Thermal analysis and Optimization of Thermal Barrier Coated Diesel Engine Piston using Taguchi method

Hina Akhtar[1], Dr. Satyendra Singh[2], Satish Kumar[3]

[1] Assistant Professor, Departmental of Mechanical Engineering, SCE Dehradun
[2] Associate Professor, Departmental of Mechanical Engineering, BTKIT, Dwarahat
[3] B.Tech Student, Departmental of Mechanical Engineering, SCE Dehradun

Abstract—In the present study, three different coating materials, coated on the top surface of diesel engine piston (AlSi) with different thermal properties are taken: yttria- partially stabilized zirconia (Y-PSZ), Mullite (($Al_6Si_2O_{13}$) and Silicon Dioxide (SiO_2). Thermal analysis is carried out for a high temperature conditions using ANSYS 15. Optimization of temperature and stresses induced within the coatings are carried on Minitab Software using Taguchi method to determine the optimum parameters for diesel engine piston. The orthogonal array, signal-to-noise ratio and the analysis of variance (ANOVA) are employed to find out the most influencing parameter for diesel engine piston. Accordingly, a suitable orthogonal array is selected and experiments are conducted. With the help of graphs, optimum parameter values are obtained.

***Key words** – TBC, Ansys, Anova, Design of Experiments, Orthogonal Array, S/N Ratio, Taguchi*

Introduction

The ceramics as thermal barrier coating in high temperature engineering application is in use for more than two decades now. Ceramic coating on diesel engine components increases the thermal efficiency of the engine and reduces the associated emissions. In an internal combustion engine heat is transferred from combustion chamber to piston head, cylinder walls and then to the cooling water circulated through water jackets around the cylinder. Generally, in diesel engines about 18-22 percent of heat energy from fuel combustion is rejected to coolant fluid. [1] To reduce heat loss to the cooling water thermal barrier ceramic (TBC) coating is used.

Ceramics have a higher thermal durability than metals. Therefore it is usually not necessary to cool them as fast as metals. Lower heat rejection from the combustion chamber through thermally insulated Components cause an increase in available energy that would increase the cylinder displacement work and the amount of energy carried by exhaust gases, which could also be utilized. [2] Using the coated piston the required temperature in the combustion chamber will be maintained. This will reduce the heat loss to the piston. This reduction in the heat loss will be used to burn the unburnt gases there by reducing the polluted exhaust gases. A bond layer with a Coefficients of Thermal Expansion (CTE) in between that of the TBC and metal substrate is typically used to improve coating adhesion. [3]

Optimization- Taguchi method

Taguchi method is an experimental optimization technique that uses standard orthogonal arrays to determine the levels of control factors for experimental trial runs. By using this array it helps us to get maximum information from a minimum number of experiments and also the best level of each parameter can be found.

Basic TBC Design

The basic design consists of a top layer of thermally insulted material and an intermediate bond coat. The inter layer, usually known as bond coat basically provides sufficient adhesive strength between ceramic layer and substrate and to aid to that it also acts as a protection barrier for oxidation and corrosion. Basically, the material of top coat must possess certain properties to make it suitable for thermal barrier coating. The very basic requirement amongst them is low thermal conductivity value. Ceramics with their high thermal resistance offer an excellent coating surface by absorbing the thermal shocks and protecting the substrate. However, there is sufficient difference in the thermal expansion coefficient values of the top coat material and the substrate.

Materials used for TBC in Engine Piston

Al_2O_3: It has very high hardness and chemical inertness. Alumina has relatively high thermal conductivity and low thermal expansion coefficient compared with yttria stabilized zirconia. [4] Even though alumina alone is not a good thermal barrier coating candidate, its addition to yttria stabilized zirconia can increase the hardness of the coating and improve the oxidation resistance of the substrate.

Y-PSZ: One of the widely used ceramic coating material. Main advantages of using yttria partially stabilized zirconia are high thermal expansion coefficient, low thermal conductivity and high thermal shock resistance [4].

Mullite: It is an important ceramic material because of its low density, high thermal stability, low thermal conductivity, stability in severe chemical environment and favorable strength and creep behavior. Compared with yttria stabilized zirconia, Mullite has a much lower thermal expansion coefficient and high thermal conductivity and is much more oxygen resistant than Y-PSZ [4]. The low thermal expansion coefficient of Mullite is an advantage relative to Y-PSZ in high thermal gradients and under thermal shock conditions.

SiO_2: It is readily available, cheap and may serve as effective TBCs. The coatings of earth oxides have lower thermal conductivity and higher thermal expansion coefficients as compared to YSZ.

Table 1. Thermal properties of Materials used

Materials	Thermal conductivity (W/mK)	Coefficient of thermal expansion /K	Density (Kg/m^3)
AlSi	155	0.000023	2700
Al_2O_3	30	0.0000081	3960
Y-PSZ	2.2	0.00001	5650
$Al_6Si_2O_{13}$	3.3	0.0000053	2800
SiO_2	1.4	0.00000055	2200

Taguchi Method

Taguchi method is an optimization technique which is based on the no. of experiments trials performed for different set of control factors. Experimental trial are conducted according to the orthogonal array which provides us effect of different control parameters in minimum number of experiments trials and optimum level parameter can be obtained.

Table2. Process Parameters used in Taguchi Method.

Level	**(A)** Thickness (µm)	**(B)** Conductivity (W/m K)	**(C)** Coefficient Of thermal expansion (/°C)	**(D)** Density (Kg/m^{3})
1	250	2.2	0.00001	5650
2	350	3.3	0.0000053	2800
3	450	1.4	0.00000055	2200

One of the two types of signal to noise (S/N) ratios, smaller the better and larger the better can be selected based on the requirement in the given problem. ANOVA (analysis of variance) provides the information about the percentage contributions of individual parameters on the selected performance parameter. In the present analysis, four parameters with three levels are considered for optimization of temperature and stresses. In Taguchi optimization, the total number of trial runs or orthogonal array can be obtained using the following expression:

$N_{Taguchi} = 1+NV\ (L-1)$ (1)

Where NV is the number of variables, L is the number of levels and $N_{Taguchi}$ is the total number of trial runs. Here, NV=4 and L=3.

Therefore $N_{Taguchi} = 9$.

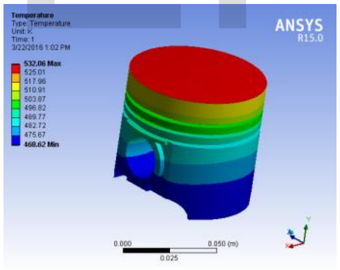
The most suitable orthogonal array for experimentation is L9 array as shown in Table 3. Therefore, a total nine experiments are to be carried out.

Case 1: Optimization of Temperature

Based on the nine cases obtained in orthogonal array in Table 3, Finite Element Simulation was carried out in Ansys 15 for high temperature condition of 650K and convection coefficient of 900 W/m^{2}K and shown in Fig 1.

Table 3: Orthogonal Array (L9)

S.No.	**A**	**B**	**C**	**D**
1	250	2.2	0.00001	5650
2	250	3.3	0.0000053	2800
3	250	1.4	0.00000055	2200
4	350	2.2	0.0000053	2200
5	350	3.3	0.00000055	5650
6	350	1.4	0.00001	2800
7	450	2.2	0.00000055	2800
8	450	1.4	0.00001	2200
9	450	3.3	0.0000053	5650



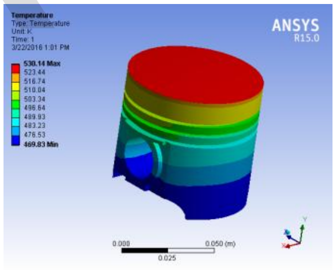
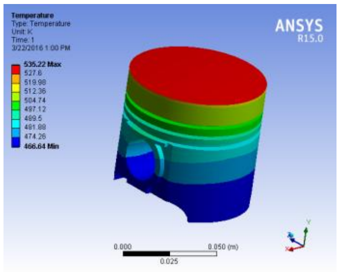


Fig 1(a) Max temperature for case 1 Fig 1(b) Max temperature for case 2



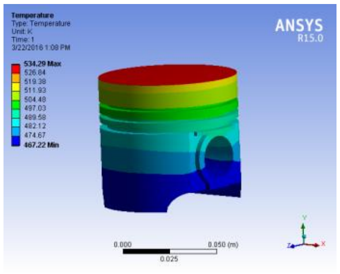
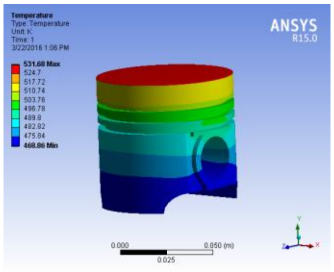


Fig 1(c) Max temperature for case 3. Fig 1(d) Max temperature for case 4.



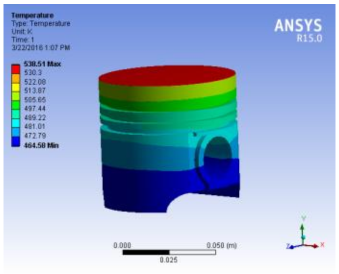
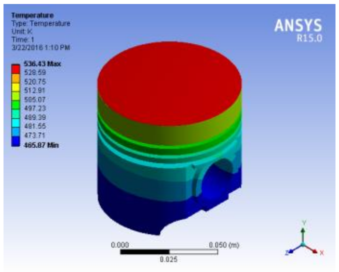


Fig 1(e) Max temperature for case 5. Fig 1(f) Max temperature for case 6.



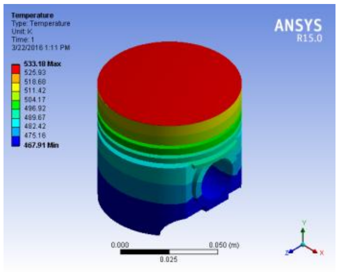


Fig 1(g) Max temperature for case 7. Fig 1(h) Max temperature for case 8.

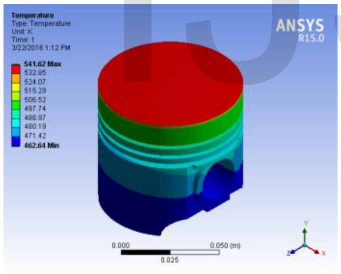


Fig 1(i) Max temperature for case 9.

S/N ratios for L9 Table for Temperature

Taguchi method stresses the importance of studying the response variation using the signal–to–noise (S/N) ratio, resulting in maximization of quality characteristic variation due to uncontrollable parameter. The maximum temperature on the piston was considered as the quality characteristic with the concept of "the larger-the-better". The S/N ratio for the larger-the-better is:

$$S/N = -10 \log_{10}\{1/n\sum 1/y^2\} \qquad (2)$$

Where n is the number of measurements in a trial, in this case, n=1 and y is the measured value in a run[5]. The S/N ratio values are calculated by taking into consideration Eqn (2) with the help of software Minitab. The values measured from the experiments and their corresponding S/N ratio values are listed in Table 4. From these values, graphs are obtained in software itself which shows the variation of mean of S/N ratios with the coating thickness (A), thermal conductivity (B), coefficient of thermal expansion(C) and density (D) respectively in Fig 2. From these linear graphs it is clear that the optimum values of the factors and their levels are as given in table 5. Regardless of the category of the performance characteristics, a greater S/N ratio value corresponds to a better performance.

Table 4. S/N ratios for L9 Table (Temp)

A	B	C	D	Max Temp (K)	S/N Ratio
250	2.2	0.00001	5650	532.06	54.5192
250	3.3	0.0000053	2800	530.14	54.4878
250	1.4	0.00000055	2200	535.22	54.5706
350	2.2	0.0000053	2200	534.29	54.5555
350	3.3	0.00000055	5650	531.68	54.513
350	1.4	0.00001	2800	538.51	54.6239
450	2.2	0.00000055	2800	536.43	54.5903
450	1.4	0.00001	2200	533.18	54.5375
450	3.3	0.0000053	5650	541.62	54.6739

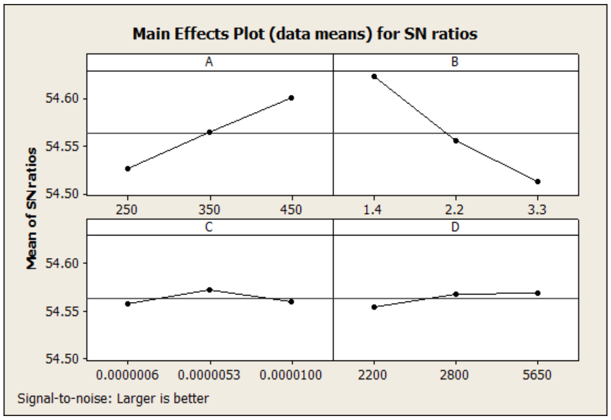


Fig 2. Graphs showing variation of mean of S/N ratios with the four parameters.

Therefore, the optimal level of the parameters is the level with the greatest S/N ratio value. Table 5 shows the optimum level for all control parameters.

Table 5. Optimum Parameters for maximum temperature

	A	B	C	D
Level	3	3	2	1
Value	450	1.4	0.0000053	5650

The above optimum conditions were solved in ANSYS 15 and shown in fig.3. Max temperature obtained after applying optimum conditions: 632.16 K (greater than achieved in cases of orthogonal array).

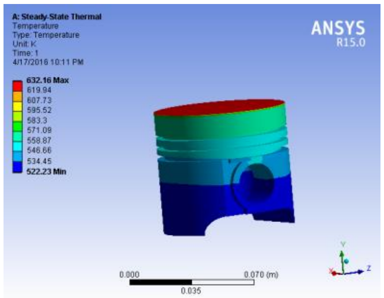


Fig.3. FEM based simulation in ANSYS for optimum conditions of temperature

Delta represents the overall change in a value. In Taguchi designs, delta is the difference between the maximum and minimum mean response across levels of a factor. Based on the values of delta, ranks are obtained which explains the impact of particular factor on the optimizing variable.

Table 6: Table for Delta and Rank (temp)

Level	A	B	C	D
1	54.53	54.62	54.56	54.56
2	54.56	54.56	54.57	54.57
3	54.60	54.51	54.56	54.57
Delta	0.07	0.11	0.01	0.01
Rank	2	1	3	4

From table 6, it is clear that parameter B (conductivity) is the most influencing parameter in case of optimizing temperature.

ANOVA and its Significance

Analysis of variance (ANOVA) is used to evaluate the response magnitude in (%) of each parameter in the orthogonal experiment. It is used to identify and quantify the sources of different trial results from different trial runs.

Table 7: Response Magnitude

SOURCE	DF	SEQ SS	SS%
A	2	0.008362	30.3
B	2	0.018490	67
C	2	0.000363	1.31
D	2	0.000365	1.32

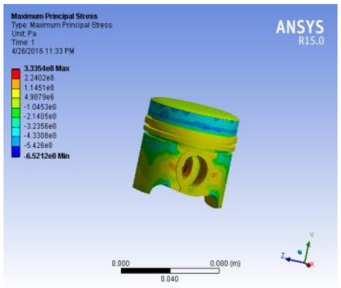
It can be seen from table 7 that the effect of conductivity (67%) is more significant than the thickness of coating (30.3 %) to obtain maximum temperature on the top surface of the thermal barrier coated diesel engine piston.

Case 2: Optimization of Thermal Stress

The minimum stress on the piston was considered as another quality characteristic with the concept of "the smaller-the-better". The S/N ratio for the smaller-the-better is:

$$S/N= -10 \log_{10}\{1/n\sum y^2\} \qquad (3)$$

Result of Finite Element Simulation (Ansys) for minimum stress



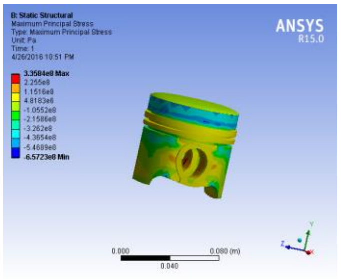
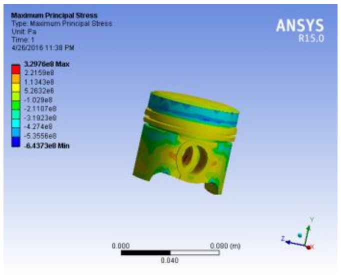


Fig4(a). Minimum stress for case 1 Fig 4(b) Minimum stress for case 2



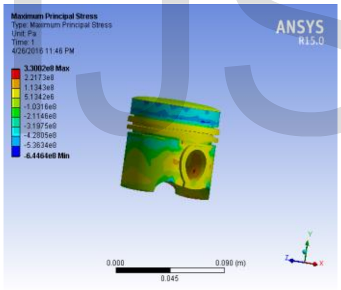
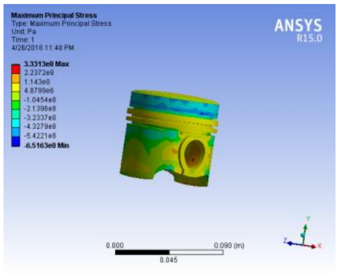


Fig4(c). Minimum stress for case 3 Fig 4(d) Minimum stress for case 4



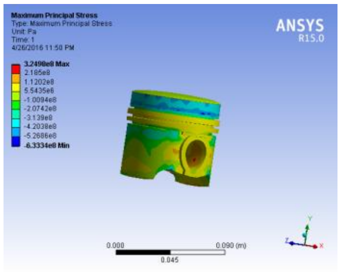
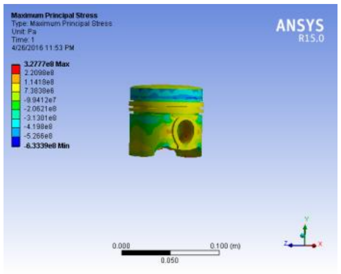


Fig4(e). Minimum stress for case 5 Fig 4(f) Minimum stress for case 6



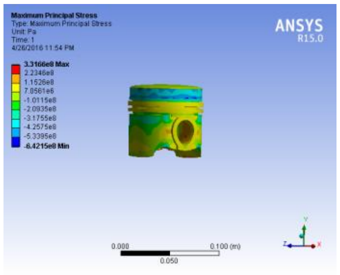


Fig 4(g) Minimum stress for case 7 Fig 4(h) Minimum stress for case 8

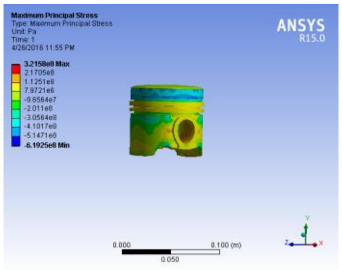


Fig 4(i) Minimum stress for case 9

Table 8. S/N ratios for L9 Table (Stress)

A	B	C	D	Min Stress (Pa)	S/N Ratio
250	2.2	0.00001	5650	333.54	50.463
250	3.3	0.0000053	2800	335.84	50.5226
250	1.4	0.00000055	2200	329.76	50.364
350	2.2	0.0000053	2200	330.02	50.3708
350	3.3	0.00000055	5650	333.13	50.4523
350	1.4	0.00001	2800	324.13	50.2371
450	2.2	0.00000055	2800	327.7	50.3095
450	1.4	0.00001	2200	331.6	50.4123
450	3.3	0.0000053	5650	321.58	50.1458

From the L9 array, table 8 obtained above mean of S/N ratios are calculated and are plotted graphically. Fig. 5 explains the variation of mean of S/N ratios with coating thickness (A), thermal conductivity (B), coefficient of thermal expansion (C) and density (D) respectively.

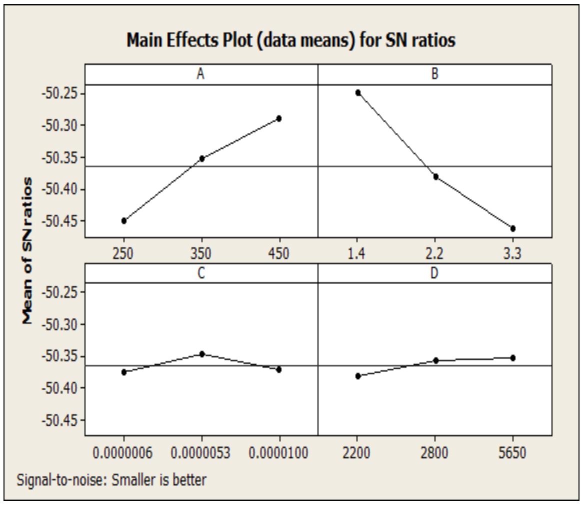


Fig 5. Graphs showing variation of mean of S/N ratios with four parameters.

From these linear graphs it is clear that the optimum values of the factors and their levels are as given in table 9. In case of thermal stress, a smaller S/N value corresponds to a better performance. Therefore, the optimal level of the parameters is the level with the smallest value of s/n ratio.

Table 9. Optimum Parameters for minimum stress

	A	**B**	**C**	**D**
Level	3	3	2	1
Value	**450**	**1.4**	**0.0000053**	**5650**

The above optimum conditions obtained in minitab software for stress was solved in ANSYS 15 as shown in fig 6. Minimum Stress obtained after applying optimum conditions: 321. 58 MPa (which is same as minimum stress achieved in cases of orthogonal array).

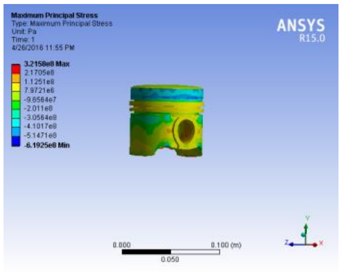


Fig 6. FEM based simulation in ANSYS for optimum conditions of Stress.

Table 10: Table for Delta & Rank (Stress)

Level	A	B	C	D
1	50.45	50.25	50.38	50.38
2	50.35	50.38	50.35	50.36
3	50.29	50.46	50.37	50.35
Delta	0.16	0.21	0.03	0.03
Rank	2	1	3	4

Table 11: Response Magnitude

SOURCE	**DF**	**SEQ SS**	**SS%**
A	2	0.039235	35
B	2	0.069631	62
C	2	0.001446	1.2
D	2	0.001502	1.3

From ANOVA, it is clear that the parameter B i.e. conductivity has a greater influence in minimizing stress (62%) than coating thickness (35%).

Conclusion:

This paper illustrates the application of the parameter design (Taguchi method) in the optimization of temperature and stress for a diesel engine piston. The following conclusions can be drawn based on the above results of this study:

I. Optimum level of the operating parameters for temperature is found to be A3 B3 C2 D1.

II. Thermal conductivity (67%) and coating thickness (30.3%) are most influencing parameters in case of optimizing temperature.
III. Optimum level of the operating parameters for thermal stress is found to be A3 B3 C2 D1.
IV. Thermal conductivity (62%) and coating thickness (35%) are most influencing parameters in case of optimizing stress.
V. The optimum coating thickness of the diesel engine piston is 450 micron, thermal conductivity is 1.4W/mK (SiO_2), coefficient of thermal expansion is 0.0000053/K (Mullite) and density is 5650 Kg/m^3 (Y-PSZ).

References

[1] Kamal Raj Sharma "Thermo Physical Investigation of Partially Stabilized Zirconia'', Lambert Academic Publishing (2015)

[2] Karuppasamy K., Mageshkumar M.P., Manikandan T.N., Naga Arjun J, Senthilkumar T., Kumaragurubaran B., Chandrasekar M. **"**The Effect of Thermal Barrier Coatings on Diesel Engine Performance**"** ARPN Journal of Science and Technology,ISSN 2225-7217, Volume 3, NO. 4, April 2013, PP 382-385.

[3] Michael Anderson Marr "An Investigation of Metal and Ceramic Thermal Barrier Coatings in Spark Ignition Engine" A thesis submitted in conformity with the requirement for the degree of Master of Applied Science, University of Toronto.

[4] Thiruselvam K. "Thermal Barrier Coatings in Internal Combustion Engine" Journal of chemical and Pharmaceutical Sciences, 7(2015), 413-418E.

[5]Krishankant, Taneja J,"Application of Taguchi method for optimizing turning process by the effects of machining parameters" International Journal of Engineering and Advanced Technology 2(2012) 263-274.