Thermo-mechanical Performance Of the Thermal Barrier Coated Piston

JF Gong¹,³, CM Peng¹, LK Xuan² and DD Guo¹

¹ School of Automobile and Traffic Engineering, Wuhan University of Science and Technology, 430065 Wuhan, China;
² National Key Laboratory on Ship Vibration and Noise, China Ship Development and Design Centre 430064 Wuhan, China
³ Corresponding author: Jingfeng Gong, nsmf_wust@163.com

Abstract. Analysis of the performance of thermal barrier coated (TBC) pistons is important for the design of adiabatic engine. The performance of the TBC piston with thermal load, mechanical load and thermo-mechanical load has been analysed using the cell-vertex finite volume method. Compared to the ordinary piston, TBC piston body withstands less thermal load and exists smaller stress and deformation, while the stress distribution is similar. The maximum stress exists in the TBC region, followed by the region around the pin boss. TBC isolated most heat to the piston body and bears large thermal load. The interface between the bonding layer and the ceramic layer has the most serious stress level. Due to the adoption of TBC, the stress on the piston fire shore arises, while the stress around the piston ring groove area decreases. The area around the pin boss exists the second stress level caused by both thermal and mechanical loads.

1. Introduction

The piston of the internal combustion engine works in harsh environment withstanding alternating high-strength mechanical loads and thermal loads. Piston with thermal barrier coatings (TBCs) makes full use of advantages of different materials to provide good technical support for improving the life and reliability of internal combustion engines. In order to manufacture TBC pistons that meet the technical requirements, it is necessary to accurately predict the thermo-mechanical performance during the design stage.

The numerical simulation of the TBC piston mainly employs commercial software based on the finite element method (FEM). Feng et al. [1-2] discussed the research status of pistons with TBCs consisting of functionally graded materials (FGM). They simplified the piston head with FGM TBCs as a cylinder for thermal stress analysis based on ANSYS software [3], and then further analysed the thermal properties of the actual piston [4]. Wang et al. used software ADINA to numerically simulate the temperature field of ordinary pistons, ceramic fiber non-gradient-reinforced pistons and ceramic fiber gradient-enhanced pistons, and the numerical results showed that the gradient-reinforced ceramic fiber piston has the best heat insulation effect on the piston [5]. Then they further studied influences of TBCs with different gradient distributions on the thermo-mechanical performance of the piston [6]. And they analysed the relation between the overall stress peak, temperature peak, inter-layer stress peak and the gradient index of the material variation, which has been verified by experiments [7].
Based on ANSYS, Buyukkaya and Cerit and their collaborators performed numerical simulations on TBC pistons. The effects of all coated laminated TBCs \[8\] and functionally graded TBCs \[9\] on the piston temperature field had been studied. Compared to the common piston, temperature and stress fields for locally coated laminated TBC pistons had been researched \[10\]. For the locally coated TBC pistons, experimental investigations of the HC emissions showed a significant reduction compared to ordinary pistons \[11\]. Gehlot and Tripathi \[12\] carried out thermal analysis of diesel engine piston coated with ceramic coating having holes on its surface using FEM and found a significant increase in the pistons top surface temperature occurs with coating having holes. However, detailed analysis of the TBC piston under thermo-mechanical load has not attracted enough attention.

As an effective alternative, the cell-vertex finite volume method (CV-FVM) proposed by the authors for the prediction of thermo-mechanical performance of TBC pistons. The accuracy and applicability of CV-FVM has already been proved \[13\]. This paper further extended CV-FVM to research the thermo-mechanical performance of the TBC piston under different conditions. Compared to the ordinary piston, the effects of thermal load, mechanical load and thermo-mechanical load on the performance of the piston with ceramic coating are discussed.

2. Numerical Simulation
In this paper, pistons with maximum explosive pressure are analysed. And it is supposed that the gas pressure reaches its maximum value at top dead centre (TDC), so that the side thrust on the piston is not considered.

2.1. Information of the piston
The geometry of the piston is symmetry, so a 1/4 simplified piston model is taken into account ignoring chamfering as shown in figure 1. The axis of the piston is along the y-axis. The diameter of the piston is \(D = 170\text{mm}\).

![Figure 1 Geometry and meshes of the considered piston](image)

Consider the gas force \(F_g\) on the top surface of the piston, the reciprocating inertia force \(F_j\) and the reaction force \(F_N\) at the pin boss, which can be calculated as

\[
F_g = \left( p_g - p_0 \right) \frac{\pi D^2}{4}
\]

\[
F_j = mr \omega^2 \left( \cos \theta + \lambda \cos 2\theta \right)
\]

\[
F_N = F_g - F_j
\]

where \(p_g\) is the explosion pressure of the gas in the cylinder, \(p_0\) is the absolute pressure of the gas in the crankcase, \(m\) is the mass of the piston, \(r\) is the crank radius, \(\omega\) is the crank rotation speed, \(\theta\) is the angle between the axis of the crank and the piston, and \(\lambda\) is the ratio of \(r\) to the length of the connecting rod \(L\).
Apply 1mm TBC to the top surface of the piston and combustion chamber. The substrate of the piston is made of ZL 109. The ceramic material is MgZrO$_3$ of 0.8mm and the bonding material is NiCrAl of 0.2mm. The material properties are listed in table 1.

| material       | $k$ (Wm$^{-1}$℃$^{-1}$) | $E$ (GPa) | $\mu$ | $a \times 10^6$ (℃$^{-1}$) |
|----------------|-------------------------|-----------|--------|-----------------------------|
| Al-Si alloy    | 155                     | 69        | 0.33   | 21                          |
| NiCrAl         | 16.1                    | 90        | 0.27   | 12                          |
| MgZrO$_3$      | 0.8                     | 46        | 0.20   | 8                           |

According to Refs [3-6,8], the TBC is divided into 5 layers and the thickness of each layer is 0.2 mm, giving different material properties.

### 2.2. Numerical method

The performance of the piston under thermo-mechanical load is numerically studied using CV-FVM. Detailed description of CV-FVM can be found in Refs [13]. The model is meshed with unstructured grids with 69207 elements and 14894 nodes as shown in f0.

Surfaces $x = 0$ and $z = 0$ are symmetric plane, which are set as adiabatic boundary and simply supported. According to the piston technical parameters shown in table 2, the gas force $F_g$ is 3.56$\times$10$^5$ N, the piston inertia force $F_j$ is 7.18$\times$10$^3$ N, and reaction force at the pin boss $F_N$ is 3.54$\times$10$^5$ N. $r'$ is the radius and $l$ is the length of the pin boss. The mechanical loads are treated as following:

1. The gas pressure on the piston head is loaded as a uniform load. The upper surface of the piston, the fire shore, and the upper wall of the first ring are loaded of 100% of the gas pressure. The inner surface of the ring groove and the lower surface are loaded of 75% of the gas pressure. The first ring land, the upper surface of the second ring and the lower surface are loaded of 25% of the gas pressure, and the inner surface of the second ring loaded of 20% of the gas pressure. The load of the gas pressure on the rest surfaces is negligible.

2. The reciprocating inertia force of the piston is loaded as a body force.

3. It is considered that the reaction force at the pin boss is distributed within 120° at the upper surface of the pin boss. The reaction force causes the surface pressure $p_N$ with parabolic distribution along the axial direction of the pin and cosine distribution along the circumference of the pin boss, namely

$$p_N = p_{N_{max}} \left( a x'^2 + b x' + c \right) \cos (1.5 \theta')$$

(0.1)

The definitions of local coordinates $x'$ and $\theta'$ are shown in figure 2.

| $\omega$ (r/min) | $p_g$ (MPa) | $p_0$ (Pa) | $r$ (mm) | $L$ (mm) | $r'$ (mm) | $l$ (mm) | $m$ (kg) |
|------------------|-------------|------------|----------|----------|-----------|----------|----------|
| 1800             | 15.73       | 0.1        | 97.5     | 350      | 65        | 59.7     | 1.62     |
Consider the thermal load on the piston and ignore the effects of piston motion on heat transfer. The heat convective coefficient and the ambient temperature of the piston surface based on the empirical formula can be found in Ref. [15].

3. Results and Discussion
Figure 3 presents the temperature field in plane $\theta = 45^\circ$ of the TBC piston and the ordinary piston under thermal load. The maximum temperature at the top surface of the TBC piston is about 134.6°C higher than that of the ordinary piston. The lowest temperature of both pistons is close and located at the skirt. Analyze thermal stress fields by compared variables at typical points as shown in Table 3. The location of points can be found in Figure 3, where subscript 1 and 2 refers to variables of the ordinary piston and the TBC piston respectively. The TBC isolates large amount of heat to the piston body, lowering the temperature, thermal stress and thermal deformation. The thermal stress in the TBC piston body changes not so much as that in the ordinary piston, but the distribution is similar. In the upper part of the piston cavity (such as point A), the radial stress $\sigma_r$ and the circumferential stress $\sigma_\theta$ are large, and the axial stress $\sigma_y$ is small. In the lower part of the piston cavity (such as point B), $\sigma_r$ is larger than $\sigma_\theta$ and $\sigma_y$. In the piston ring groove area (such as point C and point D), the piston has larger $\sigma_\theta$ while smaller $\sigma_r$ and $\sigma_y$.
Table 3. Comparison of the results based on TBC piston and the ordinary piston

| Variables | TBC piston | Common piston |
|-----------|------------|---------------|
|           | A1         | B1            | C1         | D1         | A2         | B2         | C2         | D2         |
| $T \, (^{\circ}{\text{C}})$ | 248.67     | 122.48        | 199.52     | 183.09     | 212.90     | 114.17     | 179.84     | 164.68     |
| $u_{in} \, (m)$ | 0.3858     | 0.1421        | 0.4456     | 0.3927     | 0.330      | 0.1306     | 0.3911     | 0.3464     |
| $\sigma_r \, (MPa)$ | -38.40     | 5.34          | 0.17       | -0.82      | -25.47     | 3.83       | 0.03       | 0.20       |
| $\sigma_{\theta} \, (MPa)$ | -41.88     | 7.55          | 39.21      | 32.20      | -26.77     | 6.10       | 28.24      | 25.57      |
| $\sigma_y \, (MPa)$ | -2.87      | 32.08         | 1.34       | 0.95       | -2.08      | 23.48      | 1.41       | 0.59       |
| $\sigma_{vm} \, (MPa)$ | 37.98      | 31.11         | 38.66      | 32.32      | 24.60      | 23.01      | 27.73      | 25.26      |

The thermal and mechanical properties of the TBC piston under mechanical load, thermal load and thermo-mechanical load are numerical analysed. The maximum stress exists in the TBC region, followed by the region around the pin boss. There is a large temperature gradient in the TBC region, which generates large thermal stresses. The stress level at the top surface of the TBC piston is mainly determined by the thermal load. The use of TBC increases the stress on the piston fire shore, while the stress in the piston ring groove area decreases. Compared to the results with thermal load, it can be seen that the mechanical load makes the von-mises stress $\sigma_{vm}$ at point P1 much larger (see Figure 4), since the reaction force is greatest here. $\sigma_{vm}$ around P2 is caused by both thermal load and mechanical load, where the geometric shape changes significantly and there is a stress concentration phenomenon.

Figure 4 Distribution of von-mises stress $\sigma_{vm}$ on the surface of the TBC piston under different loads
0 presents curves of $\sigma_{vm}$ at different place in the TBC region in plane $\theta = 45^\circ$. L1 lies at the interface between the piston body and the adhesive layer, L2 lies at the interface between the adhesive
layer and the ceramic layer, L3 is located at the middle of the ceramic layer and L4 is located on the top of the piston, as shown in Figure 5 (a). By compared curves of $\sigma_{vm}$, it can be found that there exists stress concentration around the junction between the combustion chamber and the top surface of the piston. The maximum effective stress appears at L2, that is, the stress at the interface between the bonding layer and the ceramic layer is the largest, which is mainly due to the thermal load and variation of material properties.

![Diagram](image)

(a) Sketch map of the location of lines (2) Curves of von-mises stress $\sigma_{vm}$ along different lines

Figure 5 Comparison of the distribution of von-mises stress $\sigma_{vm}$ in the TBC region

4. Conclusions
Thermo-mechanical performance of the TBC piston has been investigated using CV-FVM in this paper. Compared to the ordinary piston, the effects of thermal load, mechanical load and thermo-mechanical load on the performance of the piston with ceramic coating are discussed. Due to the thermal insulation of TBC, the body of the TBC piston is of lower temperature, thermal stress and thermal deformation compared to the ordinary piston. The maximum stress exists in the TBC region caused by thermal load, followed by the region around the pin boss caused by thermo-mechanical load. The use of TBC increases the stress on the piston fire shore, while the stress in the piston ring groove area decreases. With a detailed comparison of stress curves at different location, the interface between the bonding layer and the ceramic layer show maximum stress level.

References
[1] Yijian Feng, Changlin Gui and Jun Sun 2004 Functionally graded materials and its application in IC engine. *Journal of Anhui University of Technology and Science*. (19) (2004), p 71-78.
[2] Yijian Feng, Changlin Gui, Jun Sun and Hu Wang 2004 A review and prospects of the research on functionally graded materials and the application in IC engines. *Journal of Hefei University of Technology (Natural Sciences Edition)*. (27) (2004), p 597-601.
[3] Yijian Feng, Shuangsong Du, Jigui Cheng and Xianguo Hu 2008 FEM simulation and thermal analysis of functional gradient materials as thermal barrier coating of piston top. *Transaction of the Chinese society of Agricultural Machinery*, (11) (2008), p 30-34.
[4] Shuangsong Du 2008 Hefei. Steady-state thermal analysis of function gradient material as thermal barrier coatingof engine piston. (Hefei: Hefei University of Technology) 2008.
[5] Su Wang, Chunyang Ni and Xinxiong Zhu 2005 Temperature field analysis for heterogeneous material piston. *Journal of Beijing University of Aeronautics Astronautics*, (31) (2005), p 1299-1302.
[6] Su Wang, Chunyang Ni and Xinxiong Zhu 2006 Selection of material gradient equations for functional gradient material pitons. *Mechanical Science and Technology for Aerospace Engineering*, (25) (2006), p 133-138.
[7] Su Wang, Chunyang Ni, Yuning Zhu and Xinxiong Zhu 2007 Study on material composition functions of gradient aluminium matrix composite piston reinforced by ceramic fibers. *Acta Aeronautica Et Astronautica Sinica*. (28) (2007), p 234-239.

[8] Buyukkaya E and Cerit M 2007 Thermal analysis of a ceramic coating diesel engine piston using 3-D finite element method. *Surface and Coatings Technology*. (202) (2007), p 398-402.

[9] Buyukkaya E 2008 Thermal analysis of functionally graded coating AlSi alloy and steel pistons. *Surface and Coatings Technology*. (202) (2008), p 3856-3865.

[10] M. Cerit 2011 Thermo mechanical analysis of a partially ceramic coated piston used in an SI engine. *Surface and Coatings Technology*. (205) (2011), p 3499-3505.

[11] Cerit M, Ayhan V, Parlak A and Yasar H 2011 Thermal analysis of a partially ceramic coated piston: Effect on cold start HC emission in a spark ignition engine. *Applied Thermal Engineering*. (31) (2011), p.336-341.

[12] Gehlot R and Tripathi B 2016 Thermal analysis of holes created on ceramic coating for diesel engine piston. *Case Studies in Thermal Engineering*. (8) (2016).

[13] Jingfeng Gong, Lingkuan Xuan, Pingjian Ming and Wenping Zhang 2013 An unstructured finite-volume method for transient heat conduction analysis of multilayer functionally graded materials with mixed grids. *Numerical Heat Transfer, Part B*. (63) (2013), p 222-247.

[14] Jingfeng Gong, Lingkuan Xuan, Pingjian Ming and Wenping Zhang 2013 Thermoelastic analysis of functionally graded solids using a staggered finite volume method. *Composite Structures*. (104) (2013), p 134-143.

[15] Jingfeng Gong, Lingkuan Xuan, Shaowei Zhou, et al 2016 Cell vertex FVM for thermoelastic analysis of the piston with thermal barrier coating. *Journal of Harbin Institute of Technology*. 48(7) (2016), p 76-81.