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Thermo Mechanical Analysis of Coated Engine Valve Using Finite Element Method

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Abstract- Surface coating technology has emerged as a reliable technique for increasing component life. Coating material and coating thickness evaluation for different conditions is foremost requirement. The present study aims to evaluate engine valve life using the coating technology as well as computer aided engineering. The work begins with selection of engine valve and thermal barrier coatings. Five surface coating of different material were studied at three coating thickness i.e. 100 microns, 150 microns and 200 microns for compiling a comparative database. 3D modeling of engine valve for uncoated and for different coating thickness was done on ANSYS software. Analysis was performed for calculating temperature distribution, Heat flux, stress and strain values. Outcome of above study suggested that the surface coating shows potential increase in engine life by reducing thermal softening and also provides shield to sliding and erosive wear. A comparative database has been formed for Temperature fall, stress and strain values for different coatings at various thickness in view to, for selection of suitable coating material and thickness. As result, $CaZrO_3$ is reported as best coating at 200 microns for engine valve.

Keywords- Engine, coating, heat flux, stress, strain

1. INTRODUCTION

Surface coating technology has emerged as a reliable technique for increasing life of components working under serve conditions. Thermal barrier coatings have shown proven results for lowering the thermal stress and wear of components such one component in current study in exhaust engine valve. Coating powder and coating thickness are important factors for lowering thermal stress and wear. In recent years, FEM analysis using IT tools has saved lot of time and money to obtain preliminary results

Thus objective in current work is to evaluate the performance of thermal barrier coated on existing material used for manufacturing engine valves using ANSYS and to provide a comparative database for selecting the coating powder and thickness.

2. ENGINE VALVE

Engine Valve is one of the main component of which is used in all IC Engines It allows burnt gases to escape from the cylinder to atmosphere. Figure 1 shows the engine valve

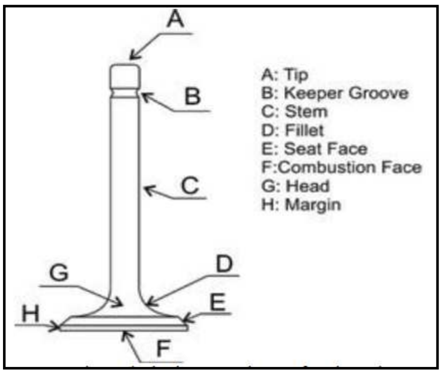

Figure 1 Descriptive image of Engine valve

An exhaust valve is subjected to:-
1. Longitudinal cyclic stresses due to the return spring load and the inertia response of the valve assembly.
2. Thermal stresses in the circumferential and longitudinal directions due to the large temperature gradient from the centre of the head to its periphery and from the crown to the stem. A typical variation of temperature in an exhaust valve is given in Figure 2
3. Creep conditions due to operation at very high temperatures, particularly in case of valve head.
4. Corrosion conditions.

Failure due to large temperature difference/ creep is stated as major reason of engine valve failure thus technique is required to reduce thermal stresses and

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increase engine valve life. Figure 2 shows typical temperature distribution.

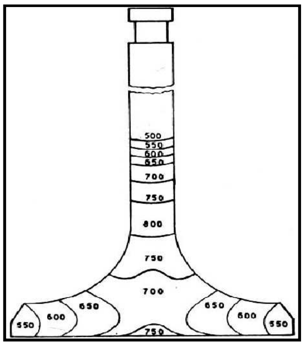

Figure 2 Typical temperature distributions in exhaust valve in degree Celsius

1.1Engine valve modelling

In current study Exhaust valve of Maruti Swift 1.3 Litre engine is selected; valve material is special steel grade known as SUH 11. It is highly alloyed (Mn-Ni-Cr-Mo-N) largely used for inlet and exhaust valve for IC engines required properties of the material are listed in table 1. Figure 3 shows the specification of engine valve.

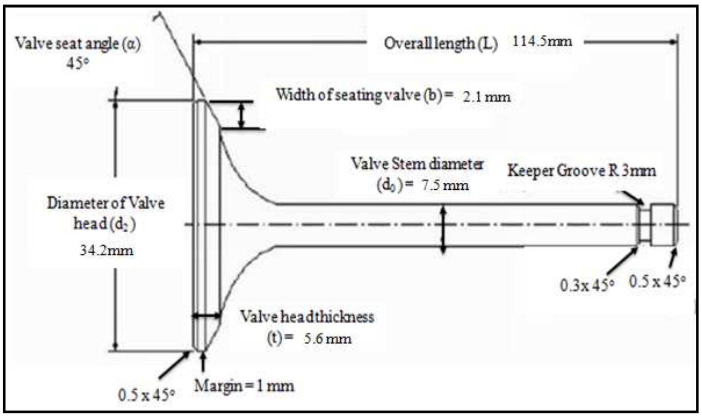

Figure 3. Specification of engine valve

Table 1 Properties of engine valve material

Type of material	**SUH 11/ X50CrSi18-2**
Young's modulus	200000 MPa
Tensile Strength	600 MPa
Fatigue strength	275 MPa
Yield Strength	250 MPa
Poisson Ratio	0.3
Density	7700 Kg/m3
Thermal expansion	10 e-6 /K
Thermal Conductivity	25 W/m K
Specific heat	460 J/Kg K
Melting temperature	1450 OC

3. SURFACE COATINGS

Surface coating is an enabling technology that is applied to the surface of an object, usually referred to as the substrate. The purpose of applying the coating may be decorative, functional, or both. Functional coatings may be applied to change the surface properties of the substrate, such as adhesion, wetability, corrosion resistance, or wear resistance. Such one category of coatings is thermal barrier coatings.

3.1 Thermal barrier coatings (TBC)

These are highly advanced materials systems usually applied to metallic surfaces operating at

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elevated temperatures. These coatings serve to insulate components from large and prolonged heat loads by utilizing thermally insulating materials. In doing so, these coatings can allow for higher operating temperatures while limiting the thermal exposure of structural components, extending part life by reducing oxidation and thermal fatigue in conjunction with active film cooling. Figure 4 shows the structure of thermal barrier coating

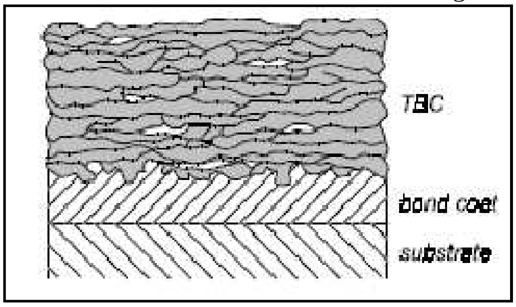

Figure 4. Shows the structure of surface coating

Thus thermal barrier coating could be the technique which can be used on engine valve guide for preventing them from creep failure.

3.2 Coating selection

Engine valve has to undergo under serve conditions such thermal shock; thermal softening, thermal fatigue and thermal wear and oxidation thus surface coat selected should be able to endure the conditions and provides its services. Depth literature survey has confirmed ceramic coatings can transform an ordinary metal into a high-performance surface applied by high energy Plasma, ceramics coatings give following benefits:-

- High hardness and durability
- Dense and pore free (sealed)
- Thermo-chemical bond strength
- Anti galling
- Electrical resistivity
- Thermal barrier coatings (TBC)
- Resistance to thermal shock

In current project five ceramic coatings are studied. Bond Coat is applied to improve the bond strength and thermal stress due to difference in thermal expansion coefficient of base material and surface coat NiCrAl is commonly used bond and is studied in current project. Properties of coatings and bond coat from literature are listed in table 2.

Table 2 Ceramic and Bond Coating properties

Property	**Units**	**NiCrAl**	**$MgZrO_3$**	**$CaZroO_3$**	**SiC**	**Mullite ($3Al_2O_32SiO_2$)**	**ZrO_2+ $Y2O_3$**
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

In current project FEA is applied on solid CAD model of uncoated and coated valve with bond coat using coupled steady state thermal and static structural analysis system. Figure 5 shows the coupled steady state thermal and static structural analysis. Figure 6 shows the 3d model of engine valve.

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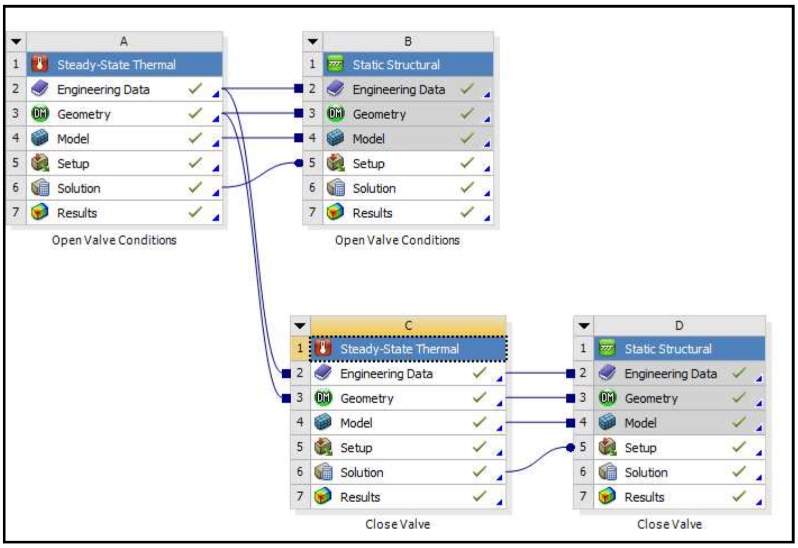
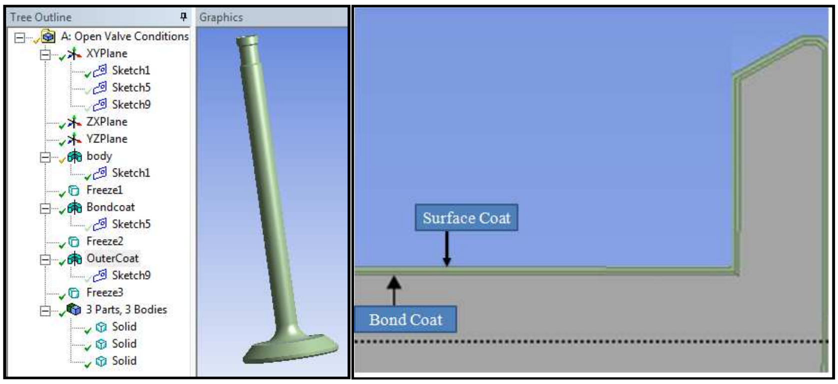


Figure5: Coupled Stead-State Thermal and Static structural analysis systems



(a) (b)

Figure 6 a) Generated model b) Cut section View of generated model

4.1 Boundary Conditions:

Steady –State thermal analysis

a) **Open Valve Condition:** Temperature at valve head 650^{o}C and 500^{o}C at Valve Stem with over all heat transfer coefficient of 500 W/m^{2o}C

b) Closed Valve Condition: Temperature at valve head 650 ^{o}C with over all heat transfer coefficient of 500 W/m^{2o}C.

Static Structural Analysis

a) Open Valve Condition: Thermal condition imported from coupled steady state thermal analysis and gas pressure at valve head 5 x 10^{6} Pa with net force of 1200N acting downward.

b) Closed Valve Condition: Thermal condition imported from coupled steady state thermal analysis and gas pressure at valve head 7 x 10^{6} Pa with net force of 800N acting upward. Figure 7 shows applied boundary conditions.

5. SOLUTION

Engine valve is evaluated to obtain results for Temperature distribution, Heat flux, Von-Mises Stress and Elastic strain. Figure 8 shows the result plots for uncoated and 200 µm $CazrO_3$ coated engine valve for open and close conditions.

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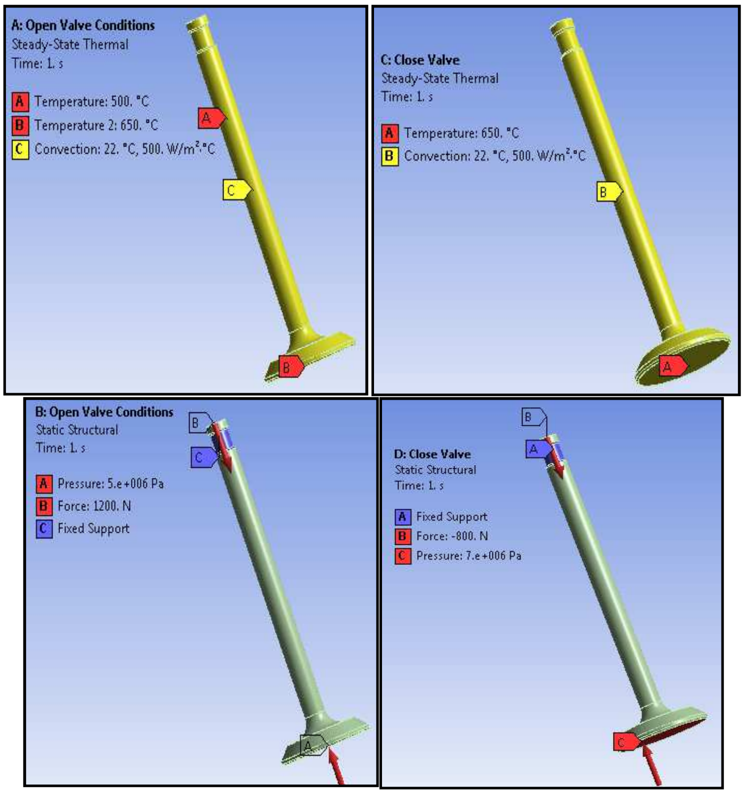

Figure 7 Applied Boundary conditions on engine valve

1.

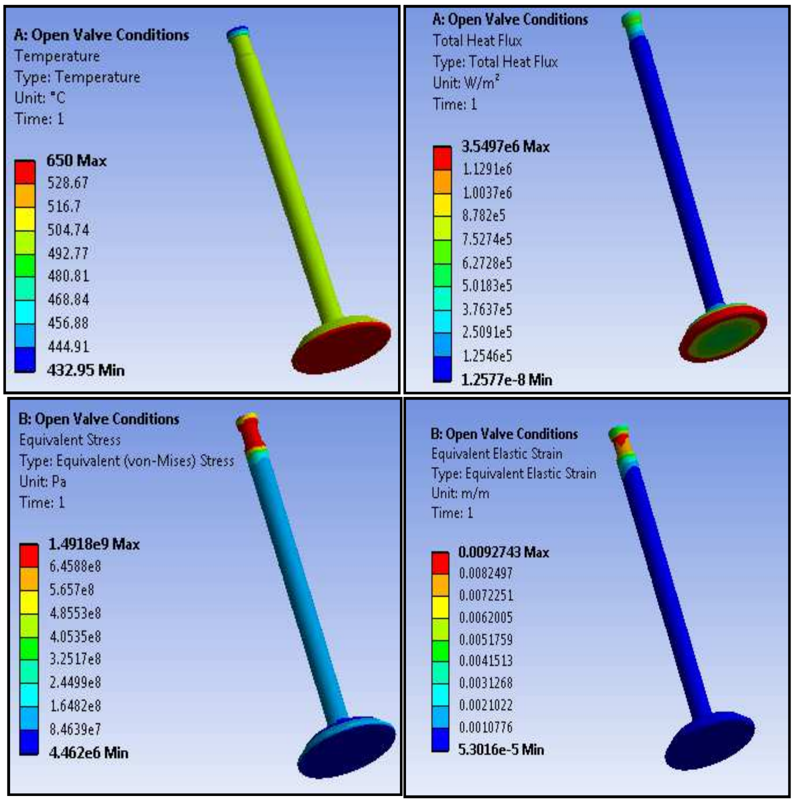

Figure 8 Results plots for uncoated engine valve in open state

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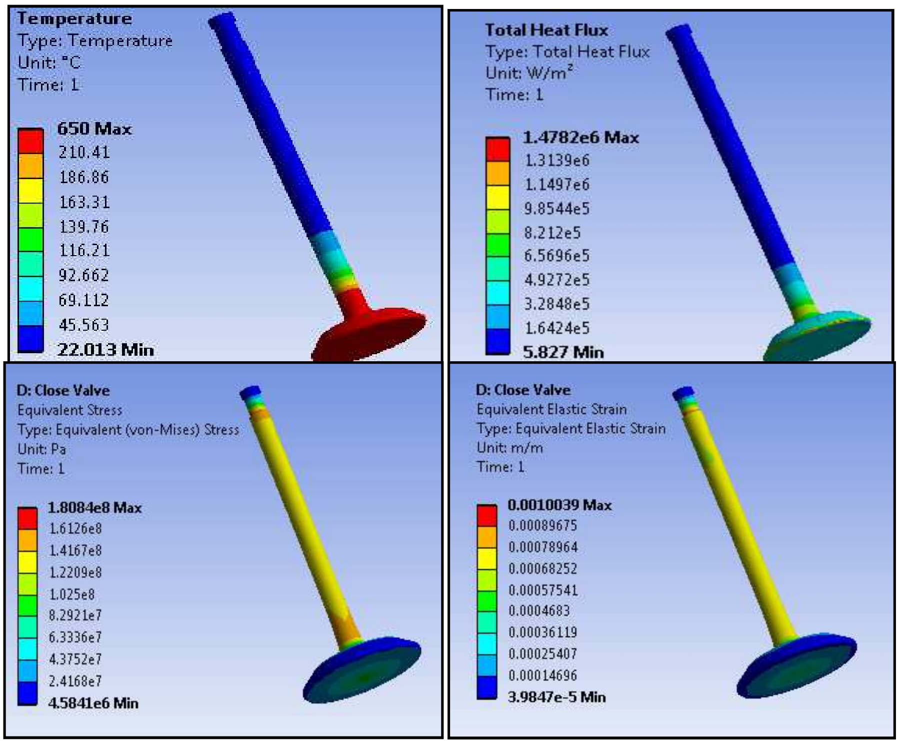

Figure 9 Results plots for uncoated engine valve in close state

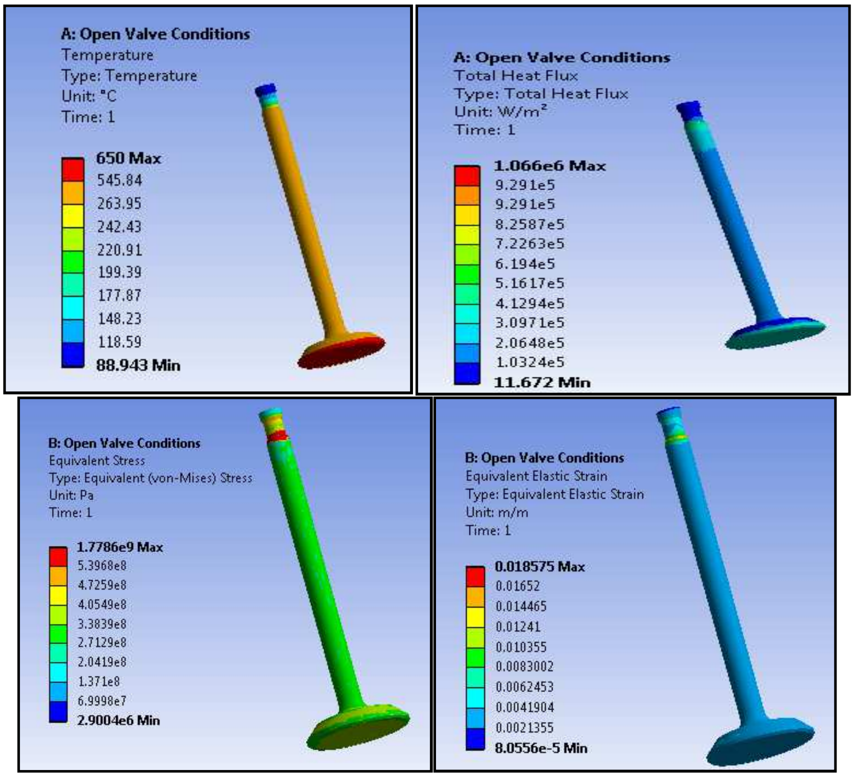

Figure 10 Results plots for open engine valve coated with 200 µm $CaZrO_3$

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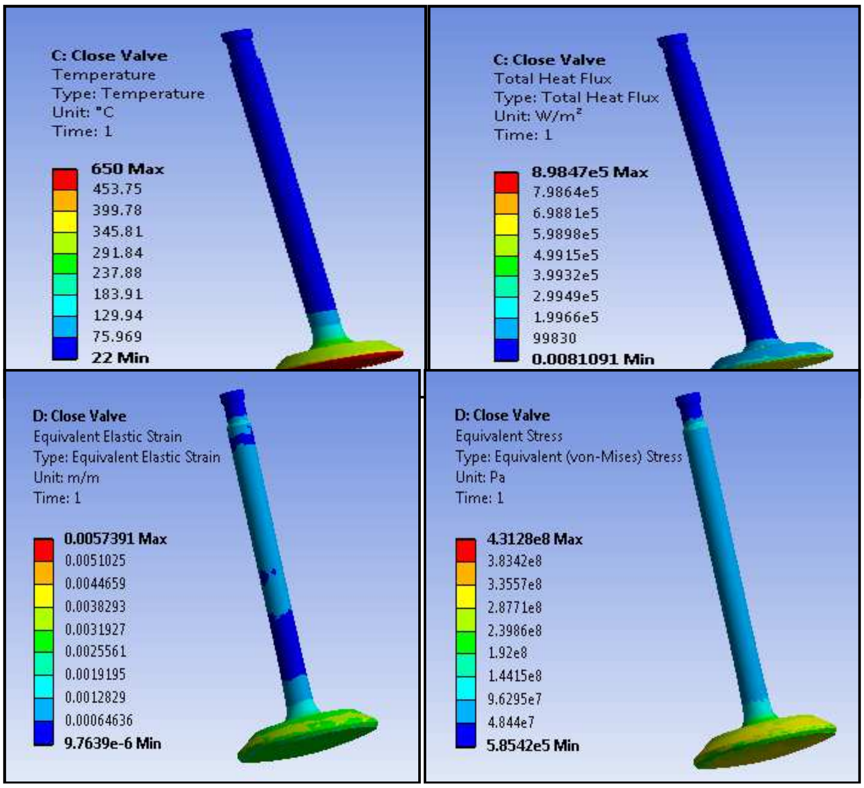

Figure 11 Results plots for closed engine valve coated with 200 µm $CaZrO_3$

6. RESULTS

In this work, engine valve is explored with thermal barrier coatings in order to enhance its performance and life. The work began with designing of engine valve and simultaneous properties of feasible surface coatings were listed. Engine valve is analysed for uncoated SUH11 material and with 5 different coatings. To acquire optimum coating thickness the coating is analysed for three coating thickness i.e. 100 µm, 150µm and 200µm. the work involves computer aided engineering; design and analysis of engine valve is done ANSYS software package.

Analysis report of engine valve on the basis of Temperature, Heat flux, equivalent Von-Mises stress and Strain is compiled in table 3 and table 4 for open valve state and close valve state. Important Graphs plotted from analysis results are shown in figure 12.

Table 3 Complied Analysis report for Engine Valve in open state

Valve Details	Coating Thickness (µm)	Temperature (°C)		Heat Flux (W/m²)		Equivalent von-Mises Stress (MPa)		Strain	
		Max	Min	Max	Min	Max	Min	Max	Min
Uncoated	0	650	432.9	3.55E+06	1.26E-08	1.49E+03	4.462	0.0092743	5.31E-05
ZrO_2 + 8% Y_2O_3	100	650	121.15	1.55E+06	5.427	1.22E+03	4.85E-01	0.029424	8.02E-04
	150	650	114.44	1.38E+06	5.7275	6.46E+02	3.43E-01	0.061545	7.21E-05
	200	650	107.22	1.33E+06	8.7874	5.17E+02	2.98E-01	0.049315	7.42E-05
SiC	100	650	133.4	3.60E+06	3.6766	6.28E+03	7.57E+00	0.13473	0.000209
	150	650	130.52	3.03E+06	3.664	5.06E+03	1.27E+01	0.013574	0.000150
	200	650	128.12	2.94E+06	4.8716	4.61E+03	5.44E+00	0.13257	0.000212
$MgZrO_3$	100	650	112.4	1.36E+06	7.8197	2.39E+03	3.4177	0.05329	6.81E-05
	150	650	103.66	1.25E+06	12.859	1.56E+03	3.0906	0.034007	5.41E-05
	200	650	96.418	1.15E+06	17.213	1.28E+03	30482	0.062963	9.48E-05

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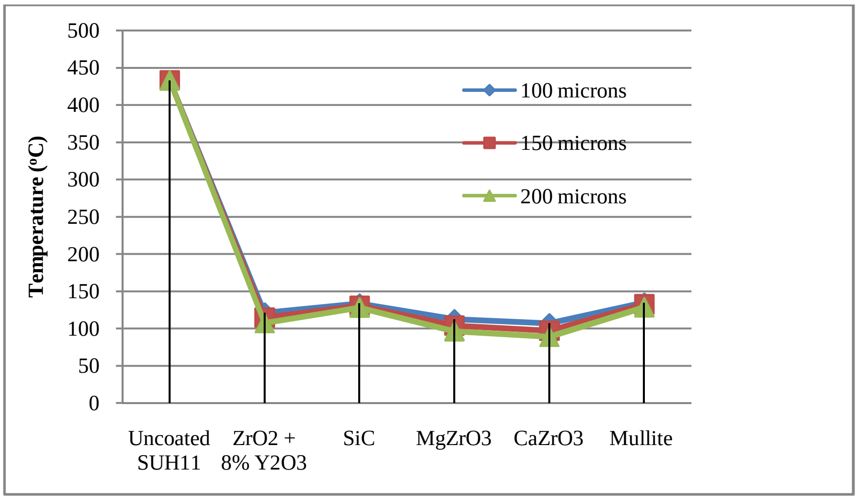
$CaZrO_3$	100	650	106.84	1.29E+06	26.061	2.93E+03	1.6808	0.5329	6.81E-05
	150	650	96.984	1.71E+06	8.4713	2.17E+03	4.8559	0.021826	7.12E-05
	200	650	88.943	1.07E+06	11.672	1.78E+03	2.9004	0.018575	8.06E-05
Mullite (3 Al_2O_3 + $2SiO_2$)	100	650	134.67	4.24E+06	6.0452	4.24E+03	4.26	0.628232	6.27E-05
	150	650	132.27	3.54E+06	1.5031	3.37E+03	1.333	0.028402	5.97E-05
	200	650	128.52	2.28E+06	4.9191	2.28E+03	4.7949	0.01933	7.67E-05

Table 4 Complied Analysis report for Engine Valve in Close state

Valve Details	Coating Thickness (µm)	Temperature (^oC)		Heat Flux (W/m^2)		Equivalent von-Mises Stress (MPa)		Strain	
		Max	Min	Max	Min	Max	Min	Max	Min
Uncoated SUH11	0	650	22.013	1.48E+06	5.827	1.81E+02	4.58E+00	0.0010039	3.98E-05
ZrO_2 + 8% Y_2O_3	100	650	22	1.48E+06	0.008805	2.16E+02	0.4935	0.017024	3.26E-05
	150	650	22	1.34E+06	0.010406	3.35E+02	2.25E-01	0.11382	5.45E-05
	200	650	22	1.26E+06	0.013971	4.27E+02	2.32E-01	0.010313	4.15E-05
SiC	100	650	22	1.77E+06	0.0092254	2.06E+03	3.23E-01	0.000475	7.31E-06
	150	650	22	1.65E+06	0.011707	1.96E+03	2.42E-01	0.004166	9.24E-06
	200	650	22	1.48E+06	0.0081463	1.78E+03	1.54E-01	0.008237	3.62E-06
MgZrO3	100	650	22	1.31E+00	0.0088223	2.90E+02	0.5908	0.005744	9.74E-06
	150	650	22	1.15E+06	0.010499	4.25E+02	3.64E-01	0.000486	6.79E-06
	200	650	22	1.00E+06	0.0078109	3.11E+02	7.42E-01	0.005736	1.34E-06
CaZrO3	100	650	22	1.22E+06	0.00088871	5.91E+02	0.43297	0.005922	1.05E-05
	150	650	22	1.07E+06	0.010489	4.89E+02	6.35E-01	4.90E-03	9.97E-06
	200	650	22	8.90E+05	0.0081051	4.31E+02	5.85E-01	0.005739	9.76E-06
Mullite (3 Al2O_3 + $2SiO_2$)	100	650	22	1.81E+06	0.0093545	7.71E+02	0.39981	0.005121	9.40E-06
	150	650	22	1.68E+06	0.01218	6.86E+02	3.97E-01	0.004704	1.02E-05
	200	650	22	1.60E+06	0.0889463	6.38E+02	5.63E-01	0.004451	1.09E-05



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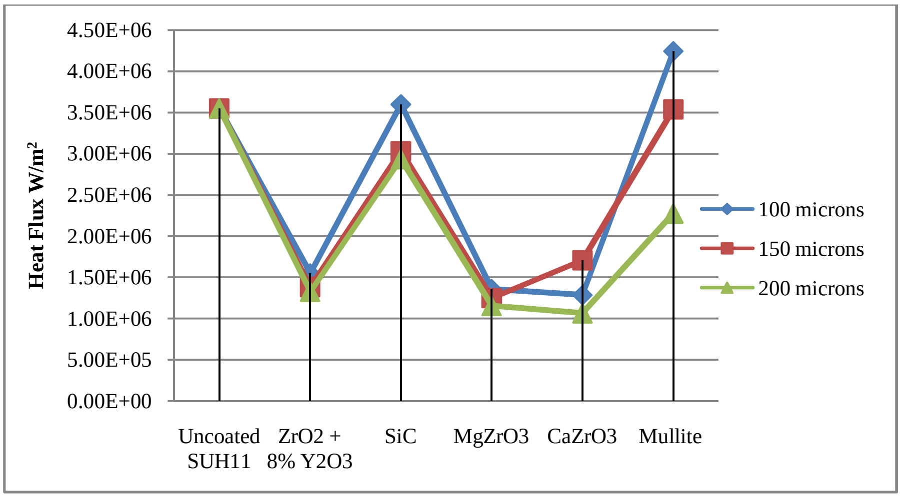

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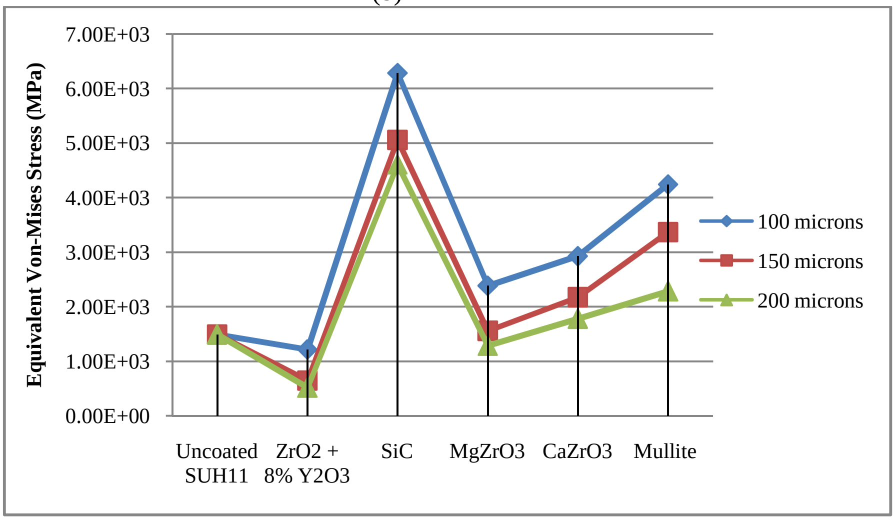

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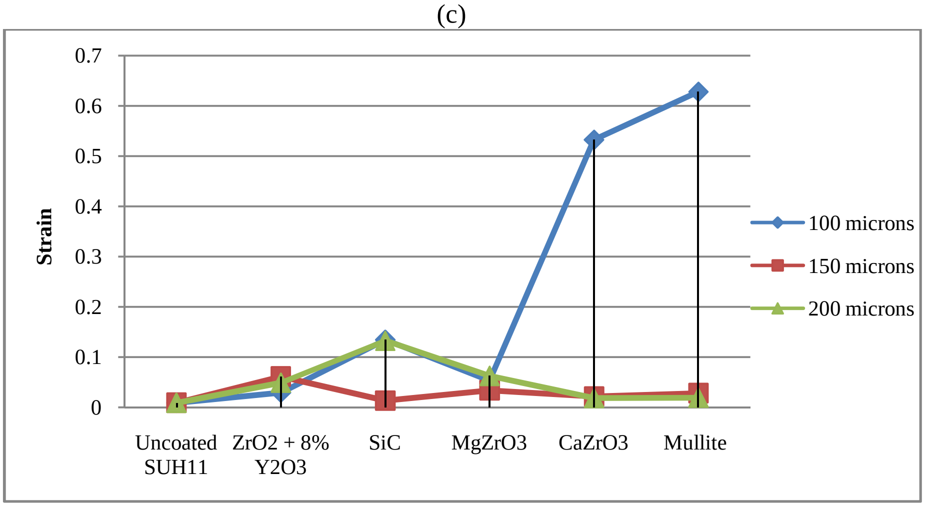

(d)

Figure 12 (a) Temperature fall plot (b) Maximum heat flux plot
(c) Maximum Von-Mises stress plot (d) Maximum strain plot

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7. CONCLUSION

1. **Coating Effect**: Analysis Reports has shown considerable temperature fall for coated surfaces than in uncoated engine valve which in turn reduce thermal stresses and will also protect from thermal softening leading to wear of engine valve. Thus surface coating technology can be utilized for lower thermal stress and reducing erosive and corrosive wear to yield enhanced engine valve life and performance.
2. **Comparative database**: the study has provided the comparative database for 5 different coatings and also coatings has evaluated for different coating thickness. The results has revealed following points
   - $CaZrO_3$ surface coating gives best result at 200 microns for temperature fall and Stress and Strain with in material prescribed limit is most suitable surface coating.
   - $CaZrO_3$ surface coating shows high stress and strain values at 100 microns. Thus minimum coating thickness should be 150 microns and above.
   - $MgZrO_3$ and ZrO_2 + 8% $Y2O_3$ are second and third most suitable coatings with little difference in temperature fall and stress and strain within prescribed material limits.
   - ZrO_2 + 8% Y_2O_3 coating can be used for lesser coating thickness with minor temperature rise due to less stress values.
   - SIC and Mullite shows almost similar results for temperature fall but both surface coats shows high stress values.

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