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Thermo mechanical analysis of a ceramic coated piston used in a diesel engine

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Abstract. The aim of this paper is to determine temperature and stress distributions in a ceramic based on Partially Stabilized Zirconia coated steel piston crown by using plasma spraying for improving performance of a marine diesel engine. Effects of coating constituent and thickness on temperature and stress distributions were investigated including comparisons with results from an uncoated piston by means of finite element method namely ANSYS. Temperature developed at the coated surface is significantly higher than that of the uncoated piston. The maximum stress components occur between bond coat and adjacent ceramic layer. Provided that coating thickness is constant as 0.5 mm, when numbers of layers increase, magnitude of the normal stress decrease about 34.1% on the base metal surface according to uncoated piston, but the base metal surface temperature of the steel piston increase about 13.1%.

Keywords: thermo mechanical analysis; diesel engine piston; ceramic TBCs; thermal stresses; loads

1. Introduction

As a common practice in engineering, thermal insulated materials have been extensively used in various engineering applications. Thermal barrier coatings (TBCs) are usually applied to thermally insulate the substrates so as to allow higher operating temperature. The materials are more investigated for TBCs by different researchers to obtain physical and chemical properties (Poerschke *et al*. 2015, Eriksson *et al*. 2015, Keyvani 2015, Su *et al*. 2015). TBCs are also applied in adiabatic engines for reducing in cylinder Low Heat Rejection (LHR) and for protecting from thermal fatigue underlying metallic surfaces. Among most prominent example of using TBC, gas turbines and pistons are commonly coated with Partial Stabilized Zirconia (PSZ) to sustain an appreciable temperature difference between the substrate and the coating surface (Yonushonis 1997, Chan and Khor 2000, Muchai *et al*. 2002, Buyukkaya and Cerit 2007 and Gilbert *et al*. 2008). Thermal barrier coatings especially can be applied in internal combustion diesel engines to insulate combustion chamber surfaces. The coatings can also be applied to the entire combustion chamber or selected surfaces like the piston crown or valves. The coating influences the combustion process, the performance and exhaust emissions characteristics of the engines (Buyukkaya *et al*. 2006, Prasad and Samria 1990 and Winkler and Parker 1993). The primary

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purpose of this is to raise surface temperatures 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 into useful work, increasing power and efficiency. Extra benefits include protection of metal combustion chamber components from thermal stresses and reducing of cooling requirements. Simpler cooling systems would reduce the weight and cost of the engine while improving reliability (Yonushonis 1997, Chan and Khor 2000).

Stabilized zirconia is a ceramic material having very low thermal conductivity values, good strength and is able to withstand much higher temperatures than metals. Ceramic coatings can be applied by a various methods, such as plasma spray which is the most common. In this method, there is a bond coat layer between TBC and metal substrate. The bond coat is an intermetallic alloy that provides oxidation resistance at high temperatures and aids in the adhesion of the TBC to the substrate. The bond coat also plays an important role in reducing the internal stresses, which may arise between substrate and ceramic coat due to thermal shock. The value of Coefficient of Thermal Expansion (CTE) of bond coat is in between that of the TBC and metal substrate (Yonushonis 1997, Chan and Khor 2000 and Buyukkaya and Cerit 2007, Cerit 2011, Cerit and Coban 2014). Jalaludina *et al*. (2013) made an experimental study of ceramic coated piston crown for compressed natural gas direct ınjection engines. The temperatures on the top of piston crown and piston underside were measured. Sivakumar and Kumar (2014) made investigation on effect of Yttria Stabilized Zirconia coated piston crown on performance and emission characteristics of a diesel engine. Vedharaj *et al*. (2014) studied an experimental and finite element analysis of a coated diesel engine fueled by cashew nut shell liquid biodiesel and the impact of coating on engine performance characteristics. Thermo mechanical analyses were investigated by many researchers. Ngo *et al*. (2014) studied the theoretical formulation, discrete approximation and solution algorithm for instability problems combing geometric instability at large displacements and material instability due to softening under combined thermo-mechanical extreme loads. Mohammed *et al*. (2014) worked on experimental study about micro-hardness and Young’s modulus of a thermo mechanically processed biomedical titanium alloy. Asgari (2015) made numerical analyses about the material distribution optimization of 2D heterogeneous cylinder under thermo-mechanical loading and subjected to steady state thermal and mechanical loadings is considered. The finite element method with graded material properties within each element (graded finite elements) is used to model the structure. Liu *et al*. (2012) investigated the laser thermal loading on diesel engine piston by using numerical simulation model of stress field of laser thermal action was established with the consideration of experimental conditions and the temperature dependent of thermal physical properties of the piston materials. Lu *et al*. (2014) investigated the thermal analysis of yttria stabilized zirkonia (YSZ) thermal barrier coatings on diesel engine piston to analyze the failure mechanisms of TBCs on aluminum piston by combining finite element simulation and experiment. Aydin *et al*. (2015) made investigation of the usability of biodiesel obtained from residual frying oil in a diesel engine with thermal barrier coating. After the coating process, biodiesel fuels were tested in the coated engine and performance of engine was reported.

The coating thickness has a hectic effect on the combustion temperature, the temperature gradient and the stress distribution in the coating and the interfacial stresses. Thermal shock resistance of a ceramic coating depends on the elastic modulus, thermal expansion coefficient and thermal conductivity (Chan and Khor 2000, Muchai *et al*. 2002, Gilbert *et al*. 2008, Hejwowski and Weronski 2002). Thicker coating may provide better insulation however, spallation tends to occur as a result of sever thermal shear for a thicker TBC. Therefore, accurate assessment of the temperature drop for the use of TBC with proper thickness plays a role, not only of academic interest but also crucial for the resulting performance of the coated system. There are many factors which influence the overall performance of coatings and cause spalling of the coating. However, oxidation and thermal mismatch are identified as two major factors affecting the life of the coating system (Buyukkaya and Cerit 2007). Thermal mismatch causes high stress value on the interfacial. On the other hand, the lifetime of the TBCs can be limited by stresses due to changing thermal loads during the operation result in crack nucleation and propagation in a parallel direction to the ceramic–bond coat interface, which leads to delamination of coating. Arising from normal stress, the other typical TBC failure occurs by spalling of the ceramic top coat from the bond coat (Buyukkaya and Cerit 2007, Gilbert *et al*. 2008 and Cao *et al*. 2004).

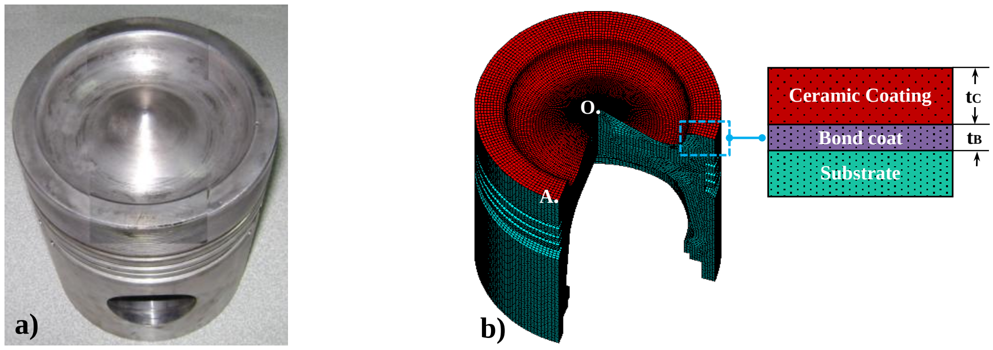
It is also important to calculate the piston temperature distribution in order to control the thermal stresses within the acceptable levels. The temperature distribution and interfacial thermal stresses can be calculated between surfaces of layers. Computer simulations of thermo mechanical analyses can significantly reduce the time and cost in designing of a piston in diesel engines before the first prototype is constructed. Several research papers have been reported on thermal analyses (e.g., Buyukkaya 2008, Esfahanian *et al*. 2006 and Padture *et al*. 2002); however, none, or very scarce if there is, exists in the open literature for investigating the thermo mechanical behaviour of the coated steel piston with TBC. In the literature, although there are a lot of experimental studies on traditional thermal barrier coatings in the internal combustion engines, there are a few numerical studies that focused on 3-D structural and thermal analyses on a multilayers coating diesel piston model.

2. Model and coating materials

Thermal analyses are employed to deposit metallic, cermet and ceramic powders such as NiCrAl, NiCrAl+ $MgZrO_3$, and $MgZrO_3$ on the piston material. The purpose of this paper is to investigate the piston temperature and the stress distribution by using various constituent of the coating materials for the performance in a diesel engine. The steel piston model used in the simulation based on for a marine diesel engine is shown in Fig. 1(a). Thermo mechanical analyses have been carried out by using Finite Element technique which is a powerful numerical tool. A three-quarters part of the model and coating parameters are shown in Fig. 1(b). Analyses have been performed for various types: uncoated, one layer, two layers, and four layers coated piston crown. Thickness and constituents of the coating layers are shown in Fig. 2(a)-(c). Variation of the temperature on the piston and coating surface and also the interfacial stresses between bond coat and coating were examined including comparisons with results from an uncoated piston.

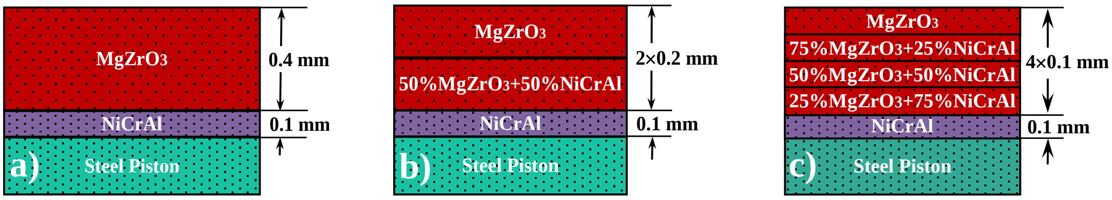
Thermal barrier coatings are used for increasing the operating temperature of the material. Usually, homogeneous ceramic coatings are applied on the metal substrates. The most important problem faced in the coated system is thermal stresses which are developed during operation due to high mismatch in the thermal expansion coefficients of metal substrate and ceramic coating. The multilayers or functionally graded coating materials having various amounts of ceramic and metallic components are used to reduce the detrimental interfacial stresses. The zirconia–based ceramic coatings are preferred as TBCs owing to their low conductivity and their relatively high coefficients of thermal expansion.

The coating has ceramic–metal configuration and may not be isotropic. Thermal sprayed ceramic material has layered structures with defect density resulting from successive impingement



(a) (b)

Fig. 1 The model used in the FE analyses: (a) Photograph of the piston used marine diesel engine; (b) The three-quarters part of the model and coating parameters



(a) One layer (b) Two layers (c) Four layers

Fig. 2 Coating models used in the analyses

of a multitude of fully or semi molten particles. The plasma sprayed coatings exhibit transversely isotropic symmetry. Although properties of coating materials are different in through thickness and in–plane directions, it behaves linear each direction. Elasticity modulus of the thermal spray ceramic coating in the in–plane directions is approximately $E_{22} = E_{33} = 1.6\ E_{11}$ (Tan *et al*. 2010). For the multilayers, material properties of the each layer between bond coat and top of ceramic coating were calculated by using simple rule of mixtures. The main characteristics of material, such as modulus of elasticity, Poisson's ratio, thermal conductivity and thermal expansion coefficient were predicted in follow equation.

$$A = B \times V_1 + C \times V_2 \tag{1}$$

Here, A is the magnitude of the new materials characteristic, B and Care the magnitudes of the component materials, V_1 and V_2 are the volume fractions (Callister 2007).

In this study, PSZ used in TBCs as deposit materials is preferred because of its superior thermal insulating properties, thermal stability at cryogenic and high thermal applications compared to coating materials. Thickness of the total coating is taken as 0.5 mm. It composes of 0.1 mm bond coat (NiCrAl) and 0.4 mm ceramics ($MgZrO_3$). Their constituents vary along the thickness of the coating (see Fig. 2). Thermo mechanical properties of the stabilized zirconia, interlayer metallic bond coat, rings and piston made of cost iron are listed in Table 1 (Buyukkaya 2008). That is, except bond coat, multilayers coatings are laminated by one, two and four sub–layers varying compositions on piston crown.

Table 1 Materials properties of the piston, bond coat and coating (Buyukkaya 2008)

Material	Modulus of elasticity [GPa]	Poisson's ratio	Thermal conductivity [W/m°C]	Thermal expansion (CTE) 10^{-6} [1/°C]	Density [kg/m^3]	Specific heat [J/kg°C]
Base metal (Steel)	200	0.3	79	21	8750	960
Bond coat (NiCrAl)	90	0.27	16.1	12	7870	764
75% NiCrAl+ 25% $MgZrO_3$	79	0.26	12.2	11	7302	735
50% NiCrAl+ 50% $MgZrO_3$	68.5	0.24	8.4	10	6735	707
25% NiCrAl+ 75% $MgZrO_3$	56.5	0.22	4.6	9	6167	678
Ceramiccoating $MgZrO_3$	46	0.20	0.8	8	5600	650
Rings	200	0.30	16	12	7200	460

3. Thermomechanical analyses

Steady state thermal and structural analyses were carried out to investigate the effect of thermal barrier coating on temperature gradients and stress distributions for uncoated and multi–layers (one, two and four) coating constitute on diesel engine pistons. Thermo mechanical analyses were performed to finite element analysis (FEA) by using general purpose package namely ANSYS. The investigated cases of the coating are represented (see Fig. 2). The piston model used in simulation was manufactured for the marine diesel engine named (MVM 518 TBRHS V16).

Axially symmetric finite element model (FEM) was considered to reduce the total number of elements and computational time because of having symmetry geometry, thermal boundary condition and loading. Uniform shapes and forms of elements play an important role to obtain accuracy results. So, meshing of the piston and coating layer were constructed by using second order couple field (thermo–mechanical) element having 8–node in such a way that it can support irregular shapes without losing much of accuracy (Analysis 2012). Moreover, line to line contact elements were defined between piston rings and ring grove. The model including substrate and coating layers contain approximately 74000 elements. The system was modelled as multi distinct layers with a clearly defined interface between them. Pistons and rings are made of steel. These materials were assumed to be linear elastic and isotropic.

In the thermo mechanical analysis, it is assumed that the major mechanism of heat transfer is convection (Esfahanian *et al*. 2006). Thermal circuit method was used to model the heat transfer in the ring land and skirt region with the following assumptions: the effect of piston motion on the heat transfer is neglected, the rings do not twist, the rings and skirt are fully engulfed in oil and there is no cavitation, and also the conductive heat transfer in the oil film is neglected (Esfahanian *et al*. 2006). Symmetric constraints were imposed in the axially symmetric axis. That is, all of the displacement was set to zero in the radial direction. And also symmetric thermal boundary condition was applied to radial direction on the symmetry axis which means adiabatic. Local average heat transfer coefficient and gas temperature boundary conditions were determined by using the engine cycle simulation code for the piston top (Muchai *et al*. 2002). The code calculates the heat transfer coefficients with 1 crank angle degree interval. These values were assumed to be constant. The piston surface was heated in a point wise–like way at the outlet of the swirl chamber

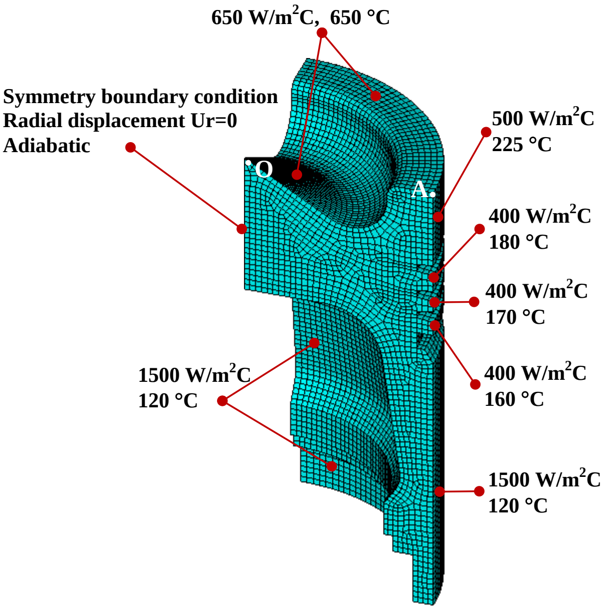


Fig. 3 Thermal boundary conditions of the piston used in the FE Analysis (Buyukkaya 2008)

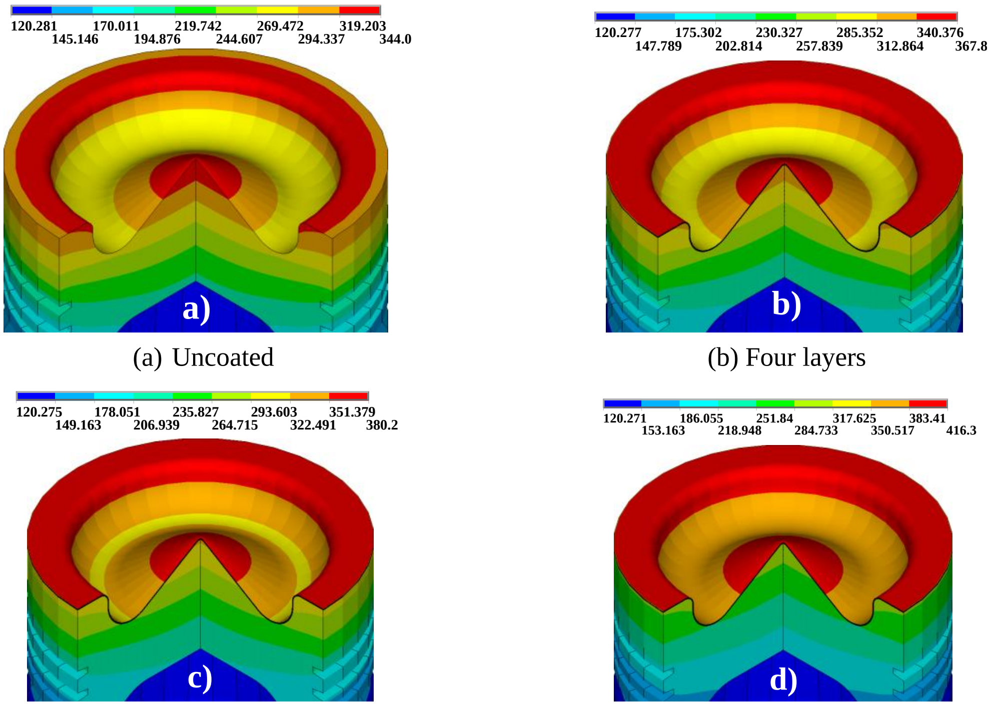
and cooled through contact with cooler components of the combustion chamber. In the analysis, following equation offered by Hohenberg (1979) was used to predict instantaneous heat transfer coefficients.

$$h_{gas}(t) = \alpha V_C(t)^{-0.06} P(t)^{0.8} T(t)^{0.4} (S_P + b)^{0.8} \quad (2)$$

where $h_{gas}(t)$ is the instantaneous convective heat transfer coefficient (W/m^2 K), $V_C(t)$, $P(t)$ and $T(t)$ are the instantaneous cylinder volume (m^3), pressure (bar) and temperature (K), and S_P are the mean piston speed (m/s), respectively. The calibration constants $\alpha$and b are calculated and used as 130 and 1.4. Cycle averaged values of heat transfer coefficient and temperature were used for the piston top. Boundary conditions for oil–cooled part of the piston were obtained from literature as 95°C and 1500 W/m^{2}K, respectively (Muchai *et al*. 2002). The other boundary conditions (temperature and heat transfer coefficient) were taken from the literature (Buyukkaya 2008 and Chan and Khor 2000). Temperatures of the rings are 200, 180, 170 and 160 °C for first and second compression, cooling and oil respectively. The average heat transfer coefficient and temperatures predicted as the boundary conditions were given Fig. 3. This model of the process is successfully applied by piston producers to evaluate design alterations (Chan and Khor 2000 and Gilbert *et al*. 2008).

4. Results and discussions

Provided constant coating thicknesses, temperature distribution of the uncoated and coated pistons having various material constituents were shown in Figs. 4(a)-(d). A special path named radial distance along line OA (see Figs. 1(b) and 3), started from crown centre O and ended outer edge A was defined. OA line is over half of the extended piston crown surface including bowl



(a) Uncoated (b) Four layers

(c) Two layers (d) One layer

Fig. 4 Temperature [°C] distributions of the piston and coating top surface for various case

length. The temperature of top coating surface versus radial distance along line OA for various cases was plotted in Fig. 5.

On the uncoated piston surface, a maximum temperature of 344℃ was observed in the crown centre and minimum was at the bottom of the bowl as seen in Fig. 4a and Fig. 5. Temperature decreases from crown centre to bottom of the bowl and increase towards bowl lips and then again decrease outer of the crown surface. Since they are subjected to the heat flux circumferentially, high temperature regions were both the centre of crown and bowl lips. In the coated pistons, temperature distribution enhances with coating for each cases. It was observed that the values of maximum temperature at the crown centre of the pistons were 416.3℃, 380.2℃ and 367.8℃ for coating with one, two and four layers, in Figs. 4(b)-(d), respectively. As expected, the maximum amount of increase in the temperature were observed for one layer coating because used pure zirconia having low thermal conductivity and much more thickness of the layer. The amount of increase in temperature compared to uncoated piston was 6.9%, 10.5% and 21% for coating with one, two and four layers, respectively. The minimum increase in temperature was obtained for four layers coating. The reason is that reduction in the value of thermal conductivity of the layers is related to rate of zirconia. As for two layer coating, the value of temperature was obtained between one and four layers (see Fig. 4(c)). Lu *et al.* (2014) found that the surface temperature of top coat on the piston shows similar variation tendency with distance. However, on the top coat surface, an obvious reduction in temperature occurs at the corner of bowl, and significant increase of temperature is observed at the external rim of bowl. As the thickness of the coatings increases, the surface temperature of the top coat increases. It is obvious that these are similar with our results.

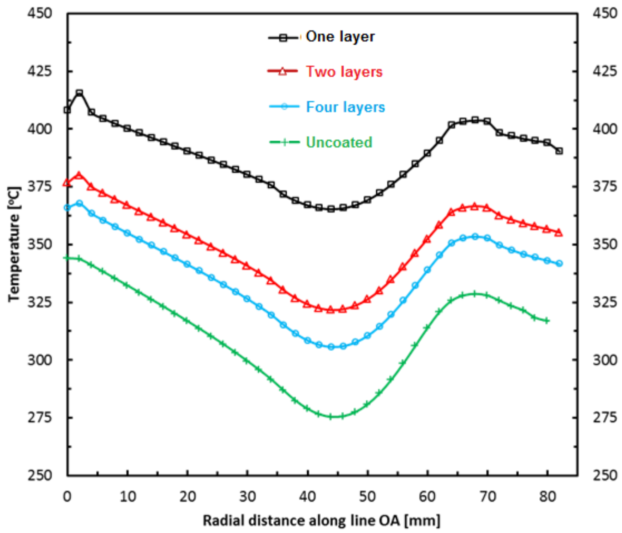
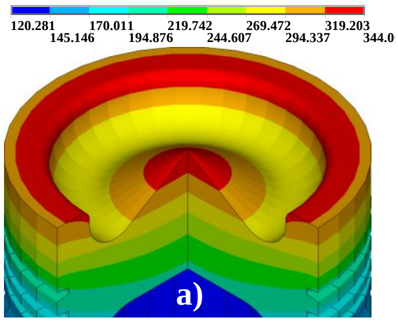
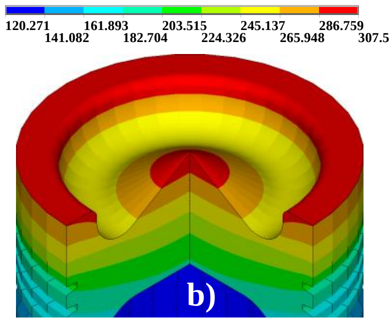


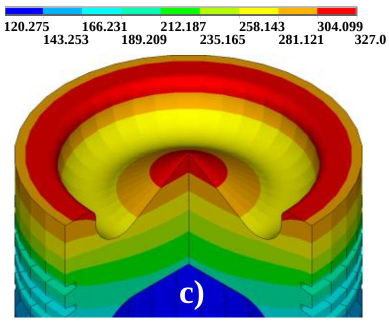
Fig. 5 Top surface temperature distributions for various coating layers



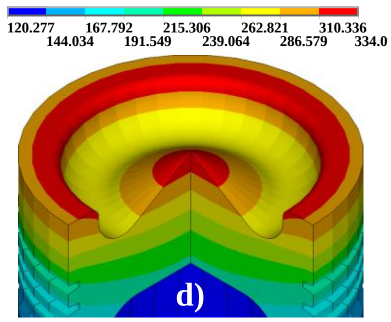
(a) Uncoated



(b) One layer



(c) Two layers



(d) Four layers

Fig. 6 Temperature [°C] distributions of the piston substrate surface for various case

Temperature distributions of the substrate surface for various coating layers and uncoated were shown in Figs. 6(a)-(d). As expected, temperature of the metal surface is significantly lower than that of the uncoated piston surface because of the coating. This reduction shows a parallel change in temperature with top surface of the coating. It was observed that the values of maximum temperature at the crown centre of the pistons substrate were 307.5℃, 327℃ and 334℃ for coating with one, two and four layers, in Figs. 6(b)-(d), respectively. The maximum amount of decrease in the substrate temperature with respected to uncoated piston was observed for one layer coating. Based on the uncoated piston, per cent reduction in temperature were 10.7, 4.9 and 2.9 for coating with one, two and four layers, respectively. The minimum decrease in temperature was obtained for four layers coating. For two layers coating, the value of temperature is in between one and four layers.

The temperature of substrate surface versus radial distance along line OA was plotted for various cases in Fig. 7. Low temperatures were seen for one layer coating case; high temperatures were shown for four layer coating case in Fig. 7. Moderate temperatures were obtained for two layer coating case. Reduction of temperature on the metal surface provides a positive contribution to strength of the material.

When the coated substrate was subjected to severe thermal loading, thermal stresses produced between interfacial layers and the coating can be damaged. It should be controlled by means of Functionally Graded Material (FGMs) applications. Based on the nature of crack, the formation of crack is at the area with maximum stresses. As the ceramic is brittle, small imperfections can easily propagate into large cracks and the coating may delaminate from the bond layer and substrate. Therefore, it is important to calculate the interfacial stresses distribution in order to control the stresses within acceptable levels. From the FEM analyses, all of stress components were maximum at the interface between the bond coat and the adjacent coating layer. That is, the maximum stress occurs at a point on the critical surface. Therefore the detailed investigation focused on bond coat surface. FE analyses present components of stress, such as radial stress, tangential stress, axial stress and shear stress for axially symmetric models. Each component will be discussed subsequently.

At the bond coat top surface, radials stress which may cause spalling of the coating distributions versus radial distance along line OA for various layers was plotted in Fig. 8. All of

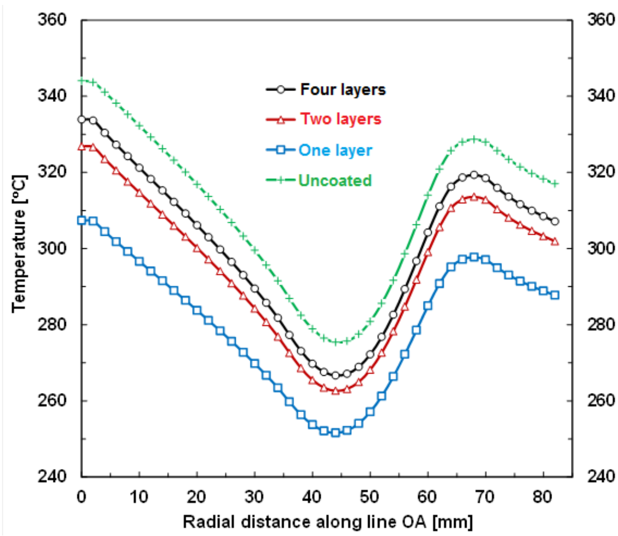


Fig. 7 Temperature distributions of the substrate surface for various coating layers

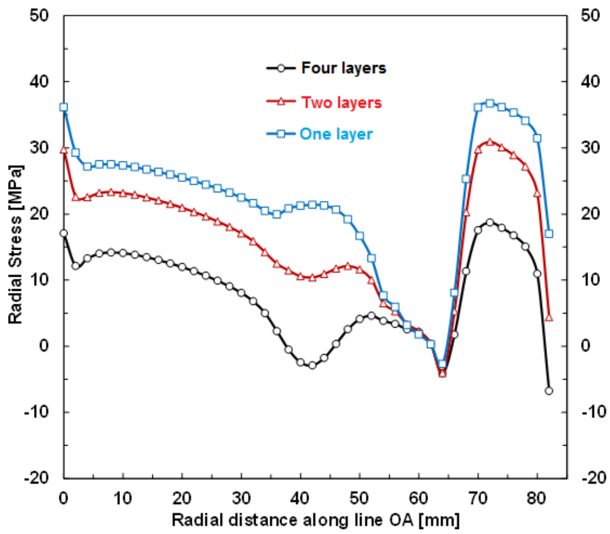


Fig. 8 Radial stress distributions for various coating layers on the bond coat surface

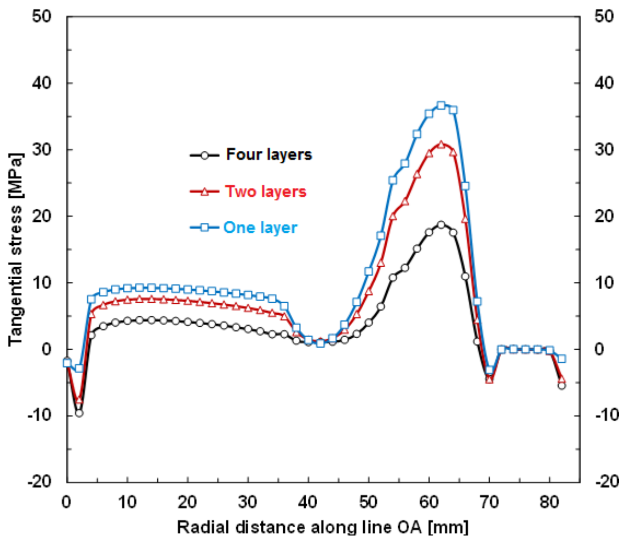


Fig. 9 Tangential stress distributions for various coating layers on the bond coat surface

the radial stress curves were nearly parallel each other but their stress values were different. The maximum radial stress was seen as 38 MPa for one layer case at the crown centre and bowl lips. For four layers case, the maximum radial stress was 18.5 MPa; this corresponds to 51.3 per cent reduction. In the case of two layers, the amount of reduction 18.4 per cent and its maximum value was 31 MPa. Reduction of the magnitude of the stress is not linear.

The tangential stress distribution versus radial distance along line OA for various layers was plotted in Fig. 9. The tangential stress distributions are complex because of piston crown geometry. All of the curves are parallel and close to each other. It is noticeable that tangential stress is nearly zero at the centre and edges of the piston crown. The maximum stress was observed as 37 MPa for

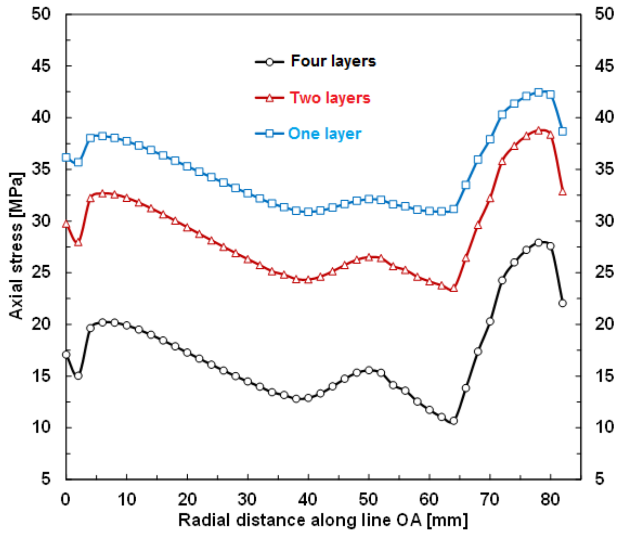


Fig. 10 Axial stress distributions for various coating layer on the bond coat surface

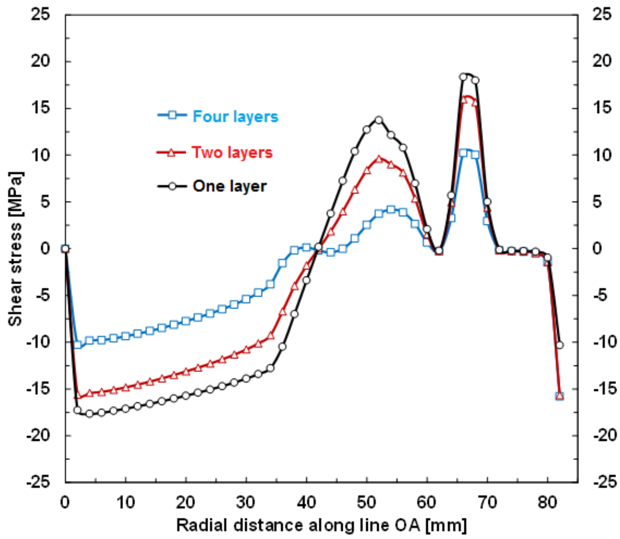


Fig. 11 Shear stress distributions for various coating layers on the bond coat surface

one layer case at the edge of the bowl rim. For four layers case, the maximum tangential stress was 19 MPa; this corresponds to 48.6 per cent reduction. In the case of two layers, the amount of reduction 16.2 per cent and its maximum value was 31 MPa.

Axial stress causes initiating and propagating lateral crack in the direction parallel to the ceramic–bond coat interface which leads to the coating delamination. Axial stress variation with radial distance along line OA for various layers was plotted in Fig. 10. All of the axial stress curves are almost parallel each other, but their stress values are unlike. The maximum axial stress was observed as 42.5 MPa for one layer case at the edges of the piston crown. For four layers case, the maximum axial stress was 28 MPa; this corresponds to 34.1 per cent reduction. In the case of two layers, the amount of reduction 9.4 per cent and its maximum value is 38.5 MPa.

TBCs have a limited life due to crack nucleation and propagation in a direction parallel to the ceramic–bond coat interface which leads to the coating delamination. The shear stress, which may cause horizontal cracks of the coating, distributions versus radial distance along line OA for various layers is plotted at the bond coat top surface in Fig. 11. The shear stress distributions are complex because of piston crown geometry. Its maximum value was 18.5 MPa at the outer edges and lip of bowl rim for one layer coating. For four layers case, the maximum shear stress was 10.5 MPa; this corresponds to 43.2 per cent reduction. In the case of two layers, the amount of reduction 13.5 per cent and its maximum value was 10.5 MPa.

The largest value of the stress was the axial component when compared with other stresses. It was observed that all stress components were quite below the yielding of the coating and substrate materials. So, thin (up to 0.5 mm) coating can be used safely for the steel piston without spallation and delamination.

Lu *et al*. (2014) found that the interfacial shear stress of coating decreases with increasing the thickness of the top coat. When the thickness of top coat is 0.3 mm. The maximum shear stress of about 15 MPa is observed at top coat/bond coat interface, which is much smaller than that of maximum normal stress. In our study the thickness of coating is 0.5 mm and the maximum shear stress is 20 MPa. That is these are similar with our results.

5. Conclusions

The numerical simulations clearly showed that the temperature distribution was a function of coating constituent. For all of cases, high temperature appears at the crown centre and edges of the bowl rim on the top surface of the coating and substrate of the piston. Temperature developed at the surface of coated region was significantly higher than that of the uncoated piston surface.

It is obvious that the maximum stress is a function of coating constituent. The maximum stress components occur in the one layer coating between bond coat and adjacent ceramic layer. Results indicate that stresses developed for multilayers coating can be considerably lower than one layer coating. The largest value of the stress is the axial component bring a long spalling of the ceramic from the bond coat occurs on the bond coat interface when compared with other stresses. At the same time, when thermal performance of the piston increase with decreasing coating layer, stresses increases or vice versa. That is, one and four layer compare with each other, per cent increase of the temperatures is 11.8 but increase of the axial stress is 34.1. Radial stress, tangential stress and shear stress components show similar behaviour.

As a result, deposited multi–layer TBC affects positively life time of the piston instead of single layer and if number of layers increase, stress values may improve better for same total coating thickness.

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CC

Nomenclature

PSZ	Partially Stabilized Zirconia
TBCs	Thermal Barrier Coatings
CTE	Coefficient of Thermal Expansion
FGM	Functionally Graded Material
LHR	Low Heat Rejection
FEM	Finite Element Method
FEA	Finite Element Analysis
OA	Curved line on section plane of the piston crown
$h_{gas}(t)$	Instantaneous convective heat transfer coefficient (W/m^2K)
$V_C(t)$	Instantaneous cylinder volume (m^3)
$P(t)$	Instantaneous pressure (bar)
$T(t)$	Temperature (K)
S_P	Mean piston speed (m/s)
α	Calibration constant
b	Calibration constant