Investigation of Surface Coated Engine Piston Using Finite Element Method

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Abstract

In automobile industry reliability is one of the major factors which decide the success in budding competition. Thus industry is in continuous race for developing new ways to make its components reliable with enhanced life. One such way under investigation is surface coatings. Engine is the main part of any automobile is made of different components. Piston is one of the major components of engine which need to be investigated with surface coating technology. Computer aided engineering has extended ways to evaluate the performance of components by simulating working conditions. In present study engine piston is analysed with five different coatings on ANSYS software package. 3D model of coated piston was developed with bond coat of 100 microns and three coating thickness of 250 microns, 350 microns and 450 microns. Analysis was performed to evaluate temperature fall, heat flux and stress values. Results were compared obtained from uncoated piston and different coating piston to prepare comparative database. Results revealed that surface coating has good potential for lowering thermal softening and reducing stress and strain. $CaZrO_3$ and $MgZrO_3$ coatings at 450 microns are best suitable for engine piston.

Keywords: Surface coating, FEM, Engine piston, computer aided engineering, Thermal Stress, thermal barrier coating

1. Introduction

Reliability has become important factor for the automobile companies these days. Budding competition has led automobile sectors to develop powerful, cost-effective and reliable vehicles. Engines are the heart of vehicle. It converts chemical energy into mechanical energy and act as prime mover. Thus reliability of engine is an important factor. To make engine reliable we need to make its components reliable. One such major component is engine piston. It converts the gas pressure into mechanical energy. Piston has to undergo very harsh working conditions. 90% of engine failures are recorded due to piston failure. So a piston needs to be developed for more service life. Thus one of the technologies which can provide solution to the requirement is surface coating. In recent years, the finite element method (FEM) has particularly become the main tool for simulating the performance of coatings in diverse situation. Thus performance of automobile components needs to be evaluated with surface coating technology for making them more reliable one such component evaluated in current project is Engine piston.

2. Piston

Piston is may be considered as one of the most important mechanical component of reciprocating engine. It was invented by German scientist Nicholas August Otto in year 1866. Piston is made gas –tight in the engine bore using piston rings. Purpose of piston to compress the engine gases and transfer the impulse force produced during combustion of gases to crankshaft. Figure 1 shows descriptive view of piston.

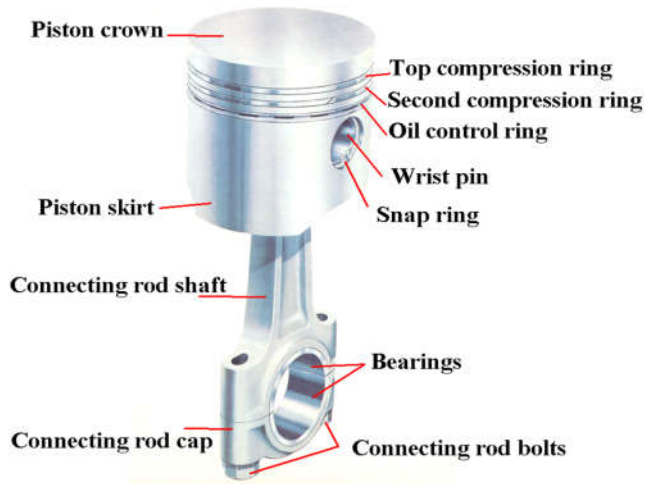


Figure 1 Descriptive image of Engine Piston

2.1 Major forces acting on engine piston

Engine piston has to work in very harsh conditions of high temperature and pressure. Piston has to bear following forces:-

1. Impulse forces due to combustion of gases.
2. Erosive forces due to burnt gas particles.
3. Compressive forces in compression stroke.
4. Friction and side wall forces.
5. Thermal stress cycle.
6. Inertial forces due to high speed reciprocation of engine piston.

Engine piston fails mainly due to mechanical fatigue and thermal fatigue. Various type of engine piston failure is as follows:-

1. **Ash deposition**: This type of failure occurs when engine working temperature becomes too hot and piston crown metal which comes into direct contact with combustion gases melts and forms tiny flakes. (Fig. 2 (a))
2. **Erosive wear**: This type of wear occurs due to erosive action of combustion particles. Further these eroded particles get crushed between piston and combustion chamber walls causing more damage to piston crown. (Fig. 2 (b))
3. **Chipped failure:** This type of failures occurs when during thermal expansion and contraction cycle some coolant is drawn in combustion chamber leading to sudden cooling, which causes brittle chipping of piston. (Fig. 2 (c))
4. **Shattered failure:** This type of failure occur when due to thermal expansion and contraction cycle clearance between piston and cylinder becomes too large, due to

which piston rattles inside cylinder leading to facture and cracking after certain time. (Fig. 2 (d))

5. **Seizure failure:** This type of failure occurs when piston become too hot and expands which causes rubbing between cylinder walls and piston skirt, leading to seizure of piston at a point or multipoint seizure. (Fig. 2 (e))
6. **Deposition on skirt**: This failure happens when combustion gases escapes combustion chamber due to which carbon gets deposited on piston skirt. (Fig. 2 (f))

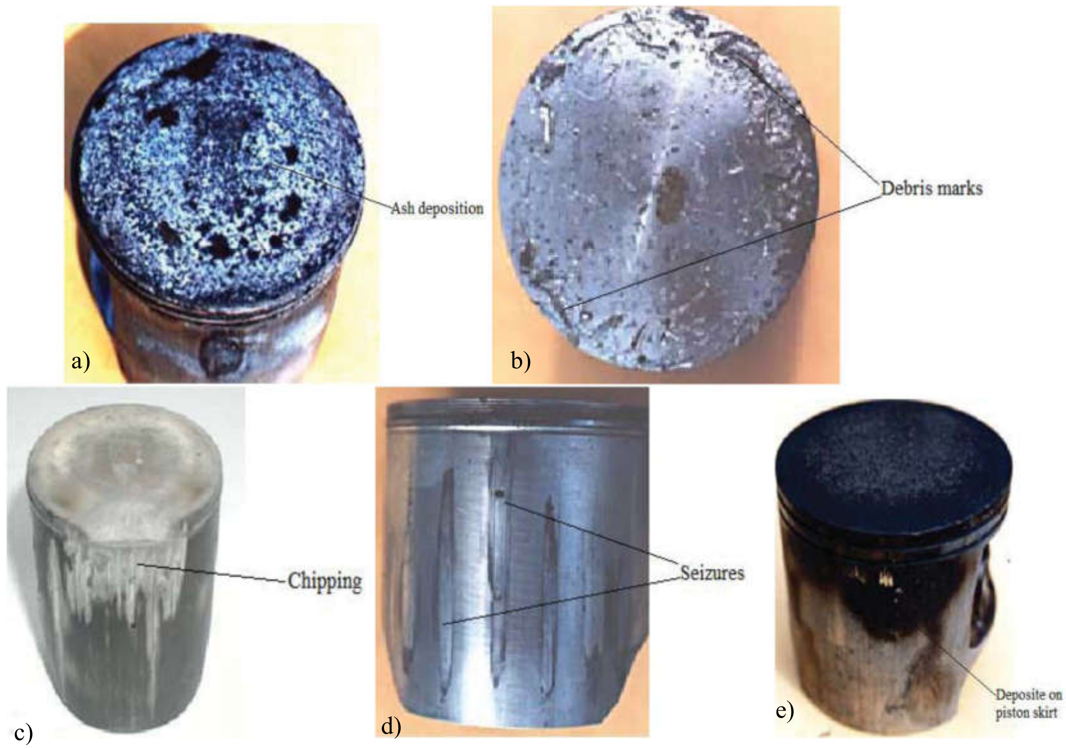


Figure 2 Various type of engine piston failure Engine valve modelling

Major reason for engine piston failure is reported as combination of mechanical and thermal fatigue. Thus for extending piston life we need to develop technologies providing high temperature resistance with adequate strength. One such technology is Surface coatings. Thermal barriers coatings (TBC) has provided better results in similar working conditions. Thus surface coating technology needs to be evaluated in depth involving various factors to enhance life and reliability of engine piston.

3. Surface Coatings

A coating is defined as layer of material having better surface properties than the substrate. Purpose of Coating may be decorative, functional, or both. One of the purposes of the coating is to provide thermal barrier to the material operating at elevated temperatures. These coatings serve to insulate components from large and prolonged heat and limiting the thermal exposure of structural components, extending part life by reducing oxidation and thermal fatigue in conjunction with active film cooling.

Such coatings need to be evaluated in detail in regards to different coating material, thickness of coating and applicability of bond coat. Computer aided engineering offers evaluation of surface coatings under working conditions.

3.1Coating Selection

Coatings used in the current study were selected on the basis of literature survey. List of coatings and their mechanical and thermal properties are given in table 1.

Table 1. Thermal and mechanical properties of different coatings

Property	**Units**	**NiCrAl**	**$MgZrO_3$**	**$CaZrO_3$**	**SiC**	**Mullite ($3Al_2O_32SiO_2$)**	**ZrO_2+ Y_2O_3**
Density	Kg/m^3	7870	5600	5110	3210	2800	5560
Coefficient of thermal Expansion	C^{-1} Reference temperature 250C	1.20E-05	8.00E-06	3.20E-06	5.12E-06	5.50E-06	1.09E-05
Young's modulus	MPa	90000	46000	1.00E+05	4.76E+05	1.51E+05	11250
Poisson's ratio		0.27	0.2	0.2	0.19	0.2	0.3
Bulk Modulus	Pa	6.52E+10	2.56E+10	5.56E+10	2.56E+11	8.39E+10	9.38E+09
Shear Modulus	Pa	3.54E+10	1.92E+10	4.17E+10	2.00E+11	6.29E+10	4.33E+09
Thermal Conductivity	$Wm^{-1}C^{-1}$	1.61E+01	8.00E-01	6.00E-01	5.00E+00	6.00E+00	1.40E+00

4. Analysis

Combination of Thermal –mechanical analysis was performed on the Engine piston. Following steps were performed**:**

1. Selection of Analysis system: Steady state thermal and static structural analysis was coupled to perform thermo-mechanical analysis. Shown in fig.3.
2. Engineering data: thermal and mechanical properties were defined to the software. Properties of piston material are listed in table 2 and coating properties are listed in table 1.
3. Geometry creation: 3D solid model of uncoated and coated engine piston was created as shown in fig. 4.
4. Mesh generation: Engine piston model was meshed into small elements to perform FEM analysis. Shown in fig. 5.
5. Setup: Boundary conditions were applied Temperature of 700°C and 0.0002 W/mm^2 for thermal analysis and pressure of 0.6 MPa was applied for structural analysis shown fig. 6.
6. Solution: Engine piston was analyzed for temperature distribution, heat flux and stress. Plots for uncoated and $MgZrO_3$ Coatings are shown in fig. 7 and fig. 8.

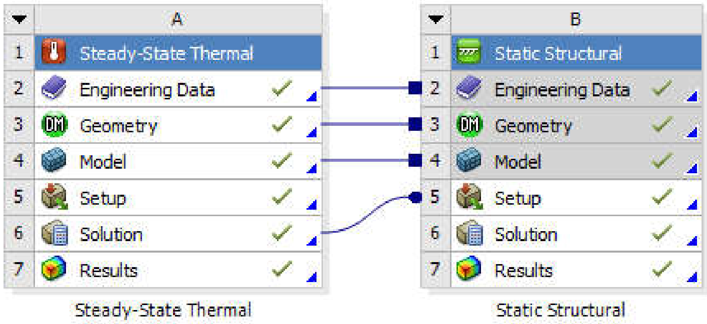


Figure 3. Coupled thermal and structural analysis

Table 2. Thermal and Mechanical properties of Piston Material

Piston Material					
Property	Density	Coefficient of thermal Expansion	Young's modulus	Poisson's ratio	Thermal Conductivity
Units	Kg/m^3	C^{-1} Reference temperature 250C	MPa		$Wm^{-1}C^{-1}$
Aluminium Alloy	2700	2.1 E-05	73100	0.33	1.55E+02

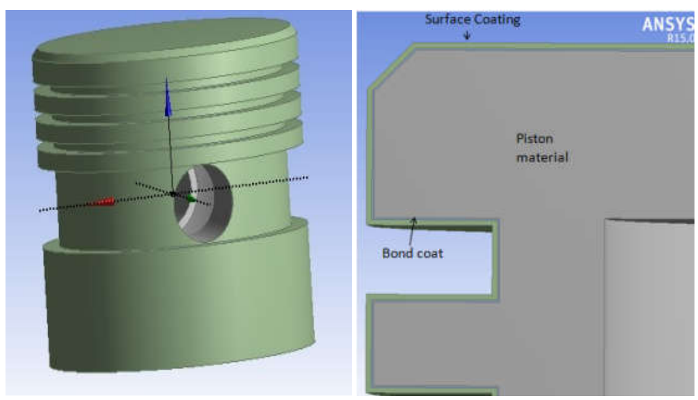


Figure 4. 3D model and cut section view of Engine piston

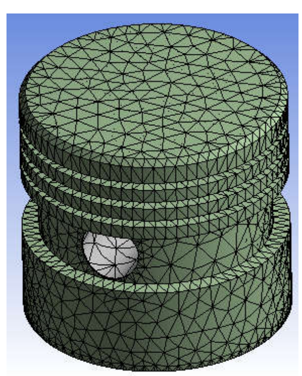


Figure 5. Mesh Model of Engine Piston

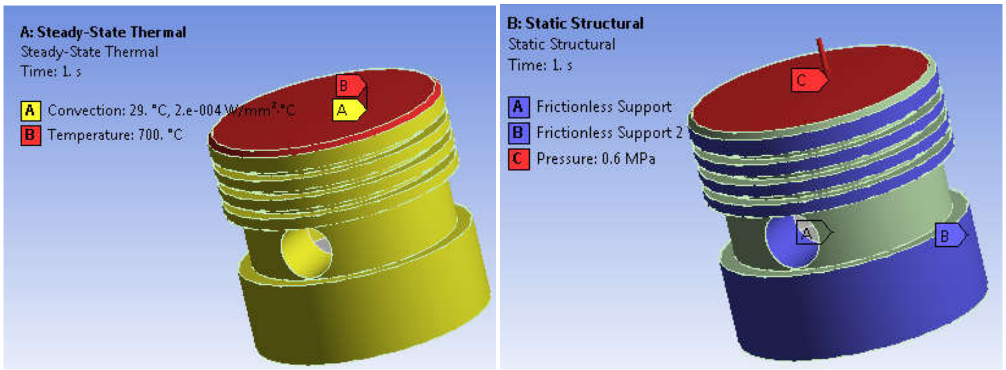


Figure 6. View of boundary conditions on engine piston

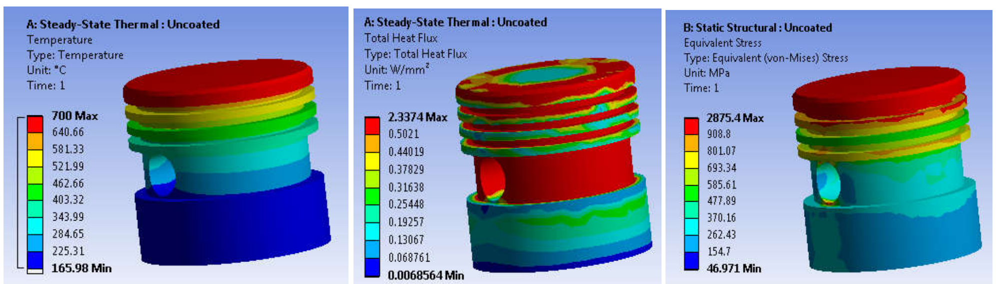
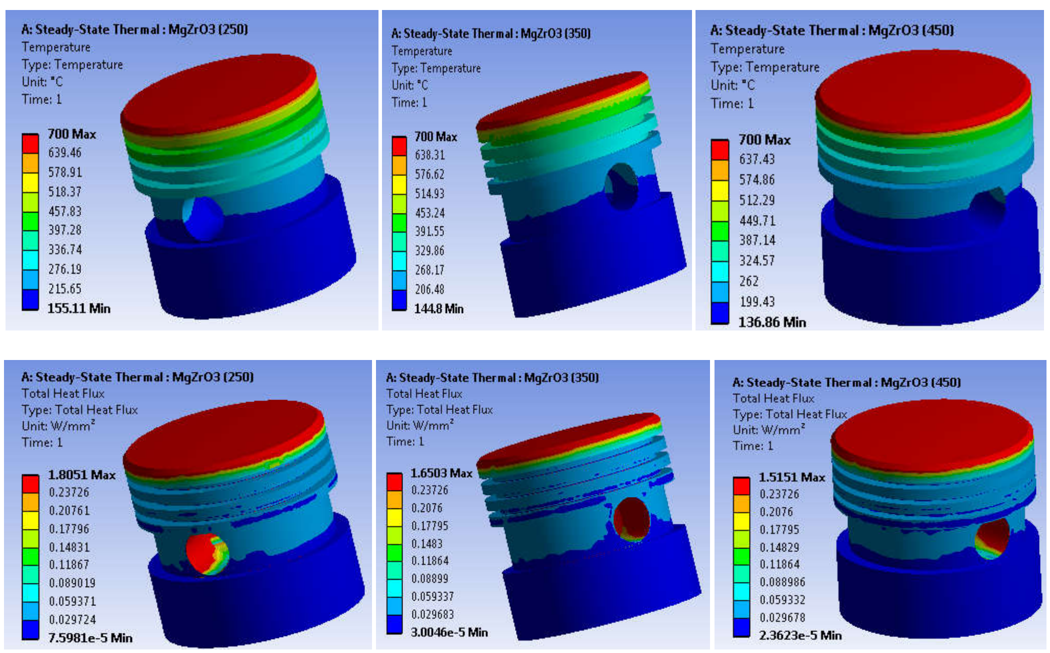


Figure 7. Plots for uncoated engine piston



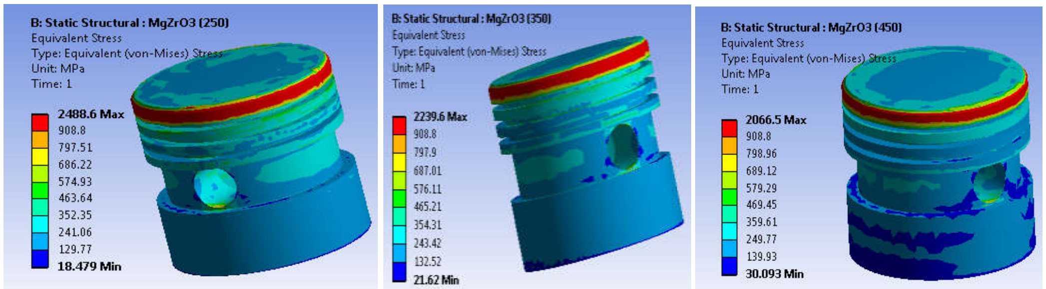


Figure 8. Plots for uncoated engine piston

5. Results

In this work, engine piston is investigated with thermal barrier coatings in order to enhance its performance, reliability and life. Evaluation of thermal barrier coating was done using computer aided engineering. 3d model of uncoated and coated piston was developed and analysed in ANSYS software package. The piston was evaluated for temperature, heat flux and Stress. The results were compiled in table 3. The plots for comparison with temperature fall, heat flux and stress are shown in fig. 9, fig.10 and fig. 11.

Table 3. Compiled results

Piston Conditions		Temperature fall (°C)		Heat flux (W/mm^2)		Stress (MPa)	
		Max.	Min.	Max.	Min.	Max.	Min.
Uncoated		700	165.98	2.3374	0.006685	2875.4	46.97
$CaZrO_3$ Coated	250 µm	700	147.55	1.6835	4.48E-05	3356.7	4.5657
	350 µm	700	135.52	1.5123	5.59E-05	2962.7	8.5406
	450 µm	700	124.5	1.36	2.11E-05	2666.8	9.5068
$MgZrO_3$ Coated	250 µm	700	155.11	1.8051	7.60E-05	2488.6	18.479
	350 µm	700	144.8	1.6503	3.00E-05	2239.6	21.62
	450 µm	700	136.8	1.5151	2.36E-05	2066.5	30.093
$3Al_2O_3$ $2SiO_2$ Coated	250 µm	700	188.6	2.2718	4.97E-05	5176.5	44.39
	350 µm	700	186.09	2.2275	3.95E-05	4933.1	46.268
	450 µm	700	183.68	2.2162	4.92E-05	4753.5	46.016
SiC Coated	250 µm	700	187.48	2.2532	4.88E-05	10767	56.858
	350 µm	700	179.64	2.1829	5.01E-05	10207	59.576
	450 µm	700	178.03	2.1869	0.000107	9575.8	62.217
ZrO_2 Y_2O_3 Coated	250 µm	700	169.26	2.0022	0.000121	2072.6	4.7165
	350 µm	700	161.63	1.8853	4.26E-05	1830.5	4.02
	450 µm	700	155.44	1.7829	3.16E-05	1949.3	12.683

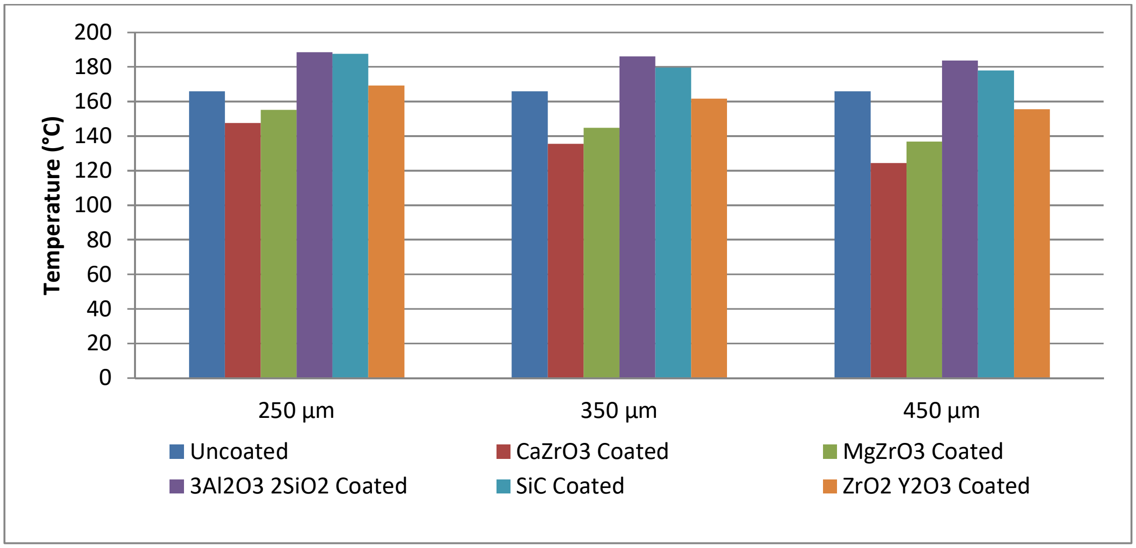


Figure 9.Temperature fall plot for uncoated and coated piston at different thickness

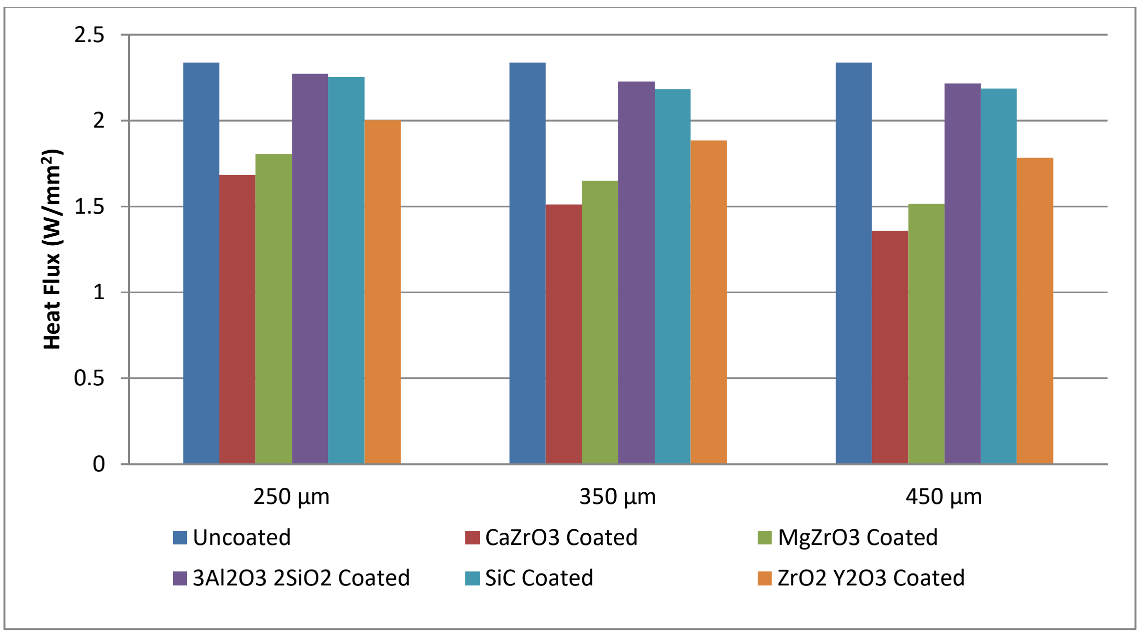


Figure 10. Heat flux plot for uncoated and coated piston at different thickness

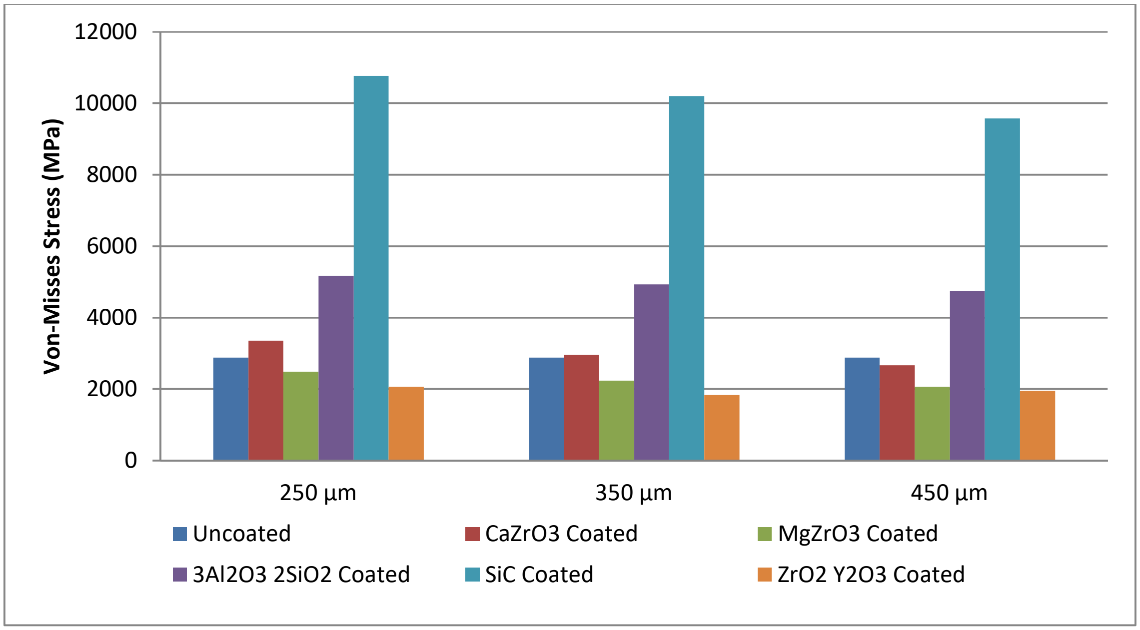


Figure 11. Von-Mises stress plot for uncoated and coated piston at different thickness

6. Conclusion

1. **Coating Effect**: Analysis report shows that there is considerable temperature fall which prevents thermal softening also lowers the heat flux and stress values.
2. **Comparative database**: Comparative database was generated for five coatings at 3 different coating thickness

- $MgZrO_3$ and $CaZrO_3$ surface coating shows the maximum temperature fall and lower stress values at 450 microns.
- ZrO_2 + 8% $Y2O_3$ coating shows stress rise with increase in thickness.
- SiC and $3Al_2O_3$ $2SiO_2$ coating gives higher value of stress with slight temperature fall

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