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Finite Element Thermal Analysis of A Ceramic Coated Si Engine Piston Considering Coating Thickness

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ABSTRACT: *In this study, 3-D finite element thermal analysis on spark ignition engine piston is carried out for investigating thermal behavior of uncoated and coated piston using commercial software called Ansys. Thermal analysis is first applied to uncoated aluminum alloy piston. Then, the behavior of top coating for four thermal barrier coatings materials namely; Yttria-stabilized Zirconia, $MgZrO_3$, Alumina and Mullite are covered the piston substrate with different thickness. After that, Temperature distribution on the piston's top surface, bond and substrate surface for coating materials is investigated. Finally, the numerical results of different coating materials are compared with each other. It is observed that the temperature distribution was a function of coating thickness and high temperature appears at the center of the top surface of the uncoated piston. Also, it was clearly found that the temperature developed at the top surface of coated region is higher than that of the uncoated piston surface. It was observed that the substrate temperature is decreasing with increase the thickness of coating. It was shown that the maximum surface temperature of Yttria-stabilized Zirconia, $MgZrO_3$, Alumina and Mullite coating is increases by 117.47%, 144.76 %, 15.014 and 44.86 % respectively for 1.6 mm thick coating.*

Keywords: *spark ignition engine piston; Thermal analysis; Thermal Barrier Coatings.*

I. INTRODUCTION

The input energy of an internal combustion engine has divided in to three parts: energy loss through coolant system, energy which is utilized for useful work and energy lost through exhaust system and only 1/3 of the total energy is converted to work. Thus, the efficiency and overall performance of internal combustion engine can be increased by utilizing these heats lose into the useful work. To minimize heat transfer and improve the performance of an internal combustion engine technology of insulating the piston, cylinder head, combustion chamber, and valve's surfaces with thermal barrier coating materials has been introduced (Gehlot and Tripathi, 2016).

In an automobile industry piston is found to be most important part of the engine which is subjected to high mechanical and thermal stresses. Due to very large temperature difference between the piston crown and cooling galleries induces much thermal stresses in the piston. Besides the gas pressure, piston acceleration and piston skirt side force can develop cycle of mechanical stresses which are superimposed on the thermal stresses. Due to this reason, thermo- mechanical stresses are one of the main causes of the failure of the piston.

The role of Thermal Barrier Coatings (TBCs) in protecting high temperature alloy substrate, reducing the working temperature and increasing working efficiency of high temperature component is becoming vital. So, they are currently being used for various engine applications in aerospace, aircraft, marine automobiles, nuclear fusion reactors and heavy-duty utilities. The TBCs have been successfully applied to the internal combustion engine, in particular the combustion chamber, to simulate adiabatic engines. The objectives are not only reduced in- cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also possible reduction of engine emissions.(Prasad and Samria, 1990; Hejwowski and Weroński, 2002) A one another reason of using TBC is the continuous increase in fuel prices and reduction in supply of high quality fuel(Hejwowski and Weroński, 2002). Hejwowski and Weronski (Hejwowski and Weroński, 2002) used thermal barrier coating to determine the performance of diesel engine piston. From the results of this analysis, it was found that ceramic coating does not produce knock in the engine and protects the piston skirt and cylinder liners from wear. Vedharaj et al.(Vedharaj et al,2014) investigated the performance of coated and uncoated piston engine operated with cashew nut shell liquid. Experimental results showed 6% higher brake thermal efficiency with coated piston compared to uncoated piston.

From a literature review, it is observed that although there are some research papers dealt with experimental thermal barrier coatings in the internal combustion engines, there are a few numerical studies focused on 3-D thermal analyses on spark ignition piston model. This paper deals with the steady state thermal analysis of aluminum alloy piston crown coated with different ceramic coatings namely; Yttria-stabilized Zirconia, $MgZrO_3$, Alumina and Mullite. Temperature distribution on the piston's top surface for uncoated case is investigated using finite element based software called Ansys. Also, the temperature distribution on top coating, bond coat and substrate surface of the piston with various thicknesses ranged from 0.1mm to 1.6 mm for each ceramic coating material is examined. Comparison between the coatings materials and uncoated piston temperature are reported.

Piston and Coating Materials Properties

The most important problem with the coated system is the thermal stresses which occur during operation because of the considerable mismatch between the thermal expansions coefficients of the metal substrate and the ceramic coating. TBCs are preferred because of their low conductivity and their relatively high coefficients of thermal expansion (Cerit and Coban, 2014). In this study, 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 Figure 1. Material properties of the piston made of aluminum alloy and the selected TBC s materials namely; Yttria-stabilized Zirconia, $MgZrO_3$, Alumina and Mullite are listed in Table 1. Magnesia-stabilized zirconia ($MgZrO_3$) coating is used as TBC s owing to its good thermal insulating properties and thermal stability at cryogenic and high temperature applications (Kamo and Bryzik 1978; Dickey et al. 1988; Hejwowski and Weroński, 2002).

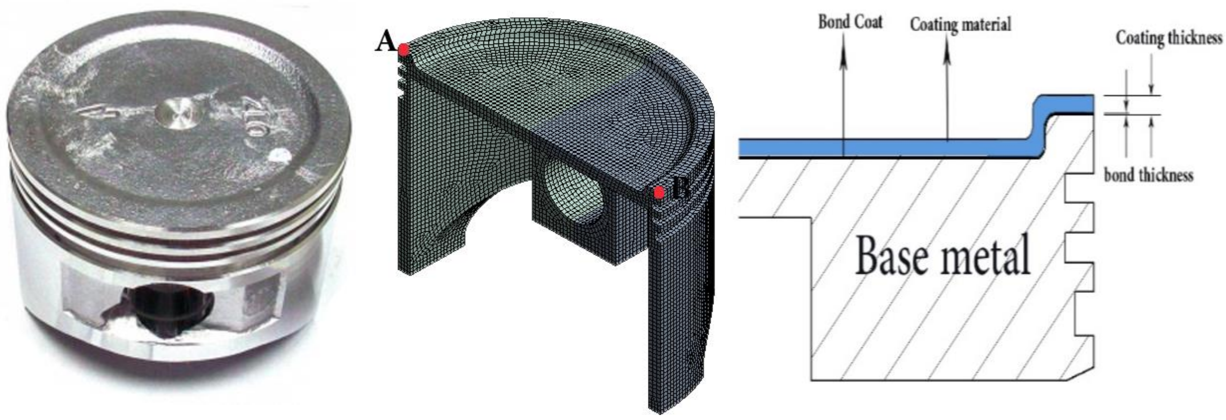

Fig 1 : The model used in the FE analyses: photograph of the partially coated piston, and the half part of the model and the parameters.

Table 1: Materials properties of the piston, bond coat and ceramic top coat (Prasad and Samria ,1990; Cao ,2004; Cerit, 2011).

Material	Modulus of elasticity [GPa]	Poisson's ratio [m/m]	Thermal conductivity [W/m °C]	Thermal expansion 10^{-6} [1/ °C]	Density [kg/m3]	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)	-	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

Finite Element Thermal Analysis

The temperature distributions with and without TBCs are investigated with numerical simulation models using ANSYS software for petrol engine piston made up of aluminum alloy. Ansys provide accurate results of analysis by dividing geometry into smaller elements.

First of all, modeling of SI engine piston for Honda GX390 Four Stroke Single cylinder with 88 mm bore and 64 mm stroke length is designed. The engine is rated 13 hpat3600 rev/min and then, material properties of the SI piston are defined. Finite element mesh is generated using 93,307 quadratic hexahedron elements and 362,289 nodes. The heat transfer analysis is checked for convergence. The meshing of piston is shown in figure 2.

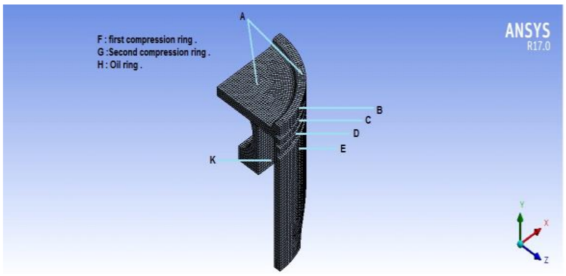

Fig 2: The meshing of piston and the thermal boundary condition of the piston used in the FE Analysis.

The FE model includes the piston and coating parts as continuous structures and a three-layer FE mesh is employed for thermal-mechanical coupled calculations. Table 2 lists all convection coefficients and the thermal boundary conditions applied in the FE simulations.(Muchai et al., 2001; Cerit et al. ,2011) In the thermal analysis for model in ANSYS, the convection boundary condition, as the surface load is inflicted on the outside surface. The upper part of the piston is having very high temperature because of direct contact with the gas. So, a temperature of 650 degrees is provided to the upper surface of the piston. The thermal boundary conditions consist of applying a convection heat transfer coefficient and the bulk temperature, and they are applied to the piston crown, land sides, piston skirt shown in Fig. 3. While running in structural and thermal analysis, some assumptions are made. The effect of piston motion on the heat transfer is neglected, the rings and skirt assumed as fully engulfed in oil, there are no cavitation, the rings are not twist, and the conductive heat transfer in the oil film is neglected. (COLAÇO and ORLANDE ,1996; Esfahanianet al., 2006)

Table 2: convection coefficients and the thermal boundary conditions applied in the FE simulations**.**

Region	[W/m^2 ^{o}C]Heat transfer coefficient	Temperature [^{o}C]
A	600	650
B	350	500
C	300	180
D	400	170
E	400	110
F	-	200
G	-	180
H	-	170
K	1500	95

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II. RESULT AND DISCUSSION

1-Temperature distribution for uncoating piston.

The result obtained from the thermal stress analysis by finite element technique, the temperature and thermal variation for uncoated piston is shown in fig. 3. The maximum temperature 221.26 ^{o}C is at the Center of the piston and at the edge and the minimum temperature 104.46 ^{o}C as shown in piston contours.

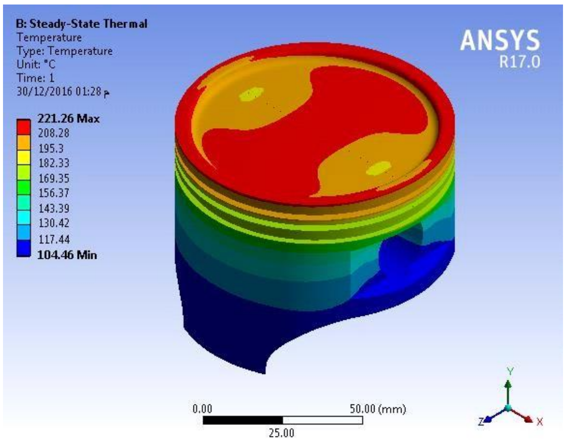

Fig 3: Temperature (°C) contours on the uncoated piston SI engine.

2-Temperature distribution for coating piston

With the same boundary conditions, thermal analysis of piston of the four TBC materials: Yttria stabilized Zirconia, $MgZrO_3$, Alumina and Mullite coating with different thickness is carried out. TBC materials have low heat transfer coefficients; therefore, high temperature can be kept at piston's top surface. The piston's top surface temperature of the uncoated piston with air cooling is found to improve approximately 15% via ceramic-coated piston. The simulation results obtained from the analysis that because of the low thermal conductivity of ceramic material compared to piston material the coated piston has higher temperature than uncoated piston. From the above analysis, it is observed that the piston's top surface temperature is increasing and the substrate surface temperature decreasing as the thickness of coatings increases. Fig. 4 shows the temperature distribution on the substrate surface of coated piston with various thicknesses.

Temperature distribution for $MgZro_3$ coating

The coating material is stabilized magnesia-zirconia which has flexural strength of 520 MPa and compressive strength of 1450 MPa. The thickness of the ceramic top coating has been changed from 0.4 mm to 1.6 mm with a 0.4 mm increment.

For the substrate surface, only the value changes and graphs remain the same. The maximum substrate surface temperature values corresponding to the 0.4 mm0.8 mm, 1.2 mm and 1.6 mm thickness are 209.42 °C, 207.96 °C ,207.09 °C and 206.4°C. Compare to the uncoated piston temperature of the substrate surface is decreased by 5.37%, 6.036 %, 6.429 % and 6.74% respectively.

Substrate surface temperature distribution with coating along the radial distance is shown in Fig.4. Maximum temperature occurs at the piston's edge and minimum temperature is at the bottom of the piston. top surface temperature distribution with coating along the radial distances shown in fig 5 and the maximum top surface temperature values corresponding to the 0.4 mm0.8 mm, 1.2 mm and 1.6 mm thickness are 397.47 °C 470.54 °C, 518.78 °C and 541.57 °C.

Fig 5 shows Maximum temperature distribution as a function of coating thickness and we noticed that the maximum top surface temp is increased as a function of coating thickness and the bond and substrate temperature is decreased as a function of coating thickness.

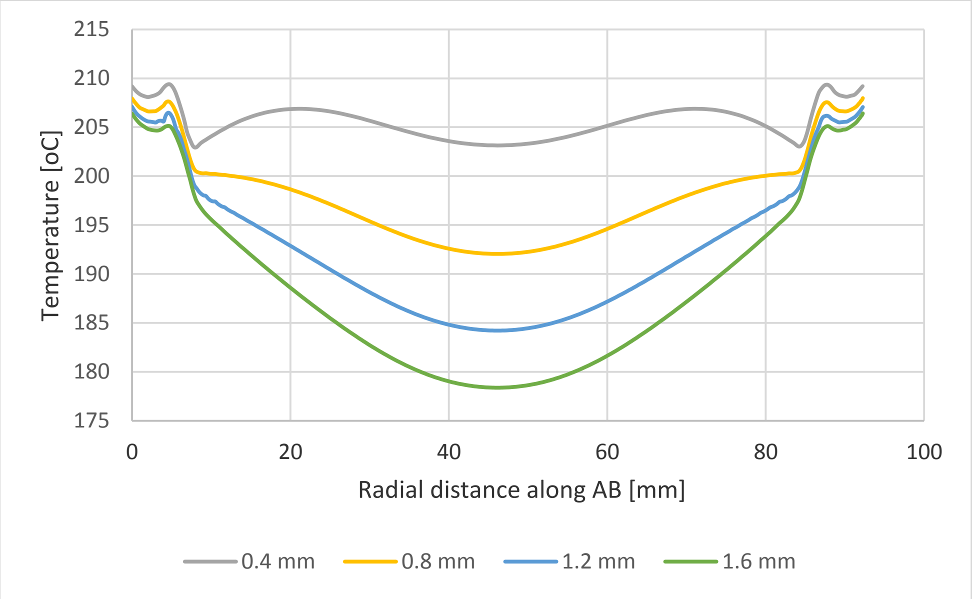

Fig 4: Substrate surface temperature distribution with coating along the radial distance.

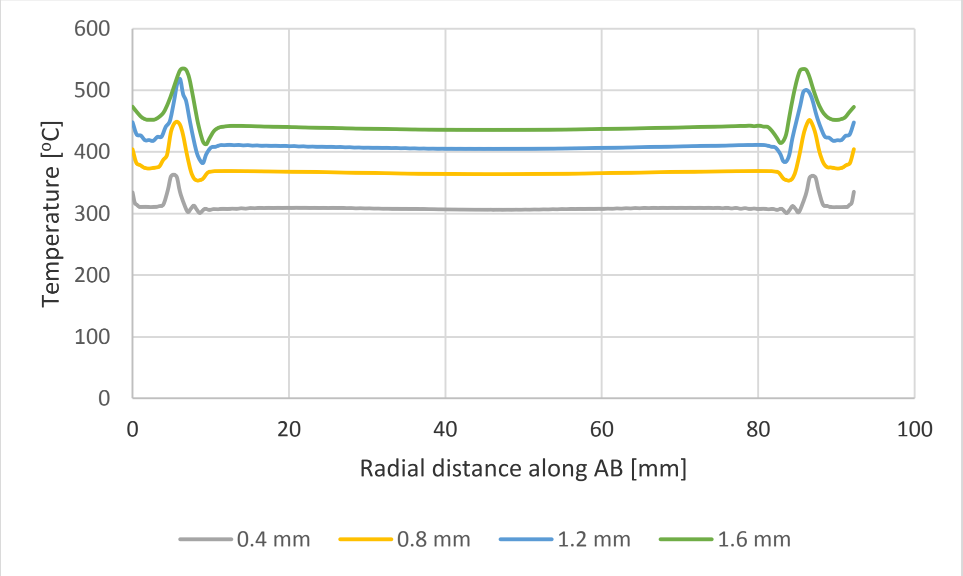

Fig 5: Top surface temperature distribution with coating along the radial distance.

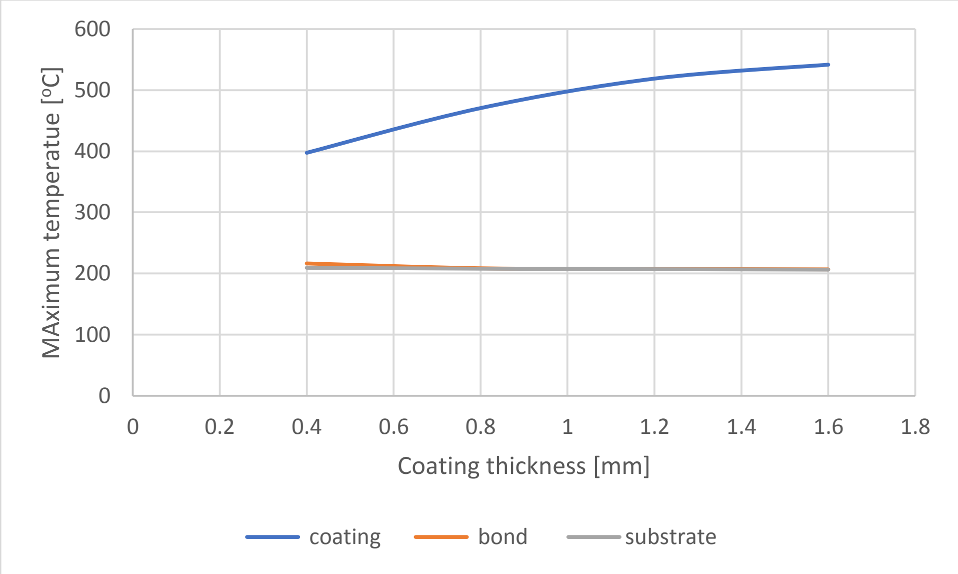

Fig 6: Maximum temperature distribution as a function of coating thickness.

Comparison between material coating

The efficiency of most commercially available engines can be improved by coating the piston crown with an insulating material. The main requirements of the thermal barrier coating materials include low thermal conductivity, resistance to corrosive and erosive environments, co-efficient of thermal expansion high enough to be compatible with metal and thermal shock resistance. Various TBC materials and its characteristics are given in Table 3.

Table 3: TBC materials and their characteristics (Shrirao et al., 2011).

Materials	Advantage	Disadvantage
YSZ	1- High thermal expansion co-efficient 10 · 10^{-6} °C 2- Low thermal conductivity 2W m^{-1} K^{-1} °C 3- High melting point 2800	1- Sintering above 1473 K K 2- Phase transformation 1443
Mullite	1-High corrosion resistant 2- Low thermal conductivity 3- Not oxygen transparent	1-Crystalization (1023–1273 K) 2- Very low thermal expansion-coefficient
$MgZrO_3$	1. Low thermal conductivity 2W m^{-1} K^{-1} 2. High fracture toughness 3. High Young's Modulus	1. Low Melting point 1600 C 2. Very low thermal expansion-coefficient
Alumina	1. High corrosion resistance 2. High hardness value 3. Not oxygen transparent	1. Phase transformation (1273 K) 2. High thermal conductivity 3. Very low thermal expansion-coefficient

With the same boundary conditions, thermal analysis of piston of the four TBC materials: Yttria stabilized Zirconia, $MgZrO_3$, Alumina and Mullite coating with different thickness is carried out

Fig.7 shows Maximum temp distribution at top coating surface as function of coating material in various coating thickness and we noticed that all of the curves is parallel but $MgZrO_3$ achieve high temperature at top surface then YTZ, mullite and alumina. Fig 8. Shows Maximum temp distribution at substrate surface as function of coating material in various coating thickness and we noticed that all of the curves is parallel but $MgZrO_3$ achieve low temperature at substrate surface then YTZ, mullite and alumina.

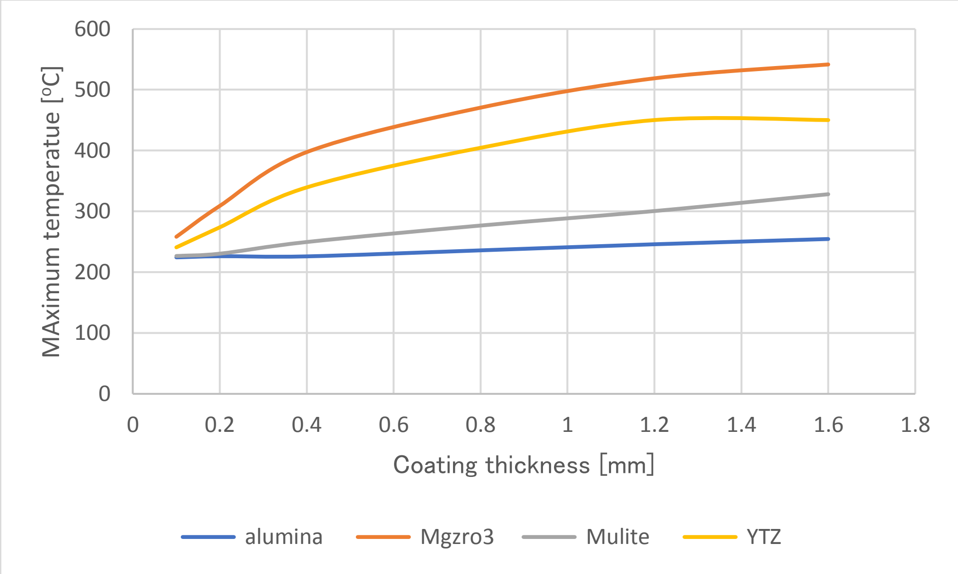

Fig7: Maximum temp distribution at top coating surface as function of coating material.

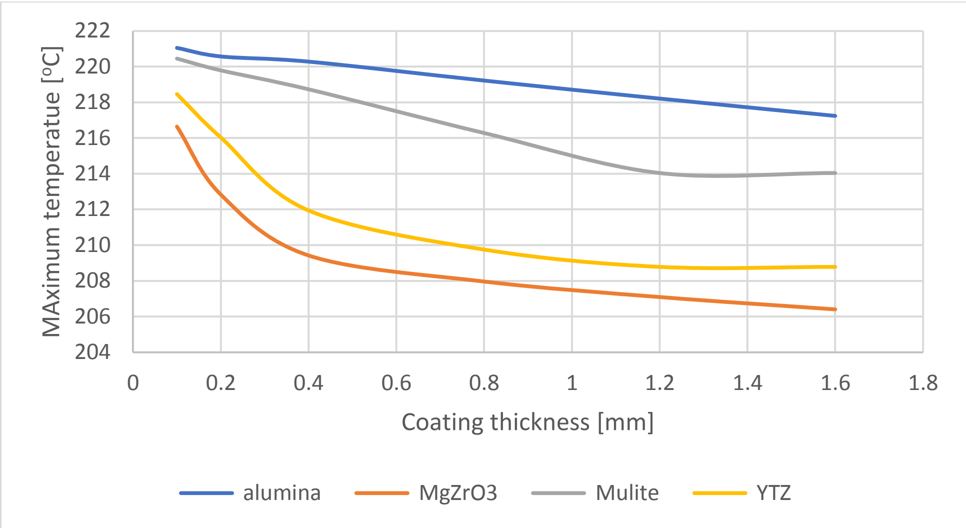

Fig 8: Maximum temp distribution at substrate surface as function of coating material.

III. CONCLUSION

The objective of the study was to predict the effect of four TBC on the thermal behavior of aluminum alloy piston using FE modeling and simulation. According to results of FE numerical simulations, it is concluded that coated piston has a significantly higher temperature than uncoated piston Because of the low thermal conductivity of ceramic material compared to piston material. The maximum temperature for top coating surface and substrate surface occurs at the center of the piston and at the piston's edge. The corresponding top surface maximum temperature for the uncoated, coated piston with YSZ, $MgZrO_3$, Alumina and Mullite for 1.6 mm coating is 221.32°C, 450.13°C, 541.57°C, 254.48°C and 328.15°C respectively. On the other hand, substrate temperature of coated piston is lower than uncoated piston. The substrate surface temperature for the coated piston with YSZ, $MgZrO_3$, Alumina and Mullite is 208.78°C, 206.4°C, 217.24°C and 214.04°C respectively. From the above analysis, it is observed that the piston's top surface temperature is increasing and the substrate surface temperature decreasing as the coating thickness increases. From the investigation of simulation results, it is noted that such a coating process is worth to investigate experimentally and may yield a significant improvement for wear and fatigue performance.

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