THERMAL BARRIER INFLUENCE ON TEMPERATURE AND STRESS FIELDS IN AN INTERNAL COMBUSTION ENGINE PISTON

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Abstract

The paper presents results of numerical Finite Element analysis of an internal combustion engine piston with a thermal barrier made of zirconia, subjected to thermal and thermo-mechanical loadings. Special emphasis was laid on investigation of the impact of the surface coating on the fields of temperature, heat fluxes, residual stresses and stresses in the coated piston in the working conditions.

For this a purpose, a methodology of developing FEM numerical models of a piston with a surface coating was elaborated, several 2D and 3D FEM models of the piston with the coating were built, and FEM analysis of the models, subjected to thermal and thermo-mechanical loadings was performed.

The results of computations proved high efficiency of the coating as a thermal barrier. The working temperature in some areas inside the piston with a coating showed a huge decrease and was 40% lower as compared with the temperature for the same piston without a coating. At the same time, the heat fluxes inside the piston were reduced almost ten times.

The developed methodology of modelling and simulation may lead to obtain higher thermal resistance, strength and durability of internal combustion engines and their elements with thermal barriers in all fields of application, including aviation.

Keywords: *thermal barriers, surface coatings, graded materials, internal combustion engines*

1. INTRODUCTION

Thermal barriers are commonly applied on various types of structures and structural elements in various kinds of industry Their application on elements of an internal combustion engine leads to upgrading the efficiency of combustion, insure better performance of the engine, lower pollution, and obtain higher strength and durability, as well as better tribological properties of its parts [3].

The most commonly used materials for thermal barriers are the so called Graded Materials (GM) and Functionally Graded Materials (FGM) [1,2,4,5,7].

Application of surface coatings for thermal barriers causes, however, severe problems to overcome, such as residual stresses resulting from the difference in material properties, above all the thermal conductivity coefficient, as well as brittleness of the coatings. A universal and unique tool for selecting parameters of the coatings is Finite Element numerical analysis.

The aim of the work was numerical analysis of an internal combustion engine piston with a surface coating as a thermal barrier and in particular, analysis of influence of the coating on the piston's strength. For this purpose, a Finite Element methodology of modelling and numerical simulation aiming at determining the effectiveness of the coating applied at the upper surface of the piston subjected to thermal and thermo-mechanical loadings was elaborated.

2. FINITE ELEMENT METHODOLOGY OF MODELLING THE PISTON WITH A COATING

It was found from literature survey that the number of publications concerning FEM analysis of a piston with a surface coating is limited and FEM discrete models of the piston applied in these works are relatively simple or simplified – two-dimensional or axisymmetric ones - often with a simplified geometry reduced to a cylinder [1,2,4,5,7].

Basing on the previous research experiences [6], and taking into account the literature review, assumptions have been defined for building complex computational FEM models of an internal combustion engine piston with a surface coating, including: material selection, range and kind of numerical analysis to carry out and specification of boundary-initial conditions. Also, the tool for FEM analysis - MSC PATRAN - was selected.

The actual material – aluminium was selected for the substrate and – on the literature grounds - zirconia ZrO_2 - for the coating. Material properties for both these materials are given in Table 1. For materials of intermediate layers the properties were selected according to the linear mixture law. All materials were assumed homogenous, elastic and isotropic.

It was of special importance to elaborate a methodology of developing a complex discrete FEM model of a piston with a surface coating. Due to great differences in geometrical and material parameters of the coating (above all its small thickness) substantial difficulties arise in FEM analysis demanding a specific development of the discrete models of such complex structures. It is necessary to suitably select the kind of finite elements, carefully conduct discretisation of the surface coating itself, and to preserve the proper selection of elements' dimensions in the transition area between the coating and the substrate. All this may lead to the fact that the resulting FEM model will be too large from the computational point of view.

Within the methodology of developing the FEM complex model of the piston with a surface coating, it was assumed to build models with an increasing level of complexity and similarity to the real system (surface coating – piston), starting with simple 2D and axisymmetric ones and ending with 3D models. The analysis of results for the model of a given level constituted a departure point for building more complicated models. Such an iterative approach to the solution of the problem seems to be the most adequate and enables to reach gradually the possibly optimal discrete FEM model of the analysed system.

Table 1. Material constants values

Constant	Aluminium	ZrO_2
Poisson's ratio	0.33	0.32
Tensile yield strength (MPa)	332	-
Ultimate tensile strength (MPa)	352	551
Compressive yield strength (MPa)	-	3000
Thermal expansion coefficient (K^{-1})	24.6×10^{-6}	9.7×10^{-6}
Density (kg/mm^3)	2.71×10^{-6}	6.07×10^{-6}
Thermal conductivity (W/(mm K))	0.171	0.001675
Specific heat (J/(kg K))	890	400

On the basis of the above-described approach it was concluded that to build a 3D model it is necessary – in order to reach a desired accuracy of results – to use the HEXA8 elements and in the process of mesh generation it is inevitable – because of the complicated geometry - to apply manual modification of the mesh.

The Finite Element analysis included:

- Residual stresses caused by the element processing – cooling from the temperature of 300°C to the room one of 25°C.

- Thermal analysis: temperature and heat fluxes in the piston with a coating in working conditions.
- Thermo-mechanical analysis: stresses in the piston and in the coating caused by the temperature field from the thermal analysis together with suitable boundary conditions.

The analysis was carried out within the non-coupled thermoelasticity. In the thermo-mechanical analysis, the boundary conditions at the piston's surface in the case of simple models included the first kind ones, while for the most complex 3D model the first and third boundary conditions were assumed, together with some boundary constraints to assure equilibrium. The majority of FEM calculations were performed within the range of non-stationary and static analysis.

3. FINITE ELEMENT MODEL AND RESULTS OF CALCULATIONS

According to the accepted methodology of modelling, a number of FEM 2D and 3D models of the piston with a surface coating were elaborated. The most advanced of 3D models of the piston with a surface coating had the real dimensions (Fig. 1). A 30° „cake slice" of the piston without the pinhole area was modelled with HEXA8 finite elements. Because of the model's size, the ZrO_2 coating of 0.45 mm thickness was initially modelled only with one layer of finite elements. The model consisted of 51 654 nodes and 45 586 elements.

Within the thermal analysis the following calculations were performed:

- Temperature distribution in the piston,
- Check of residual stresses due to cooling from 300°C to 25°C,
- Thermal stresses.

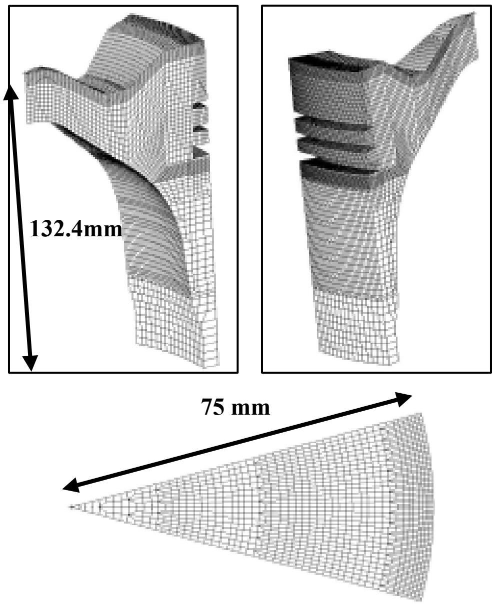

Fig. 1. 3D model of the piston (30° cake slice)

Detailed boundary conditions for the thermal analysis are given in Fig. 2 and Table 2.

In the thermo-mechanical analysis, the residual stresses corresponding to cooling from 300°C to 25°C, thermal loading from the thermal analysis and 10 MPa pressure loading at the top surface of the piston were assumed. Additionally, axial symmetry conditions and constraints on the vertical displacements of nodes close to the axis were introduced.

Table 2. Data for boundary conditions for the 3D model

Temperature	**Convection coefficients**	
$T_1 = 300$ºC	$\Phi_1 = 0.05$ W/mm^2	$\Phi_{SIT} = 0.081$ W/mm^2
$T_2 = 240$ºC	$\Phi_2 = 0.018$ W/mm^2	$\Phi_{S1B} = 0.066$ W/mm^2
$T_3 = 70$ºC	$\Phi_3 = -9\times10^{-4}$ W/mm^2	$\Phi_{S2T} = 0.066$ W/mm^2
$T_{1\text{-}2} = 180$ºC	$\Phi_4 = -0.004$ W/mm^2	$\Phi_{S2B} = 0.051$ W/mm^2
$T_{2\text{-}3} = 120$ºC	$\Phi_5 = -0.003$W/mm^2	$\Phi_{S3T} = 0.046$ W/mm^2
	$\Phi_{1\text{-}2} = 0.018$ W/mm^2	$\Phi_{S3B} = 0.032$ W/mm^2
	$\Phi_{2\text{-}3} = 0.014$ W/mm^2	

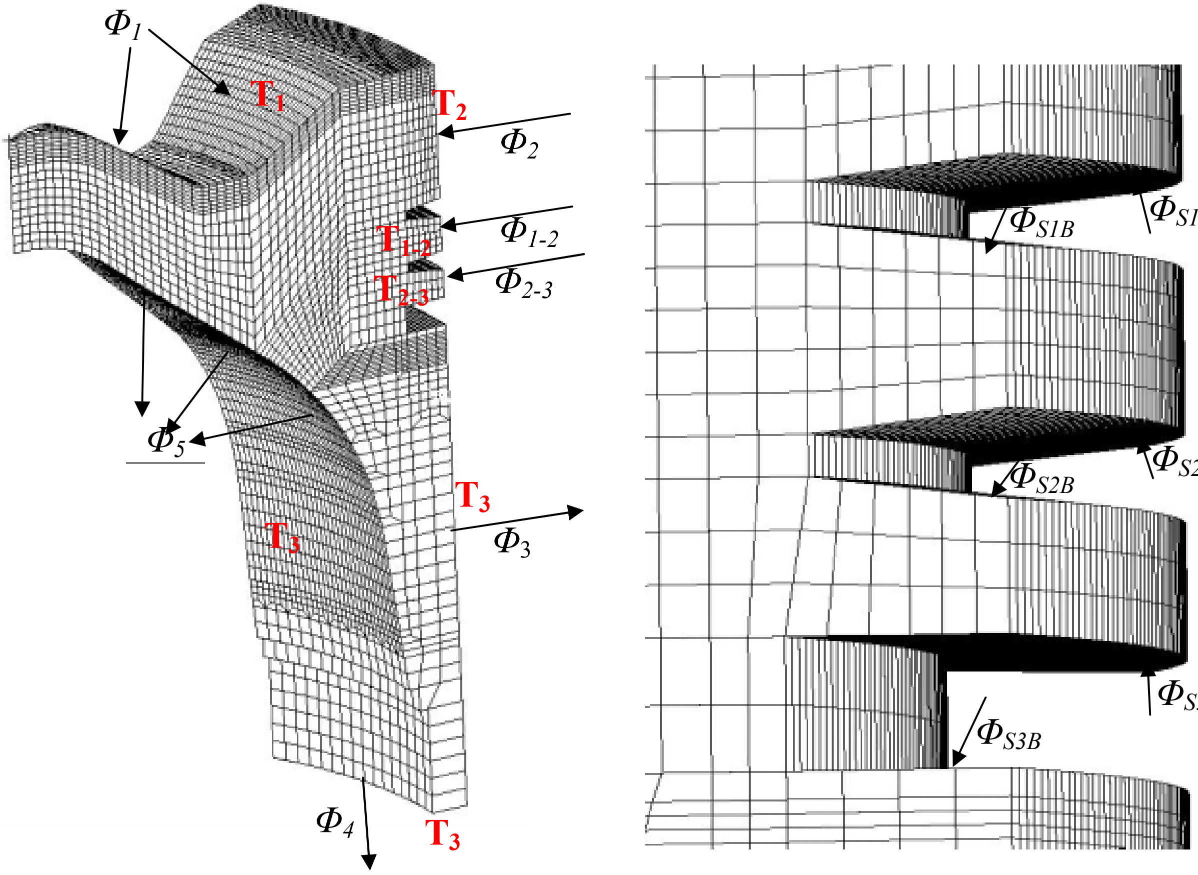

Fig. 2. Boundary conditions for the 3D model

Fig. 3 presents the comparison of temperature distribution in the piston without and with a surface coating. The coating radically reduces the temperature inside the piston – in the aluminium substrate just beneath the coating the temperature decreases by 40%. Only at the upper part of the piston's lateral side the reduction is smaller, because of the first kind boundary condition – temperature set to 240°C. It seems that it would be justified to apply the coating also onto this part of the piston's boundary. The heat fluxes inside the coated piston were reduced almost ten times. The reduction of heat fluxes in the piston without and with a coating is clearly visible in Fig. 4.

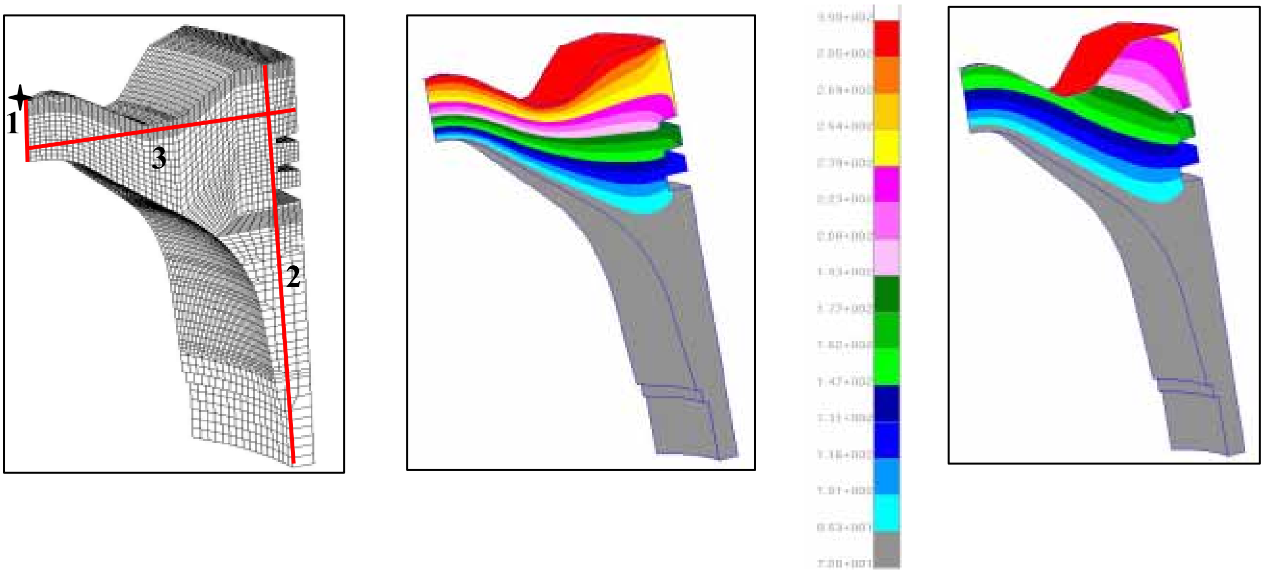

Fig. 3. Comparison of temperature distribution in the piston without (middle) and with the coating (right)

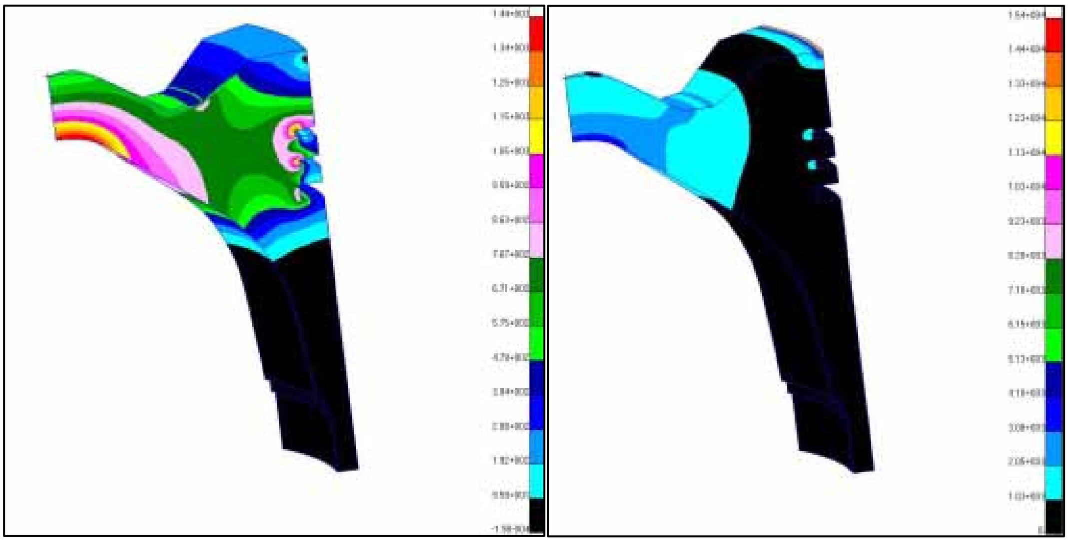

Fig. 4. Comparison of heat flux distribution in the piston without (right) and with the coating (left).

The stress field revealed very high radial compressive residual stresses in the aluminium substrate right under the coating and too high stresses in aluminium at the working temperature (Fig. 5). After thorough analysis we came to a conclusion that it was due to two reasons:

- Use of only one layer of finite elements to model the coating,
- Influence of the piston's top surface curvature changes.

Application of a second layer of coating of the same thickness as the first one, consisting of 50% aluminium and 50% ZrO_2, allowed for a considerable decrease in stresses, both residual and those at the working temperature. The following changes in the stress distribution due to the effect of the second layer were found.

Small decrease in radial residual stresses of about 100 MPa appeared inside the coating. Radial residual stresses in aluminium remained almost the same (decrease of 15 MPa). Compressive radial residual stresses in aluminium under the coating decreased by 500 MPa. Radial stresses at the working temperature decreased by 110 MPa inside the coating and by 280 MPa in the aluminium substrate. Other components of residual stress and those at the working temperature revealed no considerable changes.

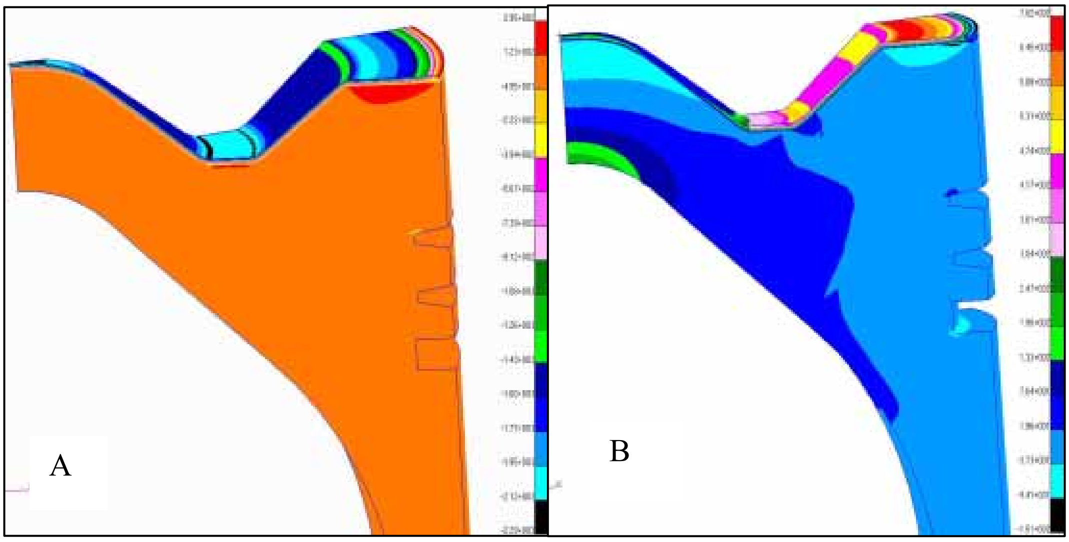

Fig. 5. Radial residual stresses (A) and radial stresses at the working temperature in the 3D model (B)

The numerical calculations confirm that the zirconia surface coating has a great impact on the strength of the modelled internal combustion engine piston. This impact is exerted by means of two mechanisms:

1. The surface coating acts as a thermal barrier,
2. It causes residual stresses in ZrO_2 – these in turn influence the working temperature stresses.

While the first mechanism is by no means beneficial for the strength and durability of the piston, the other one will be beneficial if no stresses higher than ultimate ones occur. On the grounds of analysis of results, the following conclusions concerning the two above mentioned interactions could be drawn.

- The ZrO_2 surface coating at the top of the piston shows a very high effectiveness as a thermal barrier. In some areas inside the piston with a coating, the calculated temperature at the working conditions was by about 40% lower than for the same piston without a coating.
- Only one layer of finite elements for a 100% ZrO_2 surface coating leads to too high stresses.
- Application of an intermediate layer of 50% ZrO_2 and 50% aluminium enables to radically reduce the stresses – which means that the coating should consist of a graded material.
- Three layers of finite elements of coating with a gradually changing contents of ZrO_2 lead to the best effect for the simplified model – it seems justified to expect the same effect for the most complicated 3D model.
- On the grounds of former considerations one can come to a conclusion that it would be desirable to make the coating of a functionally graded material with continuous change of properties along its thickness. We can then obtain a slightly lower decrease in temperature inside the piston, but the stress distribution will be more beneficial. Verifying this hypothesis will demand, however, application of special finite elements for FGM materials.
- The shape of the surface onto which the coating is applied is of great importance to the distribution of residual and working temperature stresses.
- Stress concentrations occur in the areas close to sharp edges. The complicated shape of the surface of the coating with curvature changes is also responsible for these concentrations and their localisation.
- The tensile residual stresses occur in aluminium right under the coating. In the coating, the stresses are compressive and exceed 1700 MPa. Axial residual stresses reach maximum in the substrate material close to the coating boundary.

- The calculations show that before applying the thermal barrier onto the piston's top it is necessary to reduce the changes of curvature of the surface in order to avoid or reduce the stress concentrations.
- The thickness of the surface coating equal 0.45 mm (assumed from literature) seems to be correct.

Finally, it can be concluded that the 0.45 mm thick zirconia surface coating, applied onto the top of the analysed internal combustion engine piston, turned out to be a very good thermal barrier.

It should be emphasised that the so far investigations do not exhaust the whole problem and give not fully satisfactory answers to all arising questions. However, more precise determination of the influence of the coating's parameters on the stresses in the piston will demand further investigation, and in particular - elaboration of new, much larger and accurate 3D FEM models, use of more advanced software and carrying out further, numerous computations and analyses.

4. CONCLUSIONS

A number of FEM models have been developed, with a growing level of complexity and approximation of the real piston – coating system, beginning with the simplest 2D axisymmetric models through to 3D models close to the real piston with real boundary conditions.

For particular models, analysis of distribution of temperature, heat fluxes, residual stresses and stresses at the working temperature of the engine subjected to thermal and thermo-mechanical loadings has been carried out. The analysis of results for a given level model of complexity constituted a starting point for developing more complex models.

The results of computations proved high efficiency of the coating as a thermal barrier. The working temperature in some areas inside the piston with a coating showed a huge decrease and was 40% lower as compared with the temperature for the same piston without a coating. At the same time, the heat fluxes inside the piston were reduced almost ten times.

Also, as far as the stresses under the working conditions of the engine are concerned, the coating leads to their decrease. However, this problem still needs further investigation in the future.

The results of calculations for the last 3D model have proved the necessity of applying a bond between the pure zirconia and the aluminium substrate layer of the piston.

The models presented herein constitute a certain stage of investigation of the influence of the thermal barrier coating on the strength and resistance of the internal combustion engine piston. The influence of residual stresses on the state of stress at the working temperature will need further research. For this purpose it will be necessary to:

- develop a complete 3D model of the piston with the coating,
- model the coating with more than one layer of finite elements,
- take into account non-stationary analysis,
- and model more exactly the boundary conditions.

However, such a 3D model will be very large. It is worth noticing that application of FEM codes with finite elements for graded materials with material properties changing along the element's thickness, which are currently wildly investigated by many researchers, would considerably facilitate the analysis.

The developed models can be straightforwardly applied for analyses of the piston with coatings made of materials other than the one analysed in this paper. Thanks to the performed modelling, a considerable experience has been gained, which will enable carrying out such an analysis for other machine elements with coatings.

The developed methodology of analysis is of a universal character, because coatings are applied not only in the construction of machine elements but also in electronic, optical, nuclear, medical and chemical systems.

Acknowledgements

The support of the Polish Committee for Scientific Research within the Grant No 5 T12C 039 24 is gratefully acknowledged.

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