 0.2 to 1.6 mm [2]. The coating is composed of a 0.1 mm bond coat (NiCrAl) and the ceramic ($MgZrO_3$) deposited onto the piston crown or substrate (SUBS) by air plasma spraying (see Fig. 1b). The variation of the temperature on the piston is examined as well as the interfacial stresses at the BC/TC and SUBS/BC interfaces. They are compared with the results of the uncoated piston.

2. Thermal barrier coating materials

Thermal barrier coatings are used to increase the operating temperature of the material. The coating has a ceramic-metal configuration and may not be isotropic. Usually, non-homogeneous ceramic coatings are applied to metal substrates. Thermally-sprayed ceramic material has layered structures with a defect density resulting from successive impact of a multitude of fully or semi-molten particles. Plasma-sprayed coatings have exhibited transversely isotropic symmetry. Although properties of coating materials are different in through thickness and in-plane directions, the material behaves linearly in each direction. Elasticity modulus of the thermal spray ceramic coating in the in-plane directions is approximately $E_x = E_z = 1.6\ E_y$ [22]. The most important problem with the coated system is the thermal stresses which occur during operation because of the considerable mismatch between the thermal expansions coefficients of the metal substrate and the ceramic coating. TBCs are preferred because of their low conductivity and their relatively high coefficients of thermal expansion.

In this study, magnesia-stabilized zirconia ($MgZrO_3$) used in TBCs as a deposit material is preferred because of its good thermal insulating properties and thermal stability at cryogenic and high temperature applications [1,3,4,6] compared with other coating materials such as alumina. The coating material is stabilized magnesia-zirconia which has flexural strength of 520 MPa and compressive strength of 1450 MPa. The thickness of the ceramic top coating has been changed from 0.2 mm to 1.6 mm with a 0.2 mm increment. Some of the thermo-mechanical properties of the zirconia, interlayer metallic bond coat, rings and piston are listed in Table 1. The piston material is aluminum alloy including silica, copper, chromium, magnesium, etc. Mechanical properties of the aluminum alloy piston are 485 MPa, 450 MPa and 295 MPa for ultimate, yield and shear strength respectively.

3. Temperature and thermal stress analyses

Steady-state thermal stress analyses are executed to study the effect of thermal barrier coating of various thicknesses of the stabilized magnesia-zirconia on diesel engine pistons. The variations of temperature and thermal stress on the piston are investigated for both coated and uncoated piston crowns. Thermal stress analyses are performed by using the general purpose package software ANSYS, produced by ANSYS Inc. PA [23]. The piston model used in the simulation is manufactured for the diesel engine. The engine chosen for this analysis is the MWM TBRHS 518-V16 direct-injection diesel engine with a 130 mm bore and 160 mm stroke. The engine is rated at 300 kW at 1500 rev/min for turbocharged configuration and water-cooled. The geometric compression ratio is 19:1 (see Fig. 1a–b).

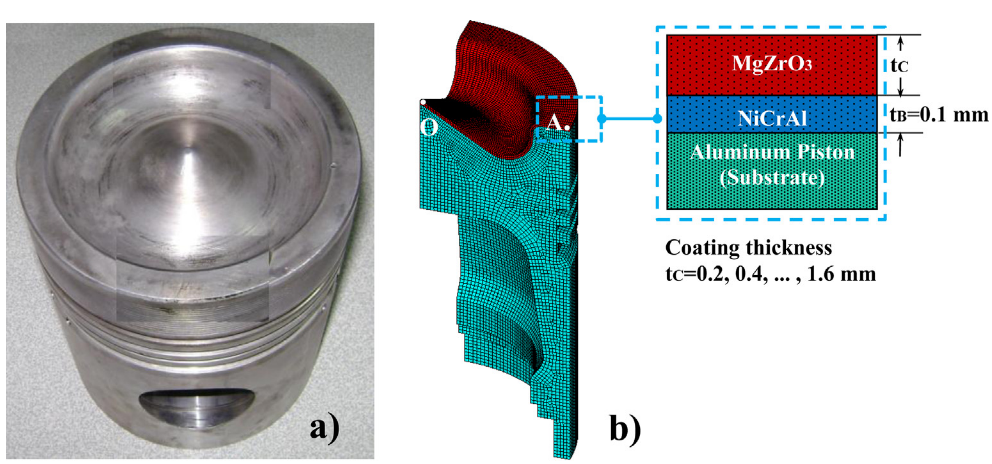

Fig. 1. The piston used in the FE analyses: a) photograph of the piston used diesel engine, b) meshing a quarter of the model and coating parameters.