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Effect of Ceramic Coatings on Thermal and Mechanical Properties of AA 2024 Aluminium Alloy Piston

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ABSTRACT

Pistons used in the cylinders of modern automobiles are made of Aluminium alloys due to their light weight and reasonable mechanical strength. But the effective heat energy generated in cylinder gets conducted and results in lower network content. Hence, in the current investigation, ceramic coatings of various thicknesses are imparted on the crown of the piston and the property evaluation is carried out. It is evident from the experimental results that the temperature gradient and distribution are different in coated and uncoated pistons and thermal efficiency has increased with coating thickness. The scope of the research further includes finite element analysis of the piston to evaluate and compare the deformation and stress patterns of uncoated and coated scenarios.

Keywords: Crown, Coating, Aluminium alloy, thermal efficiency, deformation

I. INTRODUCTION

Piston is the main component in an internal combustion engine where the chemical energy is converted into mechanical work and acts as a seal between combustion chamber and crank case. Pistons are commonly categorized by their cooling arrangement, field of application and by their structure. Typical piston materials include Cast Iron, Aluminium alloys, Forged steel etc and the selection of material is done based on the application to fulfill the requirements such as low density, high strength, high heat conductivity, good wear resisting characteristics.

In IC engines, coatings and surface treatments are commonly applied on one or several components of the piston, piston ring and cylinder liner. The coatings on the pistons improve the properties namely sliding characteristics, wear resistance, thermal properties and knock resistance. Plasma Spraying, high velocity oxy-fuel coating, chemical vapour deposition, electro plating etc [1] are mainly applied on piston rings to improve wear resistance. Molybdenum coating is employed for preventing hot gas erosion deterioration of the piston ring face surfaces [2]. For tribology applications, Titanium Coating on Aluminium substrates have given wide improvement of properties [3]. Wear and scuffing resistance of Aluminium pistons in Aluminium cylinder liner is obtained by Ni-W coating of piston skirt [4]. To enhance the air swirl and engine performance with reduced emissions, piston crown geometry can be altered [5]. The intensification of swirl is studied by number of grooves on the crown of the piston [6]. The effects of heights and shapes of squish areas and crown outside of it are investigated at different loads for recording combustion performance [7]. Effect of partially thermal barrier coating on piston temperature distribution and cold start HC emissions of a spark ignition engine are investigated numerically and experimentally and it was found that HC emissions considerably decreased compared to the standard engine without any degradation in engine performance [8].

Thermal Barrier Coatings (TBC) can reduce the heat rejection rate in engine cylinders so that the heat transfer to the cooling jacket and exhaust system is reduced to a great extent contributing to the mechanical efficiency [9]. Effects of the coating thickness on temperature and thermal stress distributions of the piston and rings are investigated and the results are compared to that of the uncoated piston by means of the finite element analysis. It was found that temperature at the coated surface is significantly higher than that of the uncoated piston [10]. In the current investigation, 4-stroke single cylinder petrol engine piston is chosen for thermal and mechanical property evaluation with ceramic coating.

II. METHODS AND MATERIAL

2.1 Piston Material: A 4 stroke single cylinder 100 cc stationary petrol engine is chosen for experimentation. The engine has dome type Aluminium alloy Al 2024 piston with 50 mm diameter. Aluminium alloys are used as piston materials owing to their light weight and lower coefficient of expansion. The current research includes thermal analysis using experimental investigation. The scope also includes thermal and stress analysis of the piston using finite element method.

2.2 Coating: The piston crown is coated with Yitria stabilized Zirconia (YSZ), a ceramic material with the thicknesses of 0.2 and 0.4 mm. Thermal spraying technique is used for the coating of chosen ceramic on the piston. Zirconia oxide is one of the ceramics doped by Yitrium Oxide to stabilize its crystal structure. Fig (1) shows the uncoated and YSZ coated pistons.

Figure 1. Uncoated and Coated piston

2.3 Muffle furnace: The pistons are tested for their heat transfer from the top of the crown to the other side employing a muffle furnace with a provision for a thermocouple for measuring temperature.

III. Experiments Carried out

3.1 Simulated Experiments

The pistons are now exposed to constant steady state heat by placing in the muffle furnace in order to find out the temperature on the skirt portion. Care is taken with insulator for preventing the transfer of heat in other areas of piston. Table 1 shows the temperature distribution for all the pistons. It is found that the temperature distribution pattern is such that the heat loss/conducted through piston is minimal in coated pistons and reduced with the increase of thickness of coating.

Table 1 Temperature Distribution

Temperature Applied (^oC)	Temperature Measured (^0C)		
	Uncoated (^oC)	Al Alloy Piston with 0.2mm YSZ (^oC)	Al Alloy Piston with 0.4mm YSZ (^oC)
100	45	38	25
200	50	46	45
300	90	85	82
400	174	152	142
500	272	245	201

3.2 Test runs

Three pistons are taken for experimentation in the engine and the mechanical efficiency is computed at constant load and speed. Table 2 shows the efficiency of the pistons employed in the experimentation.

Table 2 Mechanical Efficiency

Piston Coating Thickness(mm)	Speed (rpm)	Load(N)	Mechanical Efficiency (%)
0.0(Uncoated)	2500	20	30.0
0.2	2500	20	32.2
0.4	2500	20	33.4

It is found that the mechanical efficiency increases with the increase of thickness of coating on the piston. It shows that the heat loss through the piston is reduced and the results are in line with the simulated results.

3.3 FEM Analysis of the Piston

The three dimensional solid model of the piston using the part modelling of Solidworks is taken for further analysis.. Coating layer is designed such that it is an imported assembly feature on the crown of the piston. The geometry is then imported to ANSYS after meshing with eight noded brick elements (Fig 2). The static structural and steady state thermal analysis are conducted with the boundary condition of 8 MPa and heat flux of 4.5 W/mm2 [11] on the crown of the piston. The deformation (Fig 3) and equivalent Von-Mises stress pattern for the uncoated and coated pistons are evaluated (Fig 4). Also, the temperature distribution from the crown to the skirt of the piston are also evaluated (Table 4).

Table 3 Maximum Deformation and Stress

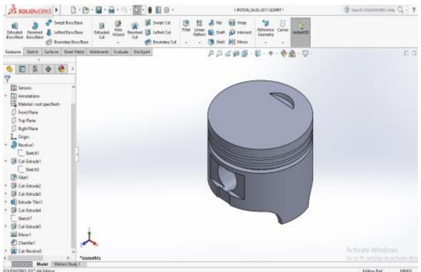
Coating Thickness (mm)	Deformation (mm)	Von-Mises Stress (MPa)
0	0.079	235
0.2	0.074	230
0.4	0.069	227

Table 4 Temperature Distribution

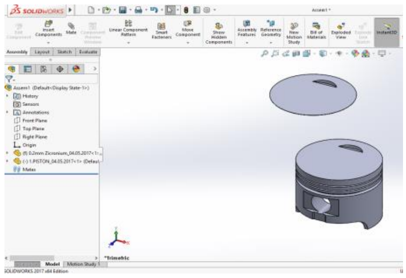
Coating Thickness (mm)	Max Temp (^{o}C)	Min Temp (^{o}C)
0	225.19	44
0.2	253.45	47
0.4	285.36	22

It is found that the deformation and equivalent stress are reduced with the increase of coating thickness. It can be attributed to the strength addition with the coatings. Similarly, the temperatures on the crown of the piston is maximum with the coatings and minimum temperature zone has increased indicates that the heat transfer through it is reduced and will be utilized in augmenting work content and thereby improvement in mechanical efficiency.

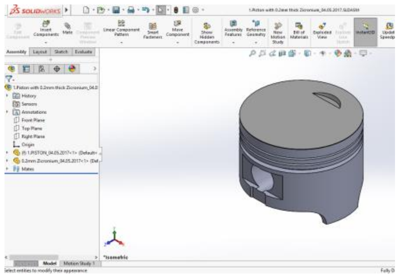
Figure 2. Solid Models



2.1 Solidworks Model of Piston

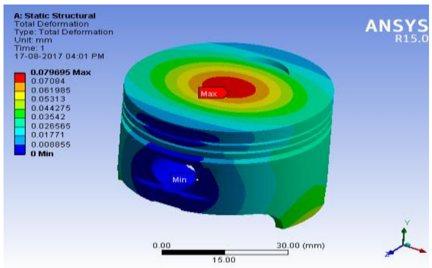


2.2 Model with layer of coating

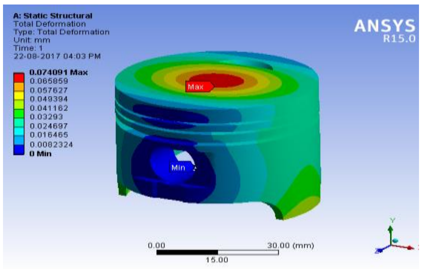


2.3 Final assembly with coating

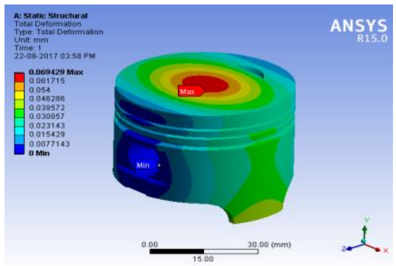
Figure 3. Total Deformation contours in ANSYS



3.1 Al Alloy Piston - Uncoated

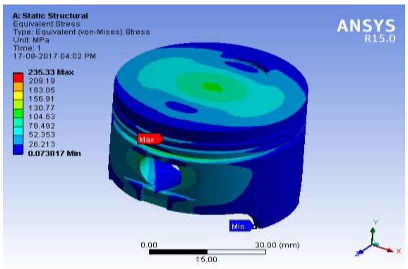


3.2 Al Alloy Piston-YSZ 0.2 mm thick

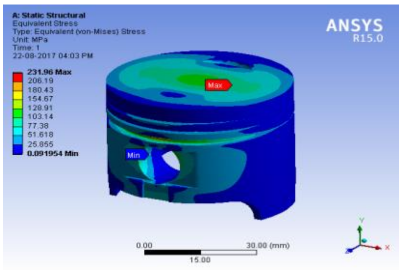


3.3 Al Alloy Piston-YSZ 0.4 mm thick

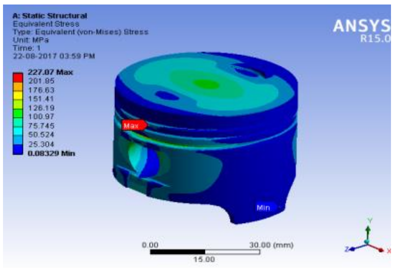
Figure 4. Equivalent (Von-Mises) Stress contours in ANSYS



4.1 Al Alloy Piston - Uncoated



4.2 Al Alloy Piston-YSZ 0.2 mm thick



4.3 Al Alloy Piston-YSZ 0.4 mm thick

IV. Discussion of Results

The piston is insulated on the exterior surface excluding the crown and the heat transfer took place from crown to skirt of the piston in one dimension mode only. It is found that the temperature is low with coated pistons indicated that ceramic coating has inhibited the heat transfer and there by net heat can be availed for improving thermal efficiency. The improvement in mechanical efficiency can be attributed to lower loss of heat through piston. The reduction in deformation and effective stress on piston in the static analysis is due to the additional strength addition by the coating. The thermal analysis results by ANSYS model and simulated experiment are in tandem with each other.

V. Conclusions

The coating of YSZ ceramic on the crown of piston has reduced the heat loss through it and subsequently increased the mechanical efficiency of the engine. The coating also improved the mechanical properties of the piston and helped in reducing the deformation.

VI.Acknowledgement

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