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FEM ANALYSIS OF FUNCTIONALLY GRADED COATING APPLIED TO DIESEL ENGINE PISTON CROWN

Functionally graded thermal barrier coating was analytically investigated by using Abaqus FEM code. Transient temperature and stress distributions in coatings applied to diesel engine piston crowns were calculated throughout the entire working cycle. Results of calculations were compared against data obtained for metal piston and classical duplex TBC.

Keywords: *Thermal Barrier Coating, Diesel engine, Finite Element Method, Functionally graded coatings*

1. Introduction

It follows from an approximate heat balance for naturally aspirated diesel engine that the extent of heat rejected to exhaust can be reduced by 35-45%, that transferred to cooling system by 15-35% and mechanical losses can be reduced by 5-10% [1]. The most promising way to raise fuel economy is heat insulation of combustion chamber walls and elimination of cooling system. According to early prognoses fuel consumption can be reduced by 30%. Results of analytical studies of Groth and Thiemann demonstrated that the major efficiency benefit can be obtained through piston crown insulation and an attempt to apply thermal insulation to liner surface alone is groundless [2,3]. The temperature raise at the surface of thermal barrier coating (TBC) made of 0.5 mm thick zirconia layer was estimated at approximately 20% and the drop in volumetric efficiency at 0.4%. Schnabel [4] found that application of thermal insulation to diesel engines can reduce fuel consumption by 10-15%. Other studies on adiabatic engines showed that improvement of thermal insulation by 60% raises fuel economy by 8% and application of thermal insulation of cylinders and exhaust system combined with turbocompounding increases by 11%, further gain by another 4% is due to cooling system partial elimination with its attendant mass and space [5].

At present, two concepts of an engine are distinguished: the adiabatic engine with ideal heat insulation and the engine with low heat rejection (LHR). Computer simulations reveal that in passenger car engine higher fraction of energy, compared to heavy-duty truck engine, is transferred to cooling system [6]. The most effective way to gain higher economy of LHR engine is turbocompounding, the effect depends on engine load which favours large engines [7].

The LHR approach is realized through applying TBC coatings, monolithic ceramic inserts, articulated pistons with air gaps or, finally, applying new piston materials. Because of combustion knock risk, low heat conducting TBCs are considered ill-suited to spark ignition engines.

The following arguments were put forward to explain lower than expected engine economy [8]: the alteration of heat release history in the engine cycle, the need of injection timing optimization, the convection-vive effect. Two competitive effects appear- higher temperatures of combustion chamber walls deteriorate volumetric efficiency but, on the other hand, it makes combustion process better.

Kvernes [9] applied thick (2mm) coatings to piston crowns of marine diesels and claimed 5% reduction in fuel consumption. Schihl et al. [10] found in tests on diesel engines with cast iron pistons minute increase in fuel consumption compared to baseline engine, which was explained by longer combustion phase.

In [11] the results of the test performed on the baseline spark ignition Daihatsu engine and the engine with pistons covered with TBC are presented. It was found that TBC increases maximum cylinder pressures and lowers by 6% fuel consumption at low loads. Mendera [8] in his analysis of published results of tests carried out on thermally insulated engines claimed that efficiency of turbocharged engines can be achieved at low engine speeds and low loads, whereas for naturally aspirated engines- at low loads. Kamo et. al. [12] considered a problem of optimum coating thickness. Compared to thick coatings, thin coatings offer the advantage of longer durability and the moderate increase in surface temperature.

Thermally sprayed TBCs are usually two-layer, the layer adjoining the substrate provides adequate adherence of the coating, protects base metal from corrosion and facilitates stress relaxation, the outermost layer is sprayed with ceramic material. Typical TBC on aviation gas turbine comprises 0.13 mm thick bond coat and a 0.25 mm thick layer of partially stabilized zirconia [13]. An example of a sophisticated coating is the triplex TBC applied to the walls of combustion chamber of the Rolls-Royce RB 211 engine. In this case, the TBC consists of a nickel-chromium bond coat and zirconia with 24 wt.% magnesia interlayered with a coating sprayed with the mixture of both [14].

Because the substrate and the coating typically have different physical and mechanical properties, failure of the coating is commonly associated with the interface. To reduce the likelihood of failure, additional layers having intermediate chemical compositions are applied between the bond coat and the ceramic coating. Numerical calculations, along with experimental data on graded coatings, lead to the conclusion that distribution of thermal stresses caused by a mismatch in thermal expansion coefficients is more even than in duplex coatings and their magnitude lower, stress concentrations at coating edges could be less dangerous and crack propagation in the coating hindered [15,16].

2. Calculation of temperatures and stresses in coating applied to diesel engine piston crown

The aim of FEM calculations presented in the paper was to find transient temperature and stress distributions throughout the entire working cycle. Values of assumed average in-cycle convection coefficients and temperatures of surroundings are given in [17], the top view of half piston crown and mesh are shown in Fig. 1. The piston model is simplified, which was necessary to complete the calculations in reasonable time, static temperature and stress distributions were, however, close to those obtained by using more precise model.

In analysis, the following assumptions were made:

- Metal piston is made of Al-Si (AK 12) alloy. Piston height is 87 mm, diameter – 89 mm. Piston side surface is assumed to be even. Piston alloy and coating are isotropic and linearly elastic. Convection coefficients and temperatures of surroundings at bottom and side piston surfaces are constant throughout the cycle. The contact between successive layers of material is tight.
- Temperatures of gas and values of heat convection coefficients over piston's crown at any moment of time are equal to the product of their average values by values of relative temperature or heat convection coefficient, similarly to [17].
- The moments of time, at which actual gas temperature and heat convection coefficient are equal to their average values, are considered to correspond to the same crankangle. Stresses and temperatures were plotted as functions of time measured from this moment.
- Piston was motionless, the effect of gas forces is omitted.

The analysis was divided into two steps, in the first, the engine was warmed-up and conditions of steady operation were achieved, in the second, final calculations were done. Input values are listed in Tab. 1. Piston crown was covered with 0.15 mm thick NiCrAl bond coat and the 0.35 mm thick three-layer coating containing partially stabilized zirconia. The content of ceramics gradually increased toward the free surface. The engine was naturally aspirated 4C90 diesel engine with swirl chamber, calculations were performed for engine speed of 1800 rpm. Results of calculations are shown in Figs 2-7. Fig.2 presents variation of temperatures at TBC's surface throughout the cycle. Numbers of data lines refer to locations of points (see Fig. 1). Maximum temperature attained by the surface is 543.6 K with the swing of 36.2 K. It is seen that temperatures at particular points considerably differ. Fig. 3 shows temperature variations over surface of the metal piston covered with TBC. The maximum temperature is 477.2 K, whereas temperature variations in the cycle are only 1.2 K. Compared to Figs 2 and 4, temperature gradient is considerably lower. Fig. 4 shows temperature distribution in the piston covered

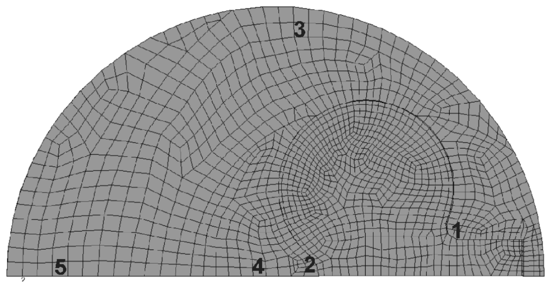

Fig.1. Piston model, mesh and locations of points

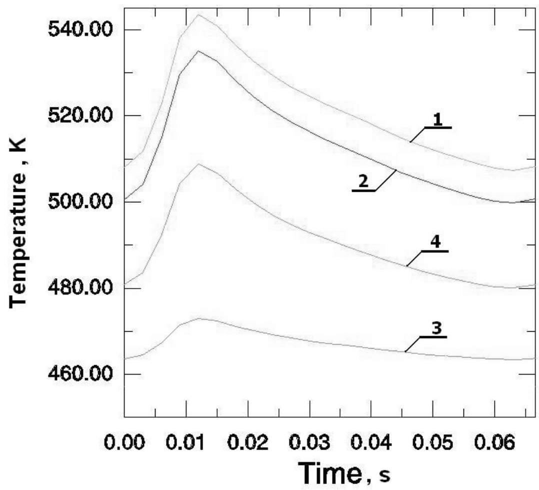

Fig. 2. Temperature variations throughout the cycle at the TBC's surface

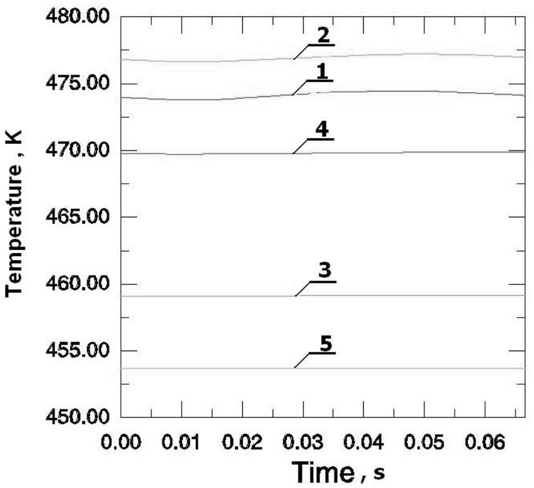

Fig. 3. Temperature variations throughout the cycle at the metal surface

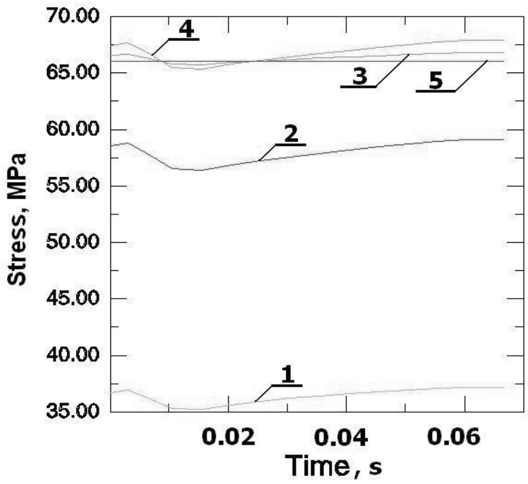

Fig. 5. Variation of von Mises' stresses in the cycle at the TBC's surface

Tab. 1. *Input properties of Al.-Si alloy and coatings*

Material	AK12 alloy	NiCrAl bond coat	ZrO_2+8wt% Y_2O_3	33 vol.% ceramics	66vol.% ceramics
Young's modulus,GPa	80	150	11.25	104	57.5
Poisson's ratio	0.28	0.25	0.25	0.25	0.25
Thermal expansion coeff., $[1/K]\cdot10^{-6}$	21	19	10.9	16.3	13.6
Specific heat [J/kgK]	960	452	620	495.28	549.7
Thermal conductivity [W/mK]	155	15	1.4	3.539	2.006
Density , $[kg/m^3]$	2700	8000	5560	7187	6373

with TBC. It can be noticed that maximum temperatures are higher than those recorded at chosen points (Fig.2). Variation of von Mises' reduced stresses at the free surface of the coating is depicted in Fig. 5. In-cycle stress variations are relatively small, coating failure does not commence at the surface. Uneven distribution of temperatures at TBC's surface causes stress gradients to appear- Fig. 6. Fig. 7 shows the distribution of the normal component of stress at the bond coat/piston interface. At the edge of the recess in metal piston crown, the normal component of stress exceeds the adhesion force of plasma sprayed coatings.

3. Discussion

The maximum temperature at the metal piston crown is 485.8 K, cyclic temperature variation at this point is of approx. 8.9 K. Double layer coating containing 0.3 mm thick ceramic layer reduces metal temperature by approx. 10 K, functionally graded coating comprising bond coat and three layers containing ceramics reduces metal temperature by 8.6 K. Maximum temperature of ceramics is of 543.6 K. Metal surface covered with TBC is no longer exposed to thermal fatigue. In graded coating, temperature variations at the top surface are even 36.2 K. Application of TBC, either duplex or graded, considerably increases temperature differences between particular points at the free surface.

4. Conclusions

Calculations showed that spalling of the functionally graded coating is most likely to appear at the edge of the recess. To alleviate this effect, edges of the recess should be redesigned to reduce stress concentration. Functionally graded coating comprising bond coat and three layers containing ceramics reduces metal temperature by 8.6 K. Metal surface covered with TBC is no longer exposed to thermal fatigue. Maximum temperature of ceramics is 543.6 K. In graded coating, maximum temperature swings at the top surface were 36.2 K.

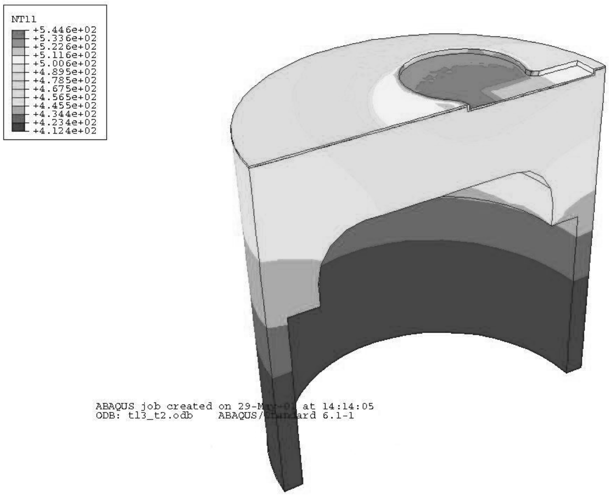

Fig. 4. Temperature distribution in the piston covered with TBC's at 12ms

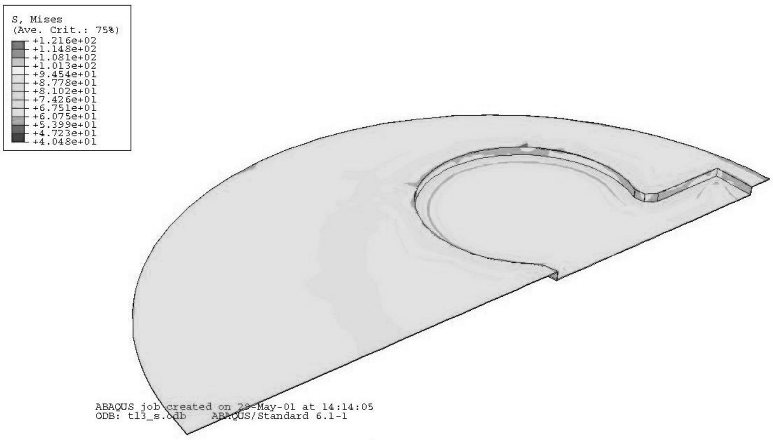

Fig. 6. Distribution of von Mises' stresses at the TBC's surface at 12ms

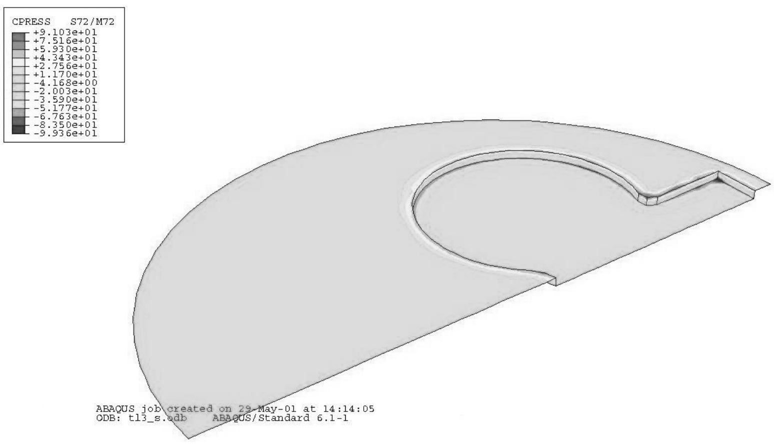

Fig. 7. Distribution of normal component of stress at bond coat/substrate interface at 15.5 ms

4. References

[1] Wajand J.A.: *Silniki o zapłonie samoczynnym*. WNT, Warszawa 1988.
[2] Groth K., Thiemann W.: *Beitrag zur Brennraumisolierung bei Viertaktdieselmotoren*. Teil 1. MTZ 1983, vol. 44 no 5, pp. 189-197.
[3] Groth K., Thiemann W.: *Beitrag zur Brennraumisolierung bei Viertaktdieselmotoren-Teil 2*. MTZ 1983, vol. 44 no 7/8, s. 287-289.
[4] Schnabel W: *Keramikteile im Dieselmotor von Ford*. MTZ 1986, vol.47 no 12, pp. 501-502.
[5] French C.C.J.: *Silniki alternatywne-ciekawostki czy rzeczywista alternatywa*. Auto-Technika Motoryzacyjna 1990 no 9, pp. 5-10.
[6] Siegla D.C., Amann C.A.: *Exploratory study of low-heat-rejection diesel for passenger car application,* SAE paper 840435.
[7] Anonim: *An uncooled diesel for cars?*. Automotive Engineering 1984, vol. 92, August, pp.67-71.
[8] Mendera K.Z.: *Efektywność barier termicznych komory spalania silnika tłokowego.* Wydawnictwo Politechniki Częstochowskiej, Częstochowa 1998.
[9] Kvernes I.: *Thermal barrier coatings in internal combustion engineS.* referat na Conf. Interfacial Engineering of Materials, Castelvecchio Pasoli, Italy, 9-14 October 1996.
[10] Schihl P., Schwartz E., Bryzik W.: P*erformance characteristics of a low rejection direct-injection military diesel engine retrofitted with thermal barrier coated pistons*. Journal of Engineering for Gas Turbines and Power 2001, vol. 123, pp.644-651.
[11] Chan S.H., Khor K.A.: *The effect of thermal barrier coated piston crown on engine characteristics*. Journal of Materials Engineering and Performance 2000, vol. 9 no 1, pp. 103-109.
[12] Kamo R., Assanis D.N., Bryzik W.: *Thin thermal barrier coatings for engines*. SAE Transactions 1989, No 980143.
[13] Miller R.A.: *Progress toward life modeling of thermal barrier coatings for aircraft gas turbine engines*. Journal of Engineering for Gas Turbines and Power 1987, vol. 109, pp. 448-451.
[14] Steffens, H-D, Kaczmarek, R.: *Welding in the World*, vol.28 no. 11-12, 1990, pp. 224-230.
[15] Finot, M., Suresh, S., J.: *Mech. Phys. Solids*, vol. 44 no. 5, 1996, pp. 683-721.
[16] Musil, J., Oberacker, R., J.: *Thermal Spray Technology*, vol 6 no.4, 1997, pp. 449-455.
[17] Hejwowski, T., Weronski, A.: *Advances in Plasma Science*, vol. 3, 2001, pp.155-160.

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