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Design and Performance Evaluation of Thermal Barrier Coated Engine Valve Using Finite Element Analysis

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ABSTRACT: Engine valve are vital components of the engine for controlling the inlet and outlet flow of gases in engine cylinder subjected to both thermal and mechanical loads. The performance and reliability of an engine rely a lot on engine valve. Surface coating technology is reported as effective way of increasing component life with increasing overall reliability of the machine.

In current work the engine valve dimensions are calculated using engine specification and solid model is created using ANSYS design modler. $MgZrO_3$ as thermal barrier coating and NiCrAL as bond coat are selected on special high strength steel 11. The performance of surface coating on engine valve is evaluated using finite element analysis in ANSYS for uncoated and coated engine valve with and without application of bond coat. The analysis results indicate lower thermal and mechanical loads on coated engine valve with bond coat gives the scope for more reliability.

KEYWORDS: Finite element analysis, Surface Coating, Engine valve

I. INTRODUCTION

Reliability has become important factor for the manufacturing companies these days with the budding competition the companies have to make cheaper and unfailing machines. On the same context automobile companies have to take care of individual components to make them reliable in minimum cost. One of the technologies which can provide solution to the requirement is surface coating.

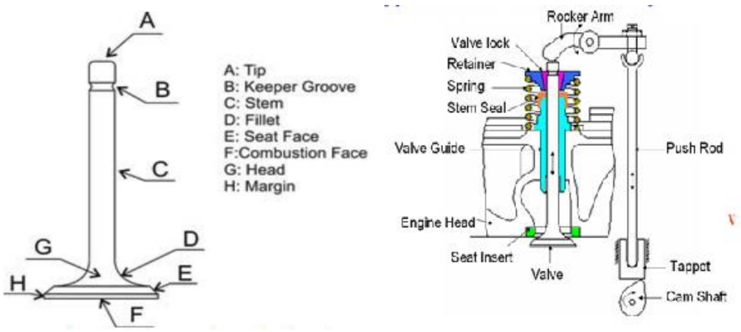
Surface coating is a covering that is applied to the surface of an object, usually referred to as the substrate and provide a way of extending the limits of use of materials at the upper end of their performance capabilities, by allowing the mechanical properties of the substrate materials to be maintained while protecting them against wear or corrosion at high temperatures [1]. Such one category of coatings is thermal barrier coatings. Thermal barrier coatings (TBC) are highly advanced materials systems usually applied to metallic surfaces operating at elevated temperatures. These coatings serve to insulate components from large and prolonged heat loads by utilizing thermally insulating materials which can sustain an appreciable temperature difference between the load-bearing alloys and the coating surface. 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.[2]

Diverse surface coating techniques are available in market out of which thermal spray technique is reported as superior and mostly used technology [3]. It is one of the many methods of applying overlay coatings for applications ranging from protection of materials in harsh environments, to dimensional restoration of worn machine elements [4]. HVOF thermal spray process is a promising method of coating application. The process provides coatings with excellent mechanical properties [5]

In current work one such component on which surface coating technology evaluated is Engine valve. Engine Valve is one of the critical components which are used in all IC Engines. Each cylinder in the engine has one inlet and one exhaust valve. Figure 1 shows the descriptive view of engine valve. Engine valve has to bear following conditions:-

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.
3. Creep conditions due to operation at very high temperatures, particularly in case of valve head.
4. Corrosion conditions.



(a) **(b)**

Figure 1 (a) Descriptive view of engine valve, (b) Assembly of engine valve

In recent years, the finite element method (FEM) has particularly become the main tool for simulating the performance of coatings in diverse situation. Thus aim of present work is to design the engine valve and evaluate the performance of uncoated and thermal barrier coated using on existing material used for manufacturing engine valves using CAE.

II. DESIGNING AND MODELING

Engine specification and data required for perform design calculations for the engine valve is shown in table 1. Engine valve is designed using special steel grade known as SUH 11 the properties of the material are listed in table 2

Table1. Engine specification and data for designing engine valve

Company	Maruti alto
Engine type	Air cooled 4-stroke
Bore X Stroke(mm)	68.5 x 72
Displacement	796 C.C
Maximum power	47.34 BHP @6000 rpm
Maximum torque	13.4Nm@6000rpm
Explosion pressure	3.9 MPa
Gas Velocity	1500 m/min
Valve Seat angle	45^0
Mean Piston Speed	320 m/min
Valve Retainer type	Keeper Grove

Table2. Material property for engine valve

Type of material	**SUH11**
Young's modulus	200000 MPa
Tensile Strength	600 MPa
Fatigue strength	275 MPa
Yield Strength	250 MPa
Poisson Ratio	0.3
Density	7700 Kg/m^3
Thermal expansion	10 e^{-6} /K

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Thermal Conductivity	25 W/m K
Specific heat	460 J/Kg K
Melting temperature	1450 ^{O}C

Theoretical Calculations performed for calculating the dimensions of engine valve are done as below and figure 2 gives the detailed dimensions of engine valve for modeling.

$$\text{Allowable Stress } (\sigma) = \frac{\text{Yield Strength}}{\text{Factor of saftey}} = \frac{250}{5} = 50 \text{ N/mm}^2$$

$$d_1 = \text{port diameter} = D\sqrt{\frac{\text{Piston speed}}{\text{Gas Velocity}}} = 68.5\sqrt{\frac{320}{1500}} = 31.6\text{mm}$$

$$t = \text{thickness of valve head} = 0.5\, d_1 \sqrt{\frac{\text{GasPressure } (P_{max})}{\text{Allowable stress } (\sigma)}} = 0.5 \times 31.6 \sqrt{\frac{3.9}{50}} = 4.5 \text{ mm}$$

$$b = \text{width of seating} = \frac{t}{4\cos\alpha} = \frac{4.5}{4\cos 45} = 2.2\text{mm}$$

$$d_0 \text{ (Valve stem dia.)} = \frac{\text{Port diameter}}{8} + 4\text{mm} = 8\text{mm}$$

Diameter of valve head (d_2) $= d_1 + 2b = 31.6 + 2 \times 2.2 = 36$ mm

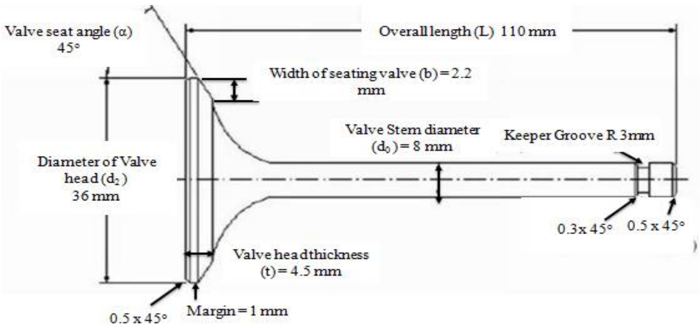

Figure 2. Specification of engine valve

Modelling of engine valve is done in ANSYS software package. Three models are developed for FEM evaluation of engine valve uncoated engine valve and coated engine valve with and without bond coat. Fig 3 (a) shows the uncoated engine valve figure 3 (b) and (c) shows cut section view of engine valve. The coating thickness is developed is 100 microns for bond coat and 200 microns for thermal barrier coat. The coating material is stabilized magnesia-zirconia ($MgZrO_3$) and bond coat powder used is NiCrAl. The properties of coating obtained through high velocity oxy flame are listed in table3

Table 3 Coating material properties obtained by HVOF process

Coating Material	Youngs modulus, GPa	Poisson's ratio	Thermal expansion coefficient x10^{-6} /^{o}C	Thermal conductivity, W/m^{o}C	Density Kg/m^{3}
Outer coat ($MgZrO_3$)	46	0.20	8	0.8	5600
Bond Coat (NiCrAl)	90	0.27	12	16.1	7870

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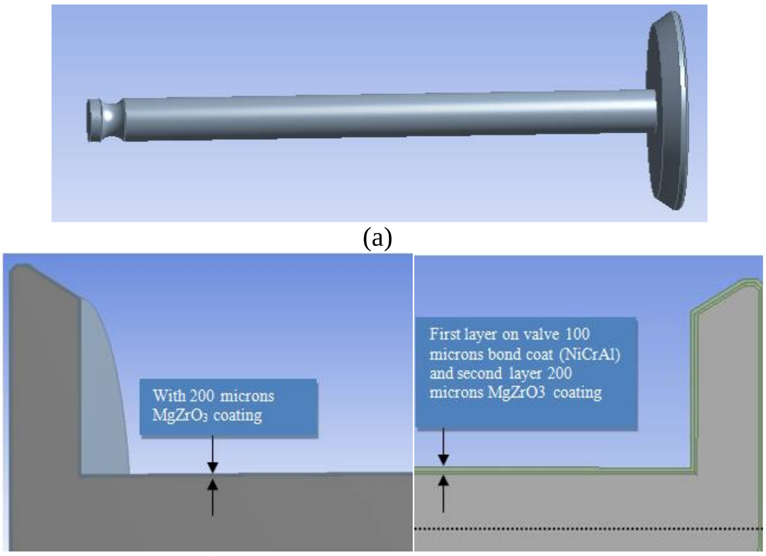

(a)

(b) (c)

Figure 3 (a) Geometric model of uncoated valve
(b) Cut section model of coated engine valve without bond coat
(c) Cut section model of coated engine valve with bond coat

III. FINITE ELEMENT ANALYSIS RESULTS

Finite element analysis is carried in ANSYS software package applying boundary condition for engine valve in both open and closed position. Following steps were carried

1. Analysis system: coupling of steady state thermal and static structural analysis system is selected for evaluating the effect of thermal condition in stress and deformation figure 4 shows coupling on the two systems

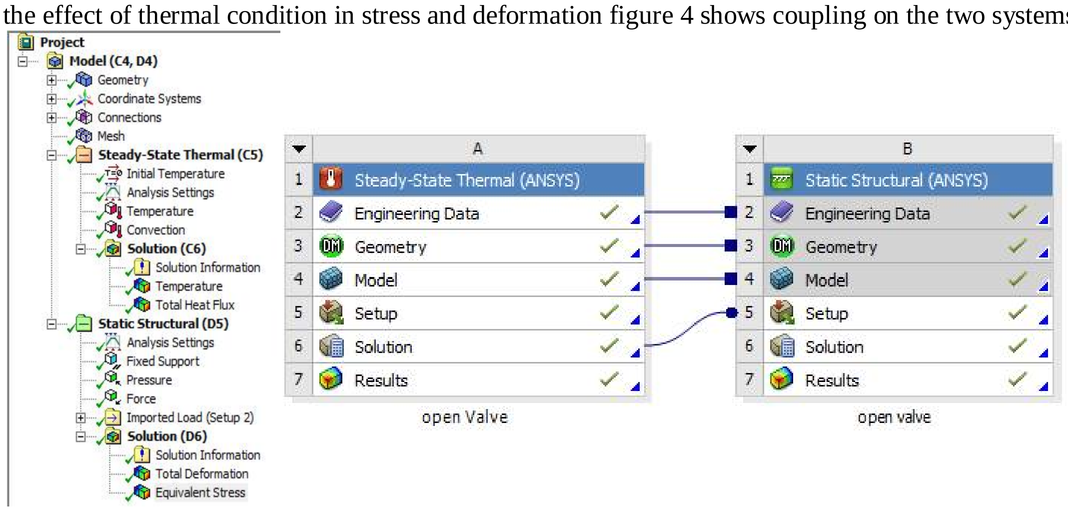

Figure 4 coupled Steady state thermal and Static structural Analysis for open valve case

2. Engineering Data: properties of valve body material, bond coat and outer coating obtained by HVOF method is feed into engineering database as listed in table 2 and table 3.
3. Geometry : Solid models are modeled in ANSYS design modeler shown in figure 3
4. Meshing is performed figure 5 shows the mesh model of engine valve

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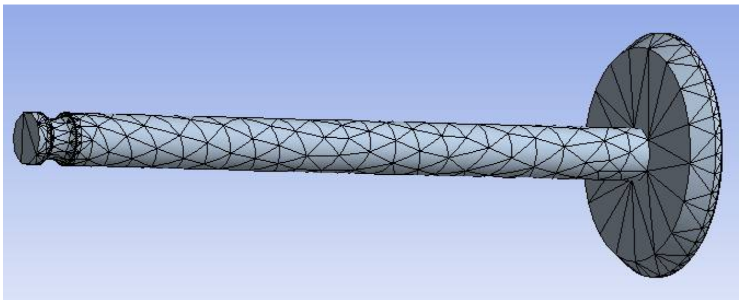
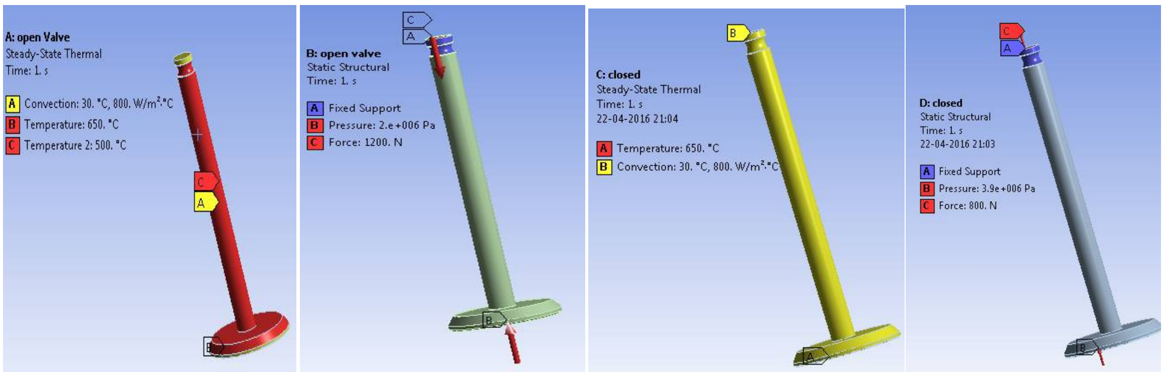


Figure 5 Mesh Model of Engine valve

5. Setup of engine valve is done by applying boundary conditions for both open and closed conditions for steady state thermal analysis and static structural analysis as listed below and shown in figure 6 boundary conditions are as follows:-
   Static State Analysis System
   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 800 W/m^{2o}C
   b) Closed Valve Condition : Temperature at valve head 650^{o}c with over all heat transfer coefficient of 800 W/m^{2o}C
   Static Structural Analysis
   c) Open Valve Condition: Thermal condition imported from coupled Static thermal analysis, gas pressure at valve head 2 x 10^{6} Pa with net force of 1200N acting downward.
   d) Closed Valve Condition: Thermal condition imported from coupled Static thermal analysis, gas pressure at valve head 3.5 x 10^{6} Pa with net force of 800N acting upward.



(a) (b) (c) (d)

Figure 6 (a) Shows Boundary conditions for Steady State thermal Analysis for open valve condition
(b) Shows Boundary conditions for Static structural for open valve condition
(c) Shows Boundary conditions for Steady State thermal Analysis for close valve condition
(d) Shows Boundary conditions for Steady State thermal Analysis for close valve condition

6. Solution is obtained for solving the engine valve for temperature distribution, heat flux, Von Mises stress and total deformation. Plots of solution for uncoated valve, coated valve with and without bond coat are shown in figure 7, 8 and 9

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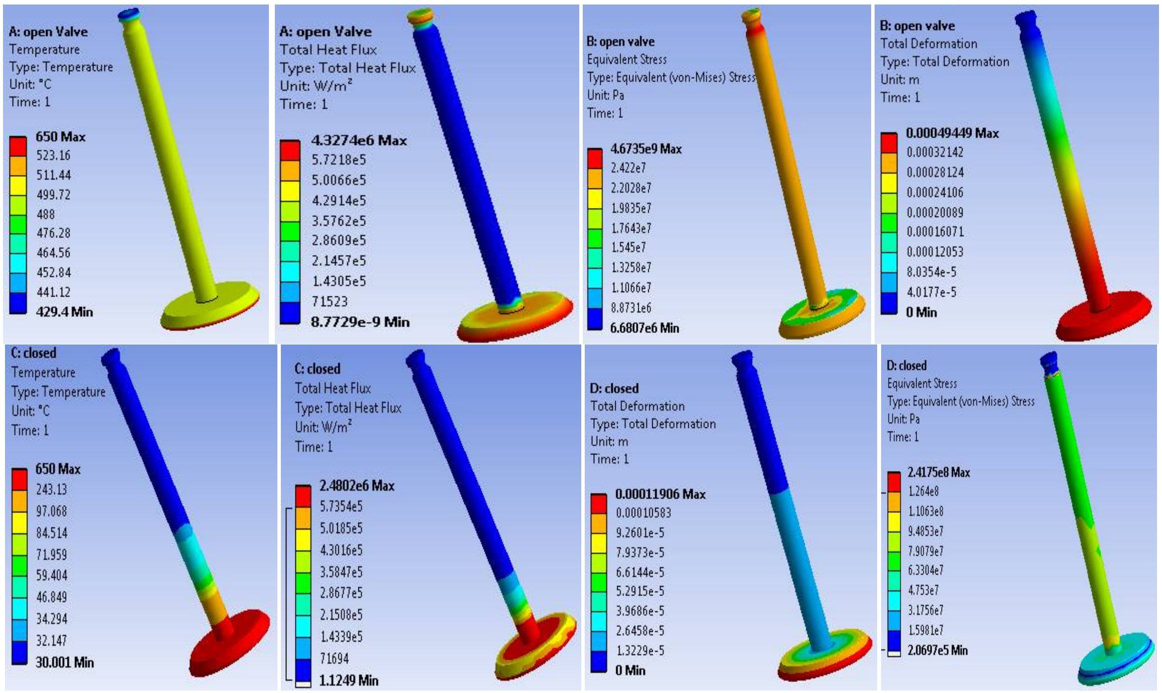

Figure 7 Shows the plots of temperature distribution, total heat flux, VonMises Stress and total deformation for uncoated engine valve in open and closed Valve Condition

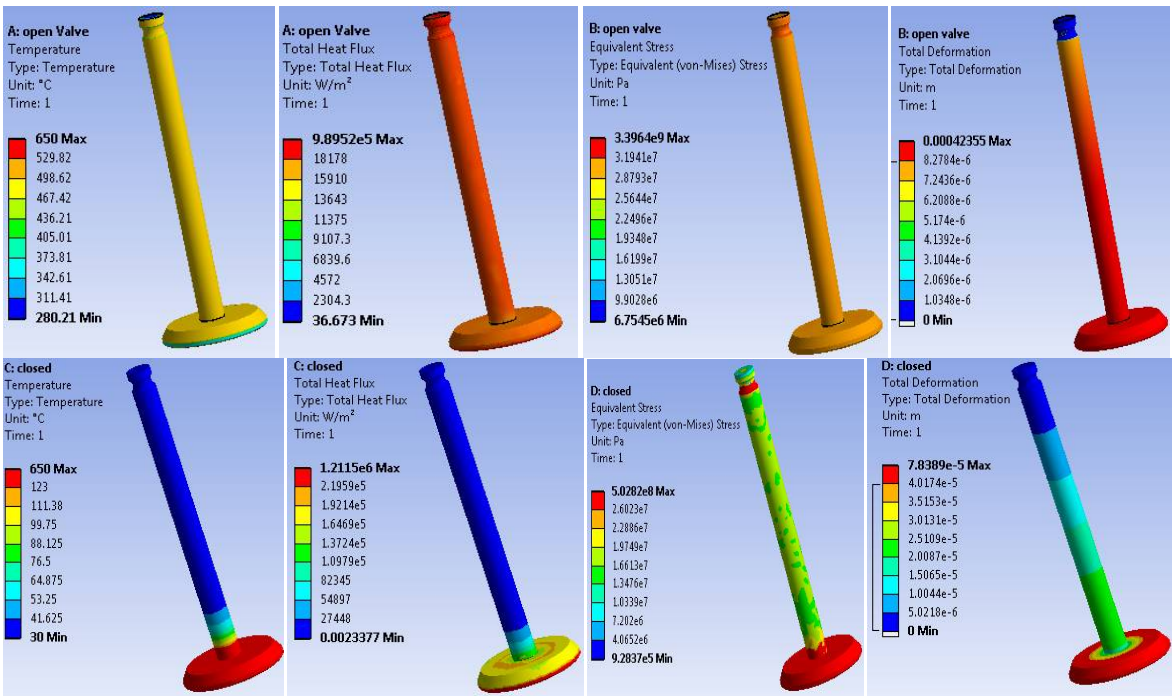

Figure 8 Shows the plots of temperature distribution, total heat flux, VonMises Stress and total deformation for Coated engine valve with bond coat in open and closed Valve Condition

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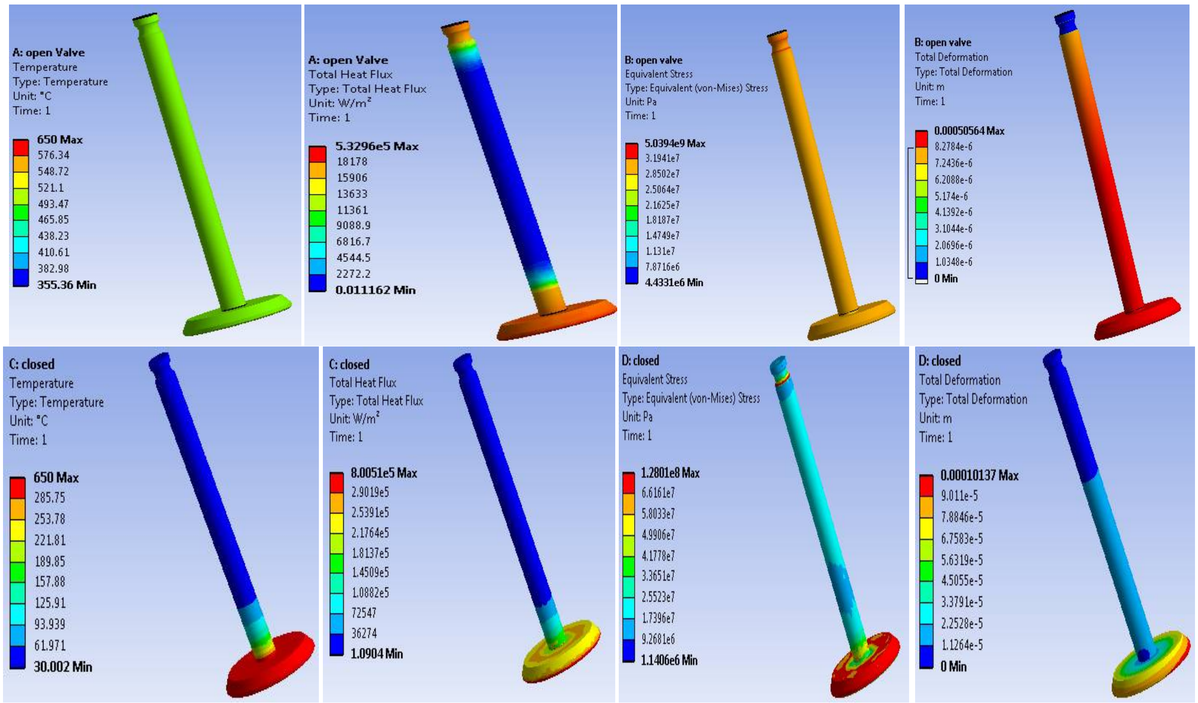

Figure 9 Shows the plots of temperature distribution, total heat flux, VonMises Stress and total deformation for coated engine valve without bond coat in open and closed Valve Condition

IV. RESULTS AND CONCLUSION

Summary of results is provided in table 4.

Table 4 gives the summation of results

Analysis	Valve Condition	Uncoated engine Valve	Coated engine valve with bond coat	Coated engine valve without bond coat
Total heat Flux W/m^2 x10^6	open	4.32	1	5.32
	close	2.48	1.211	0.80
Von Mises Stress GPa	open	4.47	3.39	5.03
	close	0.242	0.5	0.12
Total deformation m x 10^{-3}	open	.495	0.4	0.51
	close	0.1	0.078	0.10

In current work performance of engine valve is evaluated for uncoated and coated engine valve with and without the application of bond coat. The results in table 4 shows the considerable decrease in heat flux, mechanical stress and total deformation the with coated engine valve with bond coat while increase in stress is observed in coated engine valve without bond coat. The better performance of coated engine valve with bond coat thus gives the applicability of surface coating technology on engine valve for long life and reliability without using costly material for valve body also it provides better wear and corrosion resistance.

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