

Evaluation of Gasoline Engine Piston with Various Coating Materials Using Finite Element Method

Nouby Ghazaly, Gamal Fouad, Ali Abd-El-Tawwab, K. A. Abd El-Gwwad

Abstract—The purpose of this paper is to examine the piston stress distribution using several thicknesses of the coating materials to achieve higher gasoline engine performance. First of all, finite element structure analysis is used to uncoated petrol piston made of aluminum alloy. Then, steel and cast-iron piston materials are conducted and compared with the aluminum piston. After that, investigation of four coating materials namely, yttria-stabilized zirconia, magnesia-stabilized zirconia, alumina, and mullite are studied for each piston materials. Next, influence of various thickness coating layers on the structure stresses of the top surfaces is examined. Comparison between simulated results for aluminum, steel, and cast-iron materials is reported. Moreover, the influences of different coating thickness on the Von Mises stresses of four coating materials are investigated. From the simulation results, it can report that the maximum Von Mises stresses and deformations for the piston materials are decreasing with increasing the coating thickness for magnesia-stabilized zirconia, yttria-stabilized zirconia, mullite and alumina coated materials.

Keywords—Structure analysis, aluminum piston, $MgZrO_3$, YTZ, mullite and alumina.

I. INTRODUCTION

IN an automobile industry, piston is the most significant part of the engine which is subjected to high stresses due to converting the heat and pressure energy released by fuel combustion into mechanical works. The function of the piston is bearing the gas pressure and making the crankshaft rotation through the piston pin. Therefore, it is must be designed to resist damage that is induced by the extreme heat and pressure of process.

Shete et al. [1] analyzed stresses of a piston due to combustion gas load using two-dimensional photo elastic technique and FEA. They observed that reducing the piston weight leads to increase the power output of engine. Also, they concluded that stress is compressive at all the boundaries except at the back of crown, where stresses are tensile, the tensile stresses are smaller than the compressive stresses. Rajam et al. [2] analyzed the stress distribution in the piston to know the stresses due to the gas pressure and thermal variations using ANSYS. They found that the volume of the piston was reduced by 24%, the thickness of barrel was reduced by 31%, width of other ring lands of the piston was reduced by 25%, Von Mises stress was increased by 16%, and deflection was increased after optimization. But, all the parameters are good in design consideration.

Ghodake and Patil [3] evaluated total deflection occurred

during working condition considering gas pressure and material properties of piston as parameter for the simulation. Their CAE results showed that Von Mises stress was 338.41 N/mm^2 for 180 bar cylinder pressure in case of SI engine. Their CAE results found that the stresses occurred in piston were within the permissible limit of the piston material and deflection is good with the tolerance limit as provided with IS standard. Mishra et al. [4] used finite element method to analyze the coating strength of a compression ring at compression and power stroke transition. The deformation, von Misses stress and strain in the core and coating interface are discussed. It was found that the maximum von Misses stress developed at the highest combustion chamber pressure is 128 MPa.

Shinde et al. [5] investigated structural analysis on conventional piston made of Al alloy A2618. They performed analysis on piston made of Al-GHY1250 and Al-GHS1300. They studied a particular piston design and its capability for maximum gas pressure. They acted high combustion gas pressures as a mechanical load and causes major stresses in the critical region of the piston. They concluded that stress occurred by using Al-GHS1300 is lower than the permissible stress value. Amit [6] performed structural analysis using finite element method for single cylinder diesel engine for design the piston with different materials such as aluminum alloy A 413 and cast-iron FG 200. CATIV V5 R20 software and structural analysis in ANSYS workbench 14.5 were used. Their study reveals about stress distribution, critical regions and deformation in the piston materials for applied pressure load. They concluded that the cast-iron and aluminum piston stress values were less than permissible values. For cast-iron piston stress was maximum at inner side of piston pin hole, and for aluminum piston stress was maximum at top side of crown and minimum at pin hole.

Cerit [7] investigated temperature and thermal stress field of the ceramic coated piston of diesel engine. He observed that the temperature of coating surface was increased with increases in the thickness in a decreasing rate. Sivakumar and Kumar [8] carried out experimental investigation under different loading conditions in a three-cylinder diesel engine with its piston crown coated with yttria stabilized zirconia. It was concluded that the heat loss to the cooling water is reduced up to 5–10%, and the thermal efficiency is increased by 3–5% with reduction of brake specific fuel consumption by up to 28.29%. Fouad et al. [9] carried out a 3-D finite element thermal analysis on spark ignition engine piston for investigating thermal behavior of uncoated and coated piston using commercial software called ANSYS. They found that

Nouby Ghazaly is with the South Valley University, Egypt (e-mail: nouby.ghazaly@eng.svu.edu.eg).

the temperature developed at the top surface of coated region is higher than that of the uncoated piston surface. Also, they observed that the substrate temperature is decreasing with increase in the thickness of coating and the maximum surface temperature of yttria-stabilized zirconia, $MgZrO_3$, alumina and mullite coating increases by 117.47%, 144.76%, 15.014%, and 44.86% respectively for 1.6 mm thick coating.

As may be seen from the literature, most of the studies have been concerned with thermal modelling of piston. The current paper is concerned with structure analysis to analyze the stresses under the effect of mechanical load. A finite element method is used to analyze the stresses of aluminum alloy piston crown coated with different ceramic coatings namely; Yttria-stabilized zirconia, $MgZrO_3$, alumina and mullite to reduce the cold start HC emission at idle and to improve the performance characteristics at the wide-open throttle conditions. Also, the stresses and deformation distribution of the piston with various thicknesses ranged from 0.1 mm to 1.6 mm for each ceramic coating material examined. Comparison between the coating materials and uncoated piston stresses and deformation distribution are reported.

II. NUMERICAL APPROACH

During the working process of internal combustion engines, the piston is affected by the high-pressure gas pressure, the inertia force caused by high-speed reciprocating motions and friction forces. This leads to create a lot of stresses on the piston. Structural analysis is required to determine the effects of loads on the actual piston. In this study, structural analyses are carried out to investigate the effect of coating materials on stresses and strains distributions for the gasoline piston. 3D structural analyses are performed using ANSYS code. Effects of different coating thicknesses on the piston are investigated to determine the optimum coating thickness that could minimize the surface stresses.

An air-cooled SI engine piston is taken as the basis in the simulation, as shown in Fig. 1 (a). The specifications of the test engine are tabulated in Table II. A geometrical model of the piston is developed based on geometry of the actual object and modelled using SolidWorks software, as shown in Fig. 1 (b). The loads set in this case during compression stroke are at a crank location of highest gas pressure of 5 MPa. The total number of nodes and elements of the FE model is equal to 36 824 and 190 600, respectively, as shown in Fig. 1 (c). Mechanical properties of the aluminum alloy piston are 485 MPa, 450 MPa for ultimate, yield strength respectively and of cast-iron piston are 448 MPa, 310 MPa for ultimate yield strength respectively and for steel piston are 448 MPa 531 MPa for ultimate and yield respectively. The piston is coated with different thickness of yttria-stabilized zirconia, $MgZrO_3$, alumina and mullite over a 1 mm thickness of NiCrAl bond coat as shown schematically in Fig. 2. Material properties of the piston made of aluminum alloy and the selected TBC materials namely, yttria-stabilized zirconia, $MgZrO_3$, alumina and mullite are listed in Table II.

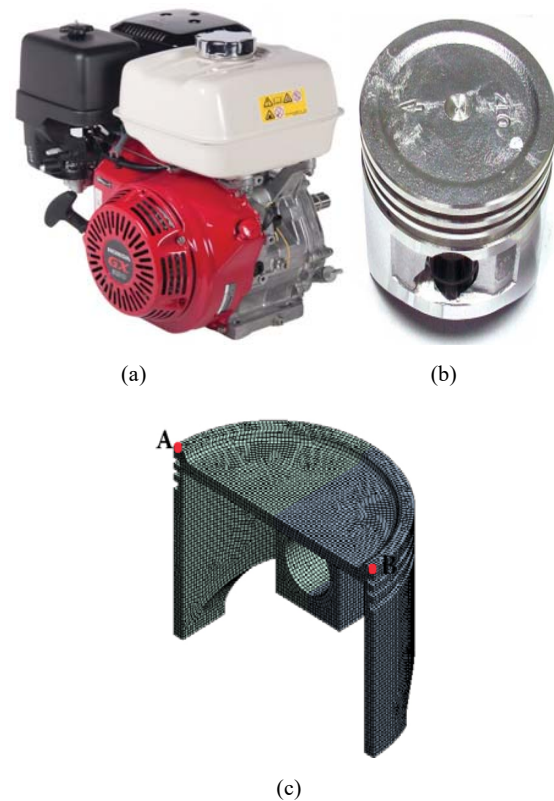


Fig. 1 The piston used in the FE analyses: (a) gasoline engine, (b) the piston, (c) meshing of the FE model

TABLE I
THE ENGINE SPECIFICATIONS

Type	Four stroke, overhead cam
Induction	Air cooled type
Bore	88 mm
Stroke	64 mm
Compression ratio	8.2:1
Power (at 3000 rpm)	11.7 hp
Maximum Torque	2.7 kg.m at 2500 rpm

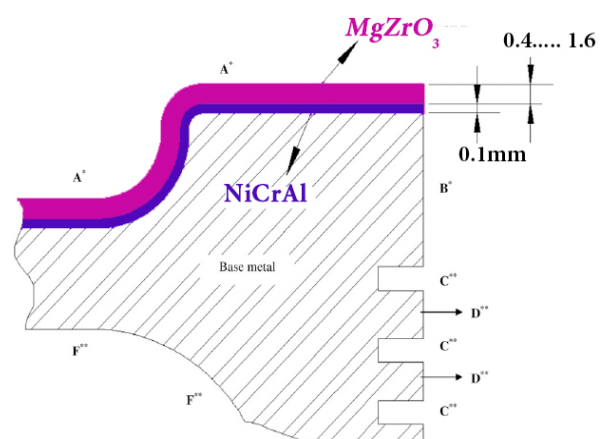


Fig. 2 Partially coated piston

TABLE II
MATERIALS' PROPERTIES OF THE PISTON, BOND COAT AND CERAMIC TOP COAT

Material	Modulus of elasticity [GPa]	Poisson's ratio [m/m]	Thermal Conductivity [W/m °C]	Thermal expansion 10^{-6} [1/°C]	Density [kg/m ³]	Specific heat [J/kg °C]
Piston (aluminum alloy)	90	0.33	155	21	2700	910
Piston (steel)	200	0.30	79	12.2	7200	7870
Piston (cast-iron)	105	0.33	50	0.1280000	7100	963
Bond coat (NiCrAl)	90	0.27	16.1	12	7870	764
Ceramic coating (MgZrO ₃)	46	0.20	0.8	8	5600	650
Ceramic coating (Alumina)	300	0.21	18	7.3	3690	880
Ceramic coating (Mullite)	3000	0.33	50	12.8	2800	963
Ceramic coating (YSZ)	11.25	0.22	1.4	10	5650	640
Rings (cast-iron)	200	0.30	16	12	7200	460

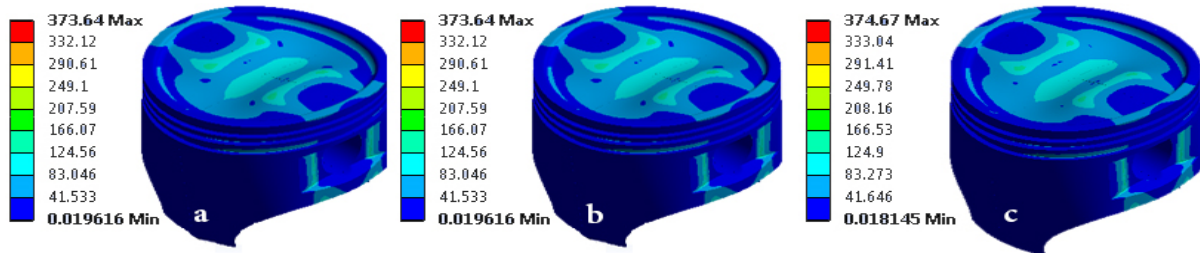


Fig. 3 Stress distribution of uncoated piston: (a) aluminum (b) cast iron (c) steel

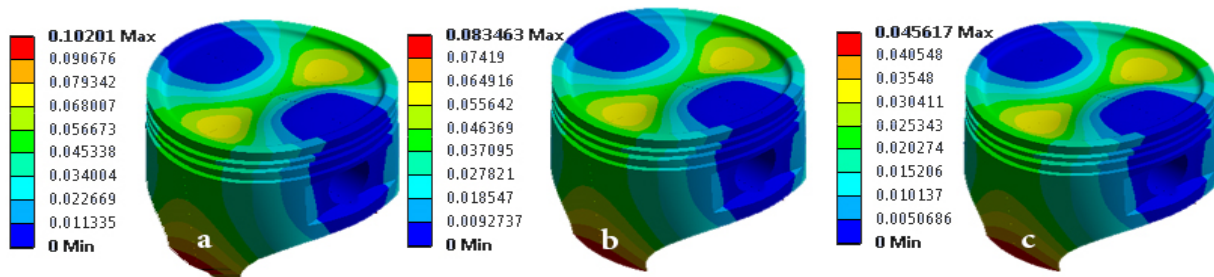


Fig. 4 Total deformation of uncoated piston: (a) aluminum, (b) cast iron (c) steel

III. RESULTS AND DISCUSSIONS

In this study, the evaluation of common materials which are used for manufacturing of the spark engine piston namely, aluminum, cast-iron and steel are listed and discussed. Mechanical stress on the piston without coating material is examined. After that, the coating material is added to the piston crown with several thickness using four different coating materials namely, (MgZrO₃, alumina, mullite and YSZ) in order to investigate the mechanical stresses for coated piston.

The results of von Mises distribution and total deformation on piston for three types of materials namely, aluminum, cast iron and steel are evaluated. Counter-plots of the stress distribution and deformation of aluminum, cast iron and steel for the uncoated pistons are shown in Figs. 3 and 4. It is found that the maximum stress distributions of the piston made of aluminum, cast iron and steel piston are 373.64 MPa, 373.64 MPa, and 374.67 MPa, respectively. Also, it is found that the deformation distributions of the piston made of aluminum; cast iron and steel piston are 0.10201 mm, 0.083463 mm, and 0.045617 mm, respectively as shown in piston contours.

A. Effect of Coating Materials on Aluminum Piston

Nowadays, various engineered coatings have been applied to improve durability. In this section, the effect of different coating materials namely MgZrO₃, alumina, mullite and YSZ with various coating thickness from 0.1 to 1.6 mm of the aluminum piston are examined. The simulation results of maximum equivalent Von Mises stresses and maximum deformations of the aluminum piston considering coated materials are plotted, as shown in Figs. 5 and 6. It is observed that the values of the maximum stresses are reduced by increasing the coating thickness for all coated materials. Also, it is found that the alumina coated material is reduced the stress and the deformation of the aluminum piston more than MgZrO₃, YSZ and mullite coated materials. Moreover, it is found that the YSZ coating material has less influence on stress and deformation of the aluminum piston.

B. Effect of Coating Materials on Cast Iron Piston

In this section, the effect of MgZrO₃, alumina, mullite and YSZ with various coating thickness from 0.1 to 1.6mm of the cast iron piston are examined. The simulation results of maximum equivalent Von Mises stresses and maximum

deformations of the cast iron piston considering coated materials are plotted, as shown in Figs. 7 and 8. It is observed that the values of the maximum stresses are reduced by increasing the coating thickness for all coated materials. Also, it is found that the alumina coated material is reduced the stress on the cast iron piston more than other coated materials. In additions, the alumina coated material is reduced the deformation of the cast iron piston more than MgZrO₃, YTZ, Mullite coated materials. Moreover, it is found that the YTZ coating material has less influence on stress and deformation of the cast iron piston.

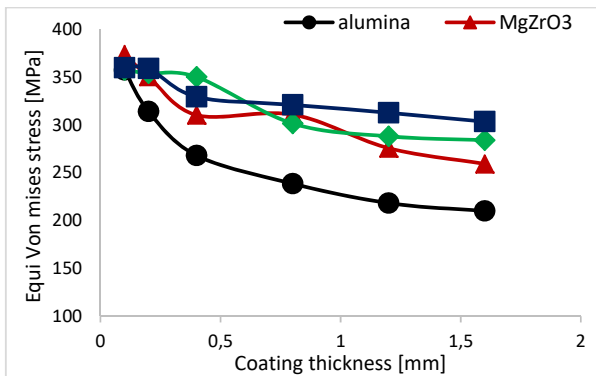


Fig. 5 Maximum von Mises stress of different coating for aluminum piston

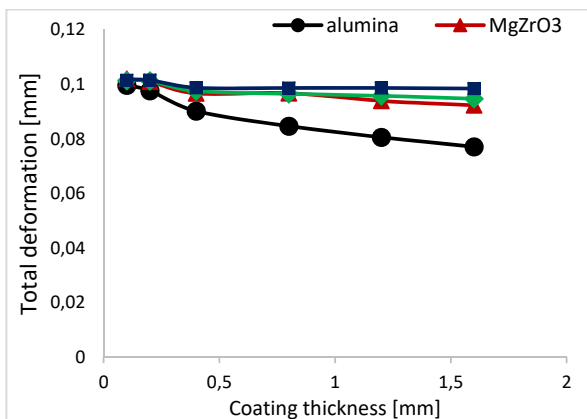


Fig. 6 Maximum deformation of different coating for aluminum piston

C. Effect of Coating Materials on Steel Piston

In this section, the effect of different coating materials namely MgZrO₃, alumina, mullite and YSZ with various coating thickness from 0.1 to 1.6 mm of the steel piston are examined. The simulation results of maximum equivalent von Mises stresses and maximum deformations of the steel piston considering different coating materials are plotted, as shown in Figs. 9 and 10. It is observed that the values of the maximum stresses are reduced by increasing the coating thickness for all coated materials. Also, it is found that the alumina coated material reduced the stress on the steel piston more than other coated materials. In additions, the alumina coated material

reduced the deformation of the steel piston more than MgZrO₃, YTZ, mullite coated materials. Moreover, it is found that the YTZ coating material has less influence on stress and deformation of the cast iron piston.

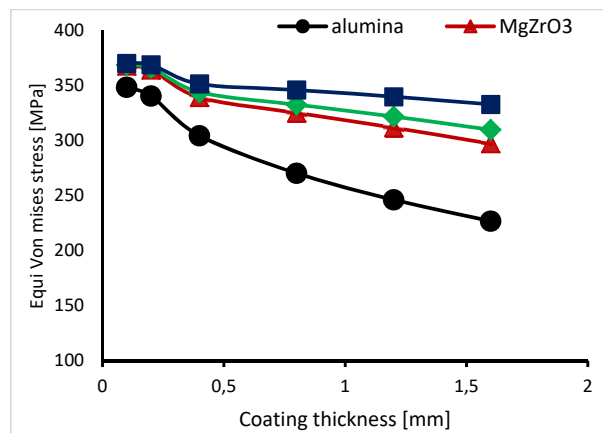


Fig. 7 Maximum von Mises stress of different coating for cast iron piston

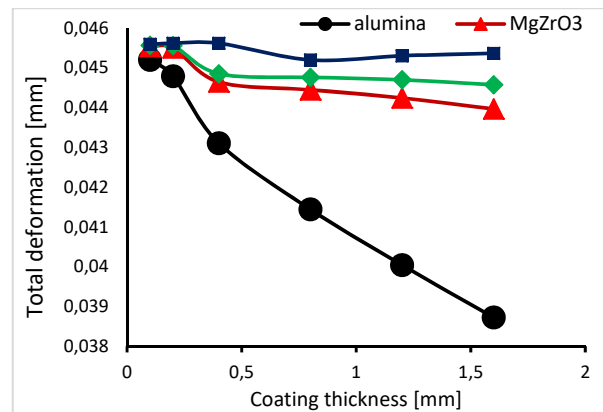


Fig. 8 Maximum deformation of different coating for cast iron piston

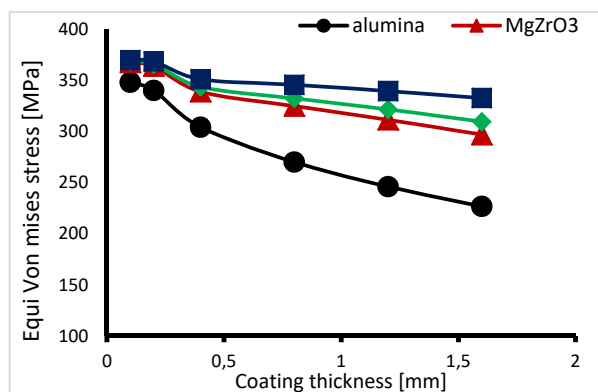


Fig. 9 Maximum von Mises stress of different coating for steel piston

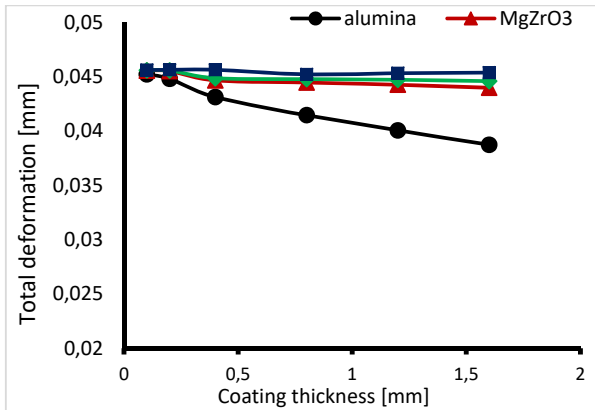


Fig. 10 Maximum deformation of different coating for steel piston

IV. CONCLUSION

Test runs are carried out for the piston of four-stroke gasoline engine. The simulation results of stresses are compared with the mechanical properties of the aluminum, steel and cast-iron alloy, it is observed that stresses values are lower than the allowable stress values of all materials. Also, it is clearly shown that the maximum deformations of the piston made of aluminum, cast iron and steel piston are 0.10201 mm, 0.083463 mm and 0.045617 mm, respectively. For all the coating thicknesses, it is observed that the values of the maximum stresses are reduced by increasing the coating thickness for all coated materials. Also, it is found that the alumina coated material is reduced the stress and deformations on the piston more than MgZrO₃, YTZ, mullite coated materials. Moreover, it is quite obvious that the YTZ coating material has less influence on stress and deformation of the cast iron piston.

REFERENCES

- [1] H. Shete, R. Pasale, and E. Eitawade, "Photoelastic Stress Analysis & Finite Element Analysis of an Internal Combustion Engine Piston."
- [2] C. V. Rajam, P. Murthy, M. M. Krishna, and G. P. Rao, "Design Analysis and Optimization of Piston using CATIA and ANSYS," International Journal of Innovative Research in Engineering & Science ISSN, pp. 2319-566, 2013.
- [3] G. AP and K. Patil, "Piston Design and Analysis by CAE Tools."
- [4] P. C. Mishra, Prakhardeep, S. Bhattacharya, P. Pandey "Finite Element Analysis for Coating Strength of a Piston Compression Ring in Contact with Cylinder Liner: A Tribodynamic Analysis" Tribology in Industry Vol. 37, No. 1 (2015) 42-54.
- [5] M. B. Shinde, T. Sakore, and V. Katkam, "Design Analysis of Piston for Four Stroke Single Cylinder Engine Using ANSYS," 2016.
- [6] A. Patil, "Analysis of Single Cylinder Diesel Engine Piston Using Finite Element Method," Imperial Journal of Interdisciplinary Research, vol. 2, no. 11, 2016.
- [7] M. Cerit, "Thermo mechanical analysis of a partially ceramic coated piston used in an SI engine," Surface and coatings Technology, vol. 205, no. 11, pp. 3499-3505, 2011.
- [8] G. Sivakumar and S. S. Kumar, "Investigation on effect of Ytria Stabilized Zirconia coated piston crown on performance and emission characteristics of a diesel engine," Alexandria engineering journal, vol. 53, no. 4, pp. 787-794, 2014.
- [9] M. Gamal Fouad, Nouby M. Ghazaly, Ali M. Abd-El-Tawwab and k. A. Abd El-Gwwad "Finite Element Thermal Analysis of A Ceramic Coated Si Engine Piston Considering Coating Thickness" American Journal of Engineering Research, 2017, Volume-6, Issue-2, pp-109-113.