

Comparative Thermo-Mechanical Performance and Material Optimization of Bare and Thermal Barrier Coated IC Engine Pistons

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Abstract - Engine pistons are subjected to extreme thermal and mechanical loads during operation, which may lead to excessive stresses, deformation and reduced service life. The present study investigates the effect of thermal barrier coating on the thermo-mechanical performance of IC engine pistons using the Finite Element Method (FEM). A Bajaj Pulsar 220 cc piston model was designed in Fusion 360 and analyzed in ANSYS Workbench under coupled thermal and structural loading conditions. Three candidate materials, namely A2618 alloy, Al-GHS1300 alloy and Ti-6Al-4V alloy, were considered for evaluation. Each material was investigated in both bare and coated configurations. A dual-layer thermal barrier coating consisting of a NiCrAl bond coat and MgZrO₃ ceramic top coat was employed to examine its influence on piston behaviour. The comparative analysis provides insight into the effect of coating and material selection on piston performance under severe operating conditions and assists in identifying the most suitable configuration for enhanced durability.

Keywords - IC Engine Piston; Finite Element Method (FEM); Thermo-Mechanical Analysis; Thermal Barrier Coating (TBC); Material Optimization; A2618 Alloy; Al-GHS1300 Alloy; Ti-6Al-4V Alloy; ANSYS Workbench.

I. INTRODUCTION

The piston is one of the most critical components in an internal combustion engine, this component act as a mediator exchanging energy release during combustion to mechanical motion which transfers it directly into crankshaft rotating, and turning over your vehicle. While in operation, the piston is subjected to very high gas pressures and extreme temperatures which lead pistons to see highly fatigue due to excessive thermal mechanical loading. This phenomenon can cause high stresses, deformation, thermal fatigue and reduced service life which degrade the engine's overall performance and reliability.

The usage of aluminium alloys as pistons has been very popular due to low density, high thermal conductivity, and workability. The current requirement of producing machines with increased power output and increased efficiency has led to the necessity of using more modern materials that will be characterized by high strength and high-temperature properties. Along with choosing the right material, the thermal analysis is also extremely important for maintaining integrity of the piston.

Thermal barrier coatings (TBCs) have emerged as an effective solution for reducing heat transfer to the piston substrate and improving thermal efficiency. Ceramic coatings with low thermal conductivity can withstand high temperatures and provide better thermal insulation, thereby minimizing thermal stresses and enhancing component durability. Furthermore, the latest developments in computer-aided design and finite element analysis have enabled accurate prediction of temperature distribution, stress concentration and deformation without the need for a lot of experimental investigations.

For the current research, Bajaj Pulsar piston with a volume of 220 cc is selected for analysis considering the thermo-mechanical aspects. Designing of the piston geometry is done using Fusion 360 and analysis is conducted using ANSYS workbench considering thermal and structural loads. Three possible material choices, including A2618 alloy, Al-GHS1300 alloy and Ti-6Al-4V alloy are considered in both bare and thermal barrier coated states. The main objective of the research is to find out how material and coatings affect the performance of the piston.

II. LITERATURE REVIEW

Thermo-mechanical behavior of pistons used in engines has received considerable attention for many years to increase the lifespan, reduce weight and increase the efficiency of

engines. With the development of computer aided numerical methods, finite element analysis has become an efficient technique to analyze the structural and thermal behavior of pistons in various situations.

Jadhav et al. [1] designed and optimized a Bajaj Pulsar 220 piston using different aluminum alloys. The paper discussed the process of analytical design and finite element analysis for comparing the response of different materials. This study emphasized the significance of material selection to reduce stress, deformation and maintain weight.

Dhamecha et al. [2] conducted thermal and structural analysis of pistons made of A2618 alloy, Al-GHS1300 alloy and Ti-6Al-4V alloy. The study showed the effect of material properties on the behavior of stress, deformation and safety factor. It is observed from the results that titanium alloys have high strength properties, however, aluminum alloys have better weight and thermal conductivity properties.

Bharath Gowda et al. [3] studied the mechanism of failure of pistons and analyzed the stress concentration under the applied loads. They concluded that thermo-mechanical loading is a critical parameter that affects the life of pistons and the numerical simulation can efficiently predict the failure locations.

Pagadala Siddiraju et al. [4] compared pistons of various materials through finite element analysis and showed that the material properties have a significant effect on the performance of engine parts. Their study provides important information about the correlation between the mechanical properties and piston behavior.

Buyukkaya and Cerit [5] conducted a threedimensional thermal analysis of ceramic coated diesel engine pistons by using finite element method. It was found in the study that the thermal barrier coating can effectively decrease the heat transfer to the substrate material and improve the thermal performance of pistons. The study shows that MgZrO₃ ceramic top coat with a NiCrAl bond layer is more effective in improving thermal insulating properties and decreasing the temperature gradients within the piston body.

Although many studies have been conducted regarding material selection and thermal barrier coatings, there is limited number of studies that discuss the combined thermo-mechanical behavior of coated and bare pistons made of advanced materials under the same working conditions. Hence, the current study intends to conduct a comparative analysis of A2618, Al-GHS1300 and Ti-6Al-4V pistons in both coated and bare situations to find a suitable combination of material and coating for better thermo-mechanical performance.

III. METHODOLOGY

The methodology adopted in this work comprises the following steps:

- Analytical design of the piston.
- CAD modelling in Fusion 360 and Coated in Ansys DesignModeler
- Material selection and coating configuration.
- Finite element modelling in ANSYS Workbench.
- Thermal and structural loading conditions.
- Coupled thermo-mechanical analysis.
- Performance comparison and optimization.

3.1 Engine Specifications and Analytical Design Calculation

Engine: Bajaj Pulsar 220 cc petrol engine.

Table-1: Engine Specifications

Parameter	Value
Engine Type	Four-stroke Petrol Engine
Cooling System	Air-cooled
Number of Cylinders	Single Cylinder
Bore (D)	67 mm
Stroke (L)	62.4 mm
Length of Connecting Rod	124.8 mm
Displacement Volume	220 cm ³
Compression Ratio	9.5 ± 0.5:1
Maximum Power	15.51 kW at 8500 rpm
Maximum Torque (T)	19.12 N-m at 7000 rpm
Number of Revolutions per Cycle	2

****Let, Mechanical efficiency of the engine (η) = 75 %.**

$$\eta = \text{Brake power (B.P)} / \text{Indicated power (I.P)}$$

$$\text{Brake power} = 2\pi NT/60 = 2\pi * 7000 * 19.12 / (60 * 1000)$$

$$\text{BP} = 14.0085 \text{ KW}$$

$$\text{Therefore, I.P} = \text{B.P} / \eta = 14.0085 / 0.75 = 18.678 \text{ KW}$$

$$\text{Also, I.P} = P * A * L * N / 2$$

$$\text{I.P} = P * \pi / 4 * D^2 * L * N / 2$$

$$18.678 * 1000 = P * \pi / 4 * (0.067)^2 * (0.0624) * (7000) / 2 * 60$$

So, $P = 1.456 \times 10^6 \text{ N/m}^2$ or $P = 1.456 \text{ MPa}$

Maximum Pressure (P_{max}) = $10 \times P = (10 \times 1.456) = 14.56 \text{ MPa}$

Nomenclature of Piston Design

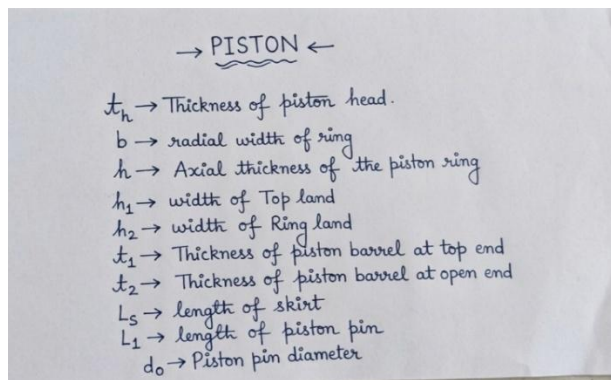
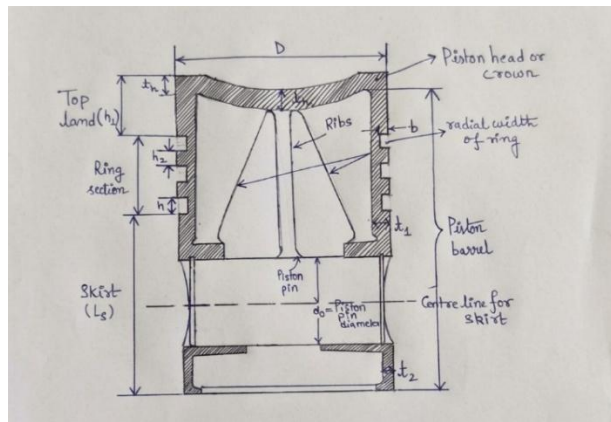


Fig. 1: Nomenclature of Piston Design

Analytical design for A2618 alloy piston:

Thickness of the Piston Head: According to Grashoff's formula the thickness of the piston head is given by

Thickness of piston head based on strength:

$$t_h = D \sqrt{(3 P_{\text{max}} / 16 \sigma_t)} \quad [D = \text{cylinder bore diameter}]$$

where $\sigma_t = \sigma_{\text{ut}} / 2.5 = 480 / 2.5 = 192 \text{ MPa}$

Therefore $t_h = 67 \times \sqrt{(3 \times 14.56) / (16 \times 192)} = 7.9892 \text{ mm}$

Piston Rings:

The radial width of the ring is given by

$$b = D \sqrt{(3 P_w / \sigma_p)} = 67 \sqrt{(3 \times 0.025 / 100)} = 1.8348 \text{ mm}$$

Axial thickness of the piston ring

$$h = (0.7 b \text{ to } b) = 0.7 \times 1.8348 = 1.28436 \text{ mm}$$

Width of Top Land and Ring Lands

Width of top land (h_1)

$$h_1 = (t_h \text{ to } 1.2 t_h) = 9.5870 \text{ mm}$$

Width of ring land (h_2)

$$h_2 = (0.75 h \text{ to } h) = 0.75 \times 1.2844 = 0.96327 \text{ mm}$$

Piston Barrel

Thickness of piston barrel at the top end (t_1)

$$t_1 = 0.03 D + b + 4.9 = 0.03 \times 67 + 1.834 + 4.9 = 8.744 \text{ mm}$$

Thickness of piston barrel at the open end (t_2)

$$t_2 = 0.25 t_1 \text{ to } 0.35 t_1 = 0.25 \times 8.744 = 2.186 \text{ mm}$$

Length of the Skirt

$$L_s = (0.6 D \text{ to } 0.8 D) = 0.6 \times 67 = 40.2 \text{ mm}$$

Length of Piston Pin in Connecting Rod Bushing

$$L_1 = 45\% \text{ of piston diameter} = 0.45 \times 67 = 30.15 \text{ mm}$$

Piston Pin Diameter

$$d_o = (0.28 D \text{ to } 0.38 D) = 0.3 \times 67 = 20.1 \text{ mm}$$

The center of piston pin should be $0.02 D$ to $0.04 D$ above center of the skirt = $0.03 \times 67 = 2.01 \text{ mm}$ above skirt center.

Similarly, analytical design for Al-GHS 1300 and Ti-6Al-4V alloy is also carried out and the dimensions of the three pistons are presented in the table below:

Table-2: Dimensions of Pistons

PARAMETERS	VALUES (mm)		
	A2618	Al-GHS 1300	Ti-6Al-4V
Thickness of piston head (t_h)	7.989	4.854	5.6789
Piston rings radial width (b)	1.834	1.834	1.834
Axial thickness (h)	1.284	1.284	1.284
Width of top land (h_1)	9.587	5.827	6.814
Ring lands (h_2)	0.963	0.963	0.963
Thickness of piston barrel at top end (t_1)	8.744	8.744	8.744
Thickness of piston barrel at open end (t_2)	2.186	2.186	2.186
Length of skirt (L_s)	40.2	40.2	40.2
Length of piston pin in connecting rod bushing (L_1)	30.15	30.15	30.15
Piston pin diameter (d_o)	20.1	20.1	20.1
Length of Piston Pin in Connecting Rod Bushing ($1.5 d_o$)	30.15	30.15	30.15

3.2 CAD Modelling

Three-dimensional model of piston was created in **Fusion 360** using the calculated dimensions. The model was imported into **Ansys DesignModeler**, where the thermal barrier coating layers were added to obtain the coated piston model for analysis.

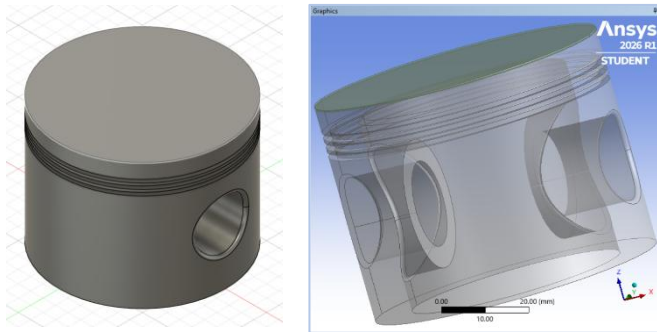


Fig. 2: 3-D CAD Model of Piston

3.3 Material Selection

Table-3: Material Properties

Parameters	A2618	Al-GHS1300	Ti-6Al-4V
Elastic Modulus (GPa)	73.7	98	113.8
Ultimate Tensile Strength (MPa)	480	1300	950
0.2% Yield Strength (MPa)	420	1220	880
Poisson's Ratio	0.33	0.30	0.33
Thermal Conductivity (W/m·°C)	147	120	7.3
Coefficient of Thermal Expansion (1/K)	25.9×10^{-6}	18×10^{-6}	8.6×10^{-6}
Density (kg/m ³)	2767.9	2780	4430

Table-4: Thermal Barrier Coating Material Properties

Property	NiCrAl Bond Coat	MgZrO ₃ Ceramic Top Coat
Thermal Conductivity (W/m·°C)	16.1	0.8
Coefficient of Thermal Expansion ($\times 10^{-6}$ /°C)	12	8

Density (kg/m ³)	7870	5600
Specific Heat (J/kg·°C)	764	650
Poisson's Ratio	0.27	0.20
Young's Modulus (GPa)	90	46

3.4 Thermal Barrier Coating

This study made use of a double layer thermal barrier coating consisting of a 0.15 mm thick NiCrAl bond layer and a 0.35 mm thick MgZrO₃ ceramic top layer. The thermal barrier coating system was selected in an attempt to enhance thermal insulation of the piston head area.

3.5 Analysis of Piston

3.5.1 Material Assignment

Material properties were assigned for the piston and coating layers in the Engineering Data module section in ANSYS Workbench.

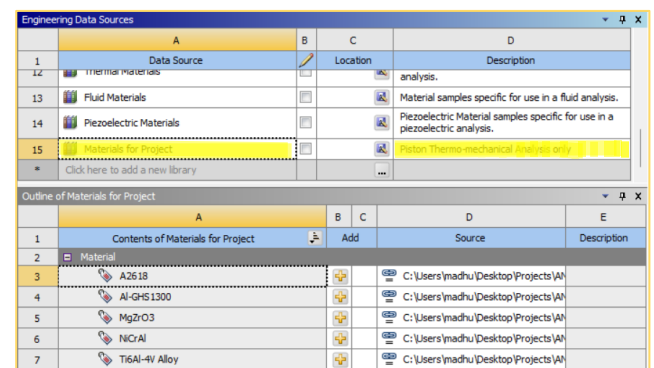


Fig. 3: Engineering Data Sources Ansys

3.5.2 Meshing

- Tetrahedral elements are used for meshing
- Element size is kept around 3 mm

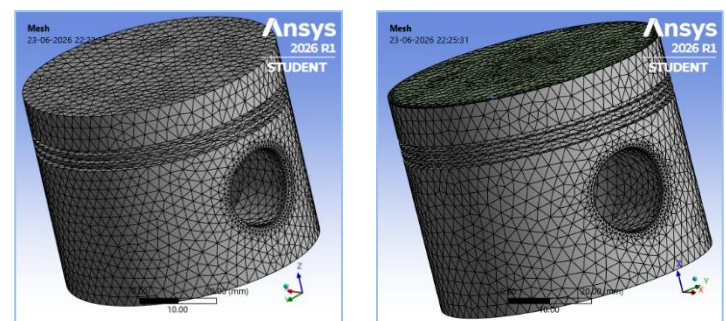


Fig. 4: Meshing of Piston Bare and Coated

3.5.3 Boundary Conditions

➤ Thermal Boundary Conditions

The convective heat transfer conditions were considered for various parts of the piston. The temperatures and convective heat transfer coefficients used in the analysis are shown below in the table.

Table-5: Applying Convection Boundary Conditions

Region	Ambient Temperature (°C)	Convection Coefficient (W/m ² ·K)
Piston Crown	650	800
Upper Ring Land	300	230
Ring Grooves	160	200
Piston Skirt, Pin Area and inside	85	60

➤ Structural Boundary Conditions

In static Structural Loading & Boundary Condition

- Pressure at the piston head: 14.56 MPa
- Apply a frictionless support at the piston pin hole to allow free pin rotation.
- Fixed supports are applied at edges of piston pin hole.

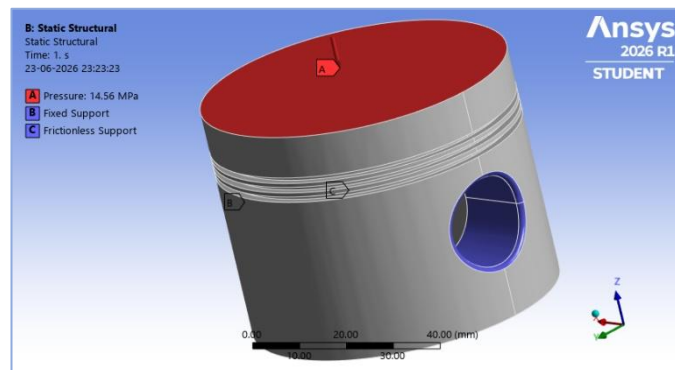


Fig. 5: Applying Static Structural Boundary Conditions

3.5.4 Steady-State Thermal Analysis

Steady-state thermal analysis was done for studying the temperature profile and heat transfer behavior. Analysis has been carried out on both uncoated and thermal barrier coated (TBC) pistons under similar thermal boundary conditions to understand the insulation property of the TBC layer.

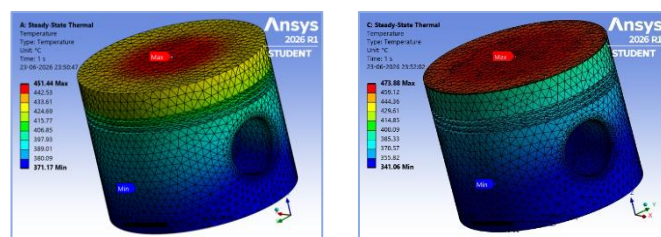


Fig. 6: Temperature distribution of bare (left) and coated (right) A2618 piston.

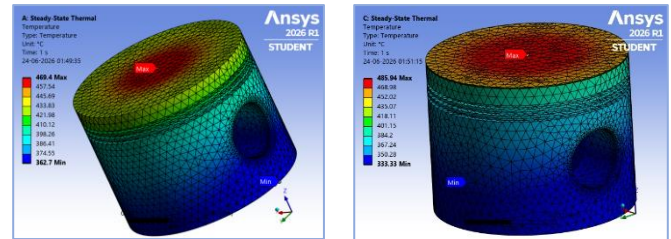


Fig. 7: Temperature distribution of bare (left) and coated (right) Al-GHS1300

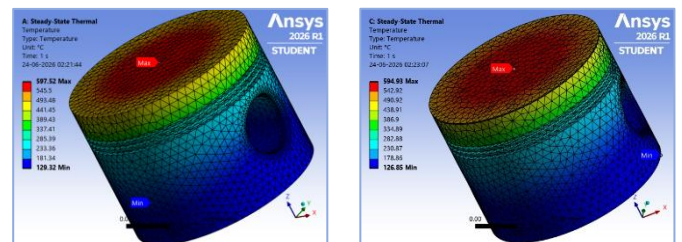
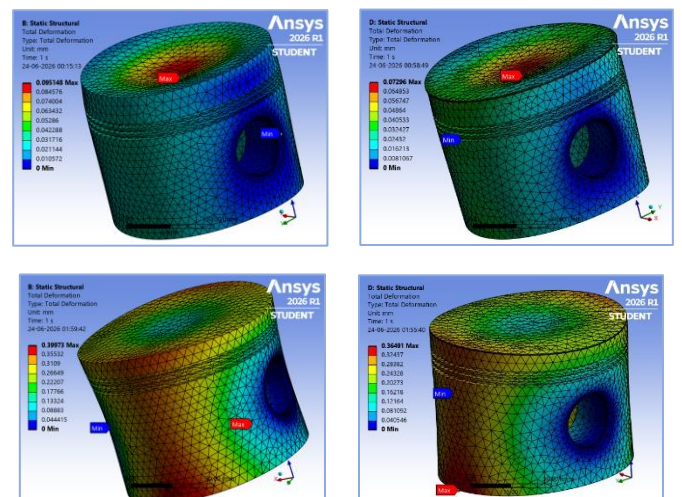


Fig. 8: Temperature distribution of bare (left) and coated (right) Ti-6Al-4V piston.

3.5.5 Thermo-Mechanical Analysis

Thermo-mechanical analysis was performed by importing the temperature field obtained from the steady-state thermal analysis into the static structural module. Combined thermal and mechanical loads were considered to evaluate the equivalent stress, equivalent strain, total deformation and factor of safety of both bare and coated piston configurations.

The thermo-mechanical behaviour of A2618, Al-GHS1300 and Ti-6Al-4V piston models in both bare and coated configurations is illustrated in Figs. 9-12



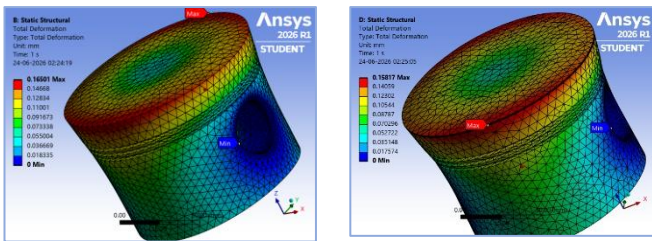


Fig. 9: Total Deformation of bare (left) and coated (right) A2618, Al-GHS1300 and Ti-6Al-4V piston.

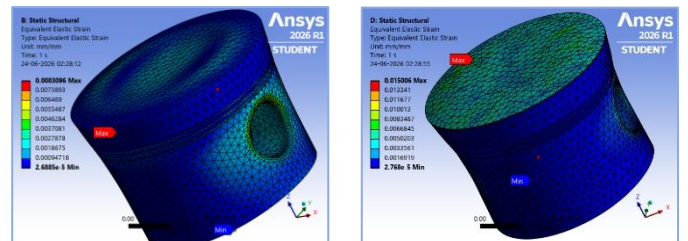


Fig. 11: Equivalent strain of bare (left) and coated (right) A2618, Al-GHS1300 and Ti-6Al-4V piston.

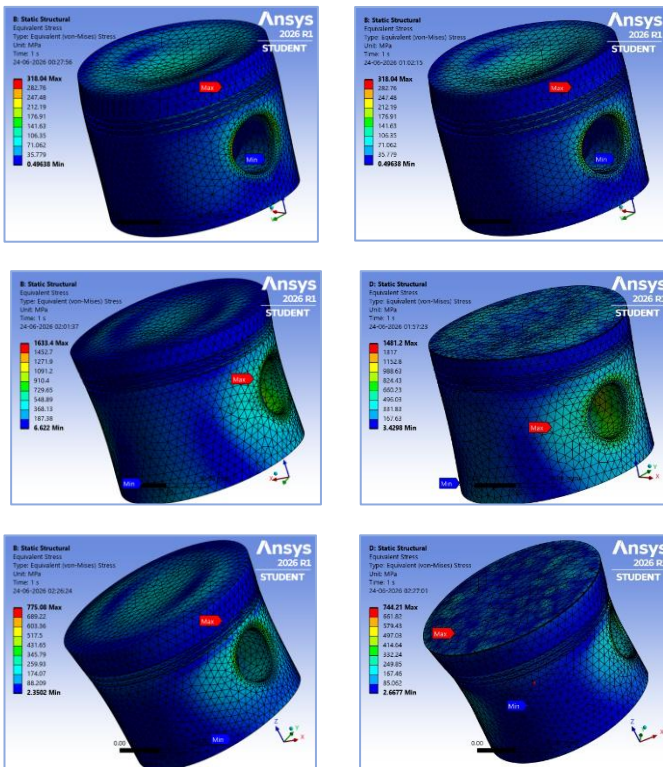


Fig. 10: Equivalent stress of bare (left) and coated (right) A2618, Al-GHS1300 and Ti-6Al-4V piston

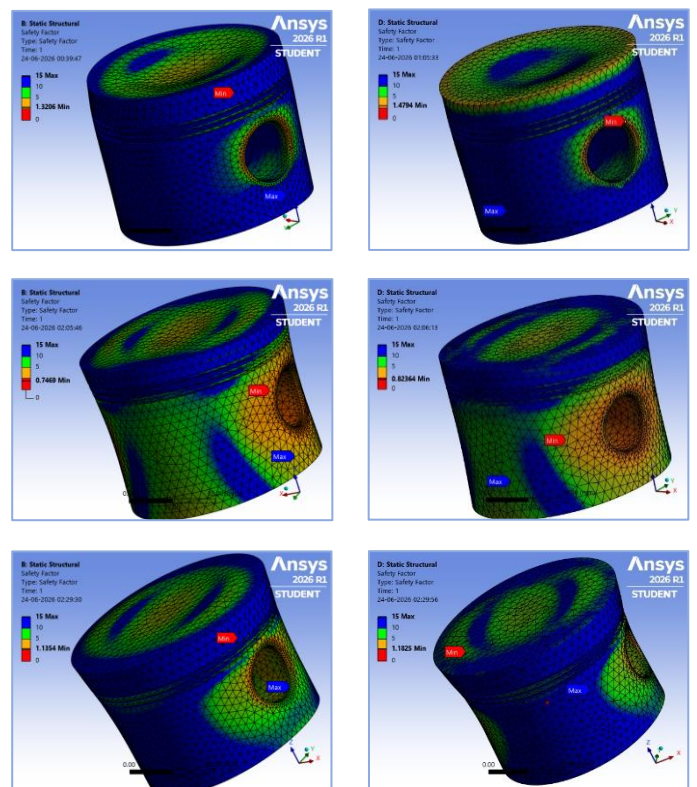
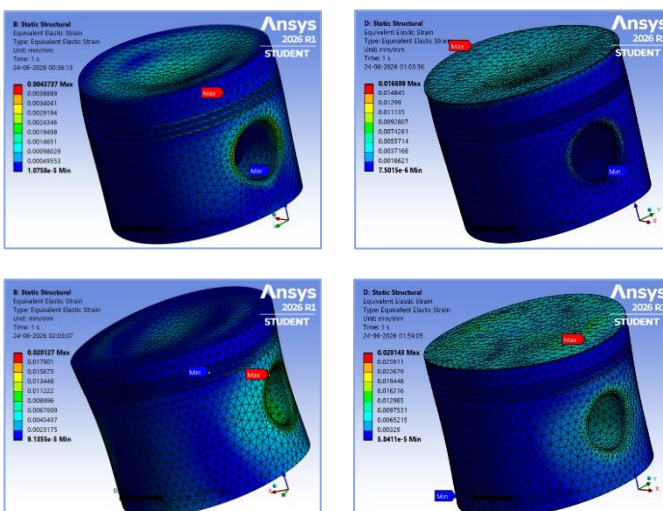


Fig. 12: Factor of safety of bare (left) and coated (right) A2618, Al-GHS1300 and Ti-6Al-4V piston.



IV. RESULTS AND DISCUSSION

4.1 Steady-State Thermal Analysis

Table-6: Comparison of temperature distribution for bare and thermal barrier coated piston models.

Parameter	A2618	Al-GHS1300	Ti-6Al-4V
Maximum Temperature (°C) – Without Coating	451.44	469.40	597.52
Minimum Temperature (°C) – Without Coating	371.17	362.70	129.32
Maximum Temperature (°C) – With Coating	473.88	485.94	594.93

Minimum Temperature (°C) – With Coating	341.06	333.33	126.85
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As seen from Figures 6-8, the coated piston configurations showed higher temperatures at the crown area and lower temperatures within the piston body than the uncoated models. This behavior confirms the capability of the thermal barrier coating to limit heat transfer into the substrate material. Among the materials considered, the Ti-6Al-4V piston attained the highest maximum temperature, whereas A2618 exhibited relatively lower temperature values. In general, the thermal barrier coating enhanced the thermal insulation performance of all three piston materials.

4.1.1 Heat Flux Analysis

The heat flux values obtained using the models without and with thermal barrier coatings have been provided in Table 7. It is evident that the use of thermal barrier coatings has led to a drop in heat flux values in all three cases of pistons, which is indicative of the decrease in heat transfer from the combustion chamber to the piston wall. The highest reduction was noted for A2618, where the value was reduced from 0.75612 W/mm² to 0.16123 W/mm² after the application of the coating. This trend was also true for Al-GHS1300 and Ti-6Al-4V.

Table-7: Heat Flux Comparison for Bare and Coated Pistons

Material	Without Coating Heat Flux (W/mm ²)	With Coating Heat Flux (W/mm ²)
A2618	0.75612	0.16123
Al-GHS1300	0.84065	0.73618
Ti-6Al-4V	0.28832	0.26859

4.2 Thermo-Mechanical Analysis

Table-8: Comparison of Thermo-Mechanical Performance of Bare and Coated Piston

Parameter	A2618 (Bare)	A2618 (Coated)	Al-GHS1300 (Bare)	Al-GHS1300 (Coated)	Ti-6Al-4V (Bare)	Ti-6Al-4V (Coated)
Total Deformation (mm)	0.095198	0.07296	0.39973	0.36491	0.16501	0.15817
Max Substrate Stress (MPa) (Body Only)	318.04	283.90	1633.40	1481.20	775.08	744.21
Max Coating Stress (MPa) (Coated Faces Only)	N/A	1376.30	N/A	424.16	N/A	309.35
Max Substrate Strain (mm/mm) (Body Only)	0.0093737	0.0043617	0.020197	0.019654	0.0083096	0.0083722
Max Coating Strain (mm/mm) (Coated Faces Only)	N/A	0.016699	N/A	0.014389	N/A	0.010326
Volume (mm ³)	59,227	100,330	89,977	91,734	92,885	99,490
Mass (kg)	0.27466	0.28573	0.25014	0.261019	0.41195	0.42252
Factor of Safety (Piston Body Only)	1.3206	1.4794	0.7465	0.8236	1.1354	1.1085

Based on the thermo-mechanical results presented in Table 8:

- The usage of the thermal barrier coating resulted in the decrease of total deformation for all the investigated piston materials. The deformation for A2618 decreased from **0.095198 mm** to **0.07296 mm** ($\approx 23.4\%$), and for other materials it decreased approximately by **8.7%** (for Al-GHS1300) and **4.1%** (for Ti-6Al-4V). It means that the thermal barrier coating positively influences the dimensional stability of the piston.
- The maximum substrate stress also decreased after the usage of the thermal barrier coating. The substrate stress for A2618 decreased from **318.04 MPa** to **283.90 MPa**, and for Al-GHS1300 from **1633.40 MPa** to **1481.20 MPa** and for Ti-6Al-4V from **775.08 MPa** to **744.21 MPa**. It indicates that the thermal barrier coating successfully reduces the mechanical stress applied to the piston body.
- The ceramic coating experiences higher localized stresses than the substrate. The maximum coating stress is found for **A2618 (1376.30 MPa)**, then for **Al-GHS1300 (424.16 MPa)** and for **Ti-6Al-4V (309.35 MPa)**. As the stresses are localized, then the metallic part of the piston is comparatively less stressed than the coating layer.
- The maximum substrate strain decreases after coating application for all materials, whereas the coating layer experiences relatively higher strains due to the different thermal expansion properties of the ceramics and metallic materials. Thus, a considerable part of thermo-mechanical strain is localized within the coating layer.
- Among the investigated materials, **A2618** demonstrates the lowest substrate stress and the highest factor of safety after coating, thus, it represents the best structural performance. **Al-GHS1300** has the highest substrate stress in bare and coated pistons, and **Ti-6Al-4V** possesses comparatively lower deformations and stress values, and it is the appropriate material for high-temperature engines.
- The presence of the **0.15 mm NiCrAl bond coat** and **0.35 mm MgZrO₃ ceramic top coat** increases the volume and mass of the piston for all materials; however, the values of the increase are insignificant relative to the improvement in the thermal insulation and structural performance.
- The factor of safety increases from **1.3206** to **1.4794** for A2618 and from **0.7465** to **0.8236** for Al-GHS1300 after coating application, which demonstrates the improvement of load-bearing

capacity. At the same time, the factor of safety for Ti-6Al-4V slightly decreases from **1.1354** to **1.1085**; nevertheless, it is greater than one, which means that the coated piston works at a safe level.

- In general, the thermal barrier coating improves the thermo-mechanical behavior of all the investigated materials due to the decrease of heat transfer into the substrate, reduction of substrate stress and deformation and improvement of overall structural response. Based on the consideration of deformation, substrate stress, strain and factor of safety, **the coated A2618 piston** represents the best overall performance.

V. CONCLUSION

The comparative thermo-mechanical performance of bare and thermal barrier coated IC engine pistons made from A2618, Al-GHS1300 and Ti-6Al-4V was analysed using ANSYS Workbench software at identical operating conditions. The geometry of the piston was designed in Fusion 360 and dual-layer thermal barrier coating made up of a 0.15mm NiCrAl bond layer and 0.35mm MgZrO₃ ceramic top layer was provided to analyse its effects on the thermal and mechanical properties.

It was observed from the steady state thermal analysis that the thermal barrier coating decreased the heat transfer to the piston body, thus providing better thermal insulation with less heat flux. Furthermore, in the case of thermo-mechanical analysis, the piston models with coating showed lower substrate deformation, stress and strain, compared to the uncoated pistons, indicating that the mechanical stability increased when subjected to both thermal and mechanical loadings. Although the stresses generated in the ceramic layer were high, it remained in the ceramic layer itself and therefore decreased the mechanical load on the metallic substrate.

As per the overall performance of the materials under investigation, A2618 had better thermo-mechanical characteristics as it had minimum substrate stress and deformations along with maximum factor of safety with the coating applied to it. Ti-6Al-4V also had good thermo-mechanical performance with relatively lower deformations and stresses whereas Al-GHS1300 showed maximum stress although it was an improvement through coating. Overall, it was found that the application of MgZrO₃-NiCrAl coating had significantly improved the thermo-mechanical performance of the pistons and the A2618 piston was the most preferable configuration of all the pistons considered in the present work.

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