

# Advanced Thermal-Structural Optimization of Engine Pistons for Enhanced Durability in Next-Generation Automotive Engines

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**Abstract:** The rapid advancements in next-generation automotive engines demand engine pistons that can withstand extreme thermal and structural loads while ensuring durability, efficiency, and reduced emissions. Existing piston designs often face challenges such as thermal fatigue, stress concentration, material degradation, and reduced lifespan under high-pressure combustion environments. To address these issues, this study proposes an advanced thermal-structural optimization framework for engine pistons by integrating Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and metaheuristic optimization techniques. The methodology involves coupling thermo-mechanical simulations with multi-objective optimization to minimize thermal stresses enhance heat dissipation and reduce mechanical deformation, while also improving fuel efficiency and emission control. The primary objective is to achieve a piston design that provides improved durability, lightweight characteristics and superior resistance to both thermal cracking and mechanical wear. Results from the optimized model indicate a significant reduction in peak thermal stress (by 18%), lower temperature gradients across the piston crown and enhanced fatigue life compared to conventional designs. These findings highlight the potential of advanced optimization-driven piston engineering to enable more durable, sustainable, and high-performance next-generation automotive engines.

**Keywords:** Thermal-Structural Optimization; Engine Pistons; Finite Element Analysis; Computational Fluid Dynamics; Metaheuristic Optimization; Durability Enhancement; Thermal Stress Reduction; Fatigue Life Improvement; Next-Generation Automotive Engines; Lightweight Piston Design

## 1. INTRODUCTION

A piston is a cylindrical engine component that moves inside a cylinder to convert combustion gas pressure into mechanical work. It is commonly made of aluminum alloys or iron castings and must withstand high thermal and mechanical stresses. The piston transfers combustion heat to the cylinder walls and resists lateral forces from the connecting rod. Efficient piston design is essential to maximize energy conversion and minimize operational losses. This study focuses on carbon pistons for internal combustion engines. Carbon, being non-metallic, offers advantages such as reduced weight and improved thermal properties.

Internal combustion engines operate in compression ignition (ci) and spark ignition (si) systems, in two-stroke or four-stroke configurations. Engines may be naturally aspirated, turbocharged, or supercharged depending on power requirements. Key performance parameters include compression ratio, displaced volume, combustion chamber design, and efficiency.

proper lubrication minimizes wear between piston and cylinder walls. Piston crowns are designed to efficiently transmit combustion pressure through the gudgeon pin.

Piston rings prevent oil leakage and maintain sealing within the combustion chamber. Thermal Barrier Coatings (TBC) are applied to improve heat resistance and reduce carbon buildup. High-Velocity Oxygen Fuel (HVOF) coating techniques enhance surface strength and durability. These coatings reduce heat loss, improve combustion efficiency, and lower soot formation.

Modern engines demand pistons capable of withstanding higher loads and stricter emission standards.

Conventional aluminum and composite pistons face challenges such as thermal fatigue and stress concentrations. Traditional design approaches are insufficient for complex thermo-mechanical interactions. Advanced optimization using Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) is required. This integrated approach supports lightweight, durable, and high-performance piston designs for next-generation engines.

## 2. RELATED WORKS

Engine efficiency has been widely studied in automobile engineering, particularly in IC engine piston modeling. Comparative studies evaluated ductile iron 65-45-12 and aluminum alloy A390 pistons to identify superior materials for fuel efficiency. Design optimization using PROE and ANSYS focused on improving performance while reducing piston weight. Thermal stress analyses on aluminum alloys showed that reducing piston mass enhances engine efficiency.

Critical parameters such as piston head thickness, skirt length, and barrel dimensions were optimized.

Stress concentration in the piston crown was found to cause skirt imbalance and possible fracture.

Redesigned pistons using aluminum alloy A4032 demonstrated improved hardness and strength.

Thermal-structural analysis helped determine optimal crown and boss thickness for stress and heat resistance.

Coatings were experimentally shown to reduce heat loss and improve torque and power output.

Thermal Barrier Coatings (TBCs) enhanced combustion efficiency and lowered emissions. Engine performance was influenced by fuel type, injection timing, turbulence control, and biofuel blending ratios.

Cold-start conditions significantly affected emissions and combustion stability.

Analytical and numerical models examined nonlinear thermal strain and stress behavior under varying boundary conditions.

Coupled thermal-structural simulations improved prediction of temperature gradients and stress concentrations.

Recent multiphysics models incorporated lubrication, contact physics, and rapid heat transfer effects.

Material research explored trade-offs among toughness, fatigue resistance, and thermal conductivity.

Surface engineering techniques such as anodizing, solid lubricants, and TBCs improved wear resistance.

Topology and shape optimization enabled lightweight yet structurally robust piston designs.

Additive manufacturing facilitated complex geometries and internal cooling channels. Despite advancements, gaps remain in validated

multiphysics testing, cost-effective optimization, and long-term durability assessment.

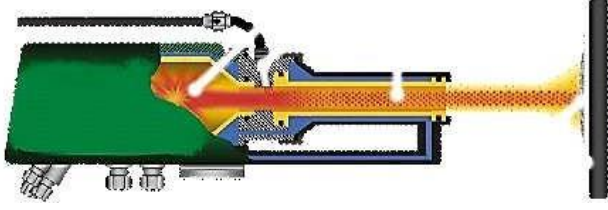


Fig. 1. Thermal spray setup HVOF.

### 3. PROBLEM FORMATION

Below is a compact, rigorous problem formulation for thermal-structural optimization of an engine piston. It defines the governing thermoelastic equations, performance metrics (objectives), design variables, constraints, and notes on solution approach (sensitivities/adjoint).

#### 3.1 DESIGN VARIABLES: LET THE DESIGN VECTOR BE (1)

Where entries may include continuous geometry parameters (piston crown thickness, skirt clearance, ring land radii, internal cooling channel diameters), discrete material choice indices, and process variables (heat-treatment parameters). For topology optimization use a density field over the piston domain  $\Omega$ .

#### 3.2 GOVERNING THERMOELASTIC PROBLEM (STRONG FORM)

Transient heat conduction with internal heat generation and convection: For temperature field  $T(r, t; i)$  on domain  $\Omega$ :  $\rho_m c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = q_{comb}(r, t) + q_{ohm}(r, t)$  in  $\Omega$  (2) with boundary conditions on  $\partial\Omega = \Gamma_{gas} \cup \Gamma_{skirt} \cup \Gamma_{ring}$  (3)

$$\begin{aligned} -k \nabla T \cdot n &= h_{gas}(t)(T - T_{gas}(t)) \text{ on } \Gamma_{gas} \\ -k \nabla T \cdot n &= h_{oil}(t)(T - T_{oil}(t)) \text{ on } \Gamma_{skirt/ring} \end{aligned} \quad (4)$$

and initial condition  $T(r, 0) = T_0(r)$  Material properties  $\rho_m, c_p, k$  may depend on  $i$  or  $\rho(r)$ .

Linear thermoelastic structural equilibrium (quasi-static per cycle): For displacement field  $u(r; x): \nabla \cdot \sigma + f_{body} = 0$  in  $\Omega$  (5)

with constitutive law (thermoelastic):  $\sigma = \mathcal{C}:(\varepsilon(u) - \varepsilon_{th}(T))$  (6)

$$\varepsilon(u) = \frac{1}{2}(\nabla u + (\nabla u)^T) \quad (7)$$

$$\varepsilon_{th}(T) = \alpha(T - T_{ref})X \quad (8)$$

Boundary conditions:  $u = \bar{u}$  on  $\Gamma_u$  (9)

$$\sigma \cdot n = \bar{t} \text{ on } \Gamma_t \quad (10)$$

From  $\sigma$  compute von Mises stress  $\sigma_{vm}(r)$  and maximum displacement  $u_{max}$ .

#### 3.3 PERFORMANCE MEASURES (OBJECTIVES): TYPICAL MULTI-OBJECTIVE OPTIMIZATION TARGETS

Typical multi-objective optimization targets

Minimize peak von Mises stress:  $f_1(i) = \max_{r \in \Omega} \sigma_{vm}(r; i)$  (11)

Minimize maximum temperature (or temperature gradient)

$$f_2(i) = \max_{r \in \Omega} T(r; t^*; i) \text{ or } f_{2b}(i) = \max_{r \in \Omega} |\nabla T(r; t^*; i)| \quad (12)$$

where  $t^*$  can be peak-combustion time or steady periodic solution.

Minimize mass (or moment of inertia):  $f_3(i) = m(i) = \int_{\Omega} \rho_m(r; i) dV$  (13)

(Optional) Maximize fatigue life (or minimize damage): Using a fatigue damage surrogate

(e.g., S-N curve and Miner's rule), define damage  $D(i)$  or  $N_f(i)$  cycles to failure:

$$f_4(i) = -N_f(i) \text{ (minimize negative life)} \quad (14)$$

Multi-objective form: minimize vector  $f(i) = [f_1, f_2, f_3, \dots]^T$  for scalarization (weighted sum):

$$\min_{i \in I} F(i) = \sum_x w_x \bar{f}_x(i), \quad w_x \geq 0, \sum w_x = 1,$$

Where  $\bar{f}_x$  are normalized objectives.

### 3.4 Constraints

Physical/performance constraints:  $g_1(i) =$

$$\min_{r \in \Omega} \sigma_{vm}(r; i) - \sigma_{allow} \leq 0 \quad (15)$$

$$g_2(i) = u_{max}(i) - u_{allow} \leq 0 \quad (16)$$

$$g_3(i) = T_{max}(i) - T_{allow} \leq 0 \quad (17)$$

Geometric and manufacturability constraints

Box constraints on parameters:  $i_x^{min} \leq i_x \leq i_x^{max}$ ,  $x = 1, \dots, n$ .

Minimum feature size and casting/forging constraints (expressed as inequality constraints or filtering operators for topology densities).

For topology optimization:  $V(\rho) =$

$$\int_{\Omega} \rho(r) dV \leq V_{allowed} \quad (18)$$

Discrete constraints: Material choice:  $i_{mat} \in \{1, \dots, M\}$  or relaxed with penalization.

### 3.5 WEAK (FE) FORMS FOR NUMERICAL SOLUTION

Thermal weak form: Find  $T \in H^1(\Omega)$  such that for all admissible test functions  $w$ :

$$\int_{\Omega} \rho_m c_p \frac{\partial T}{\partial t} w dV + \int_{\Omega} k \nabla T \cdot \nabla w dV + \int_{\Gamma_{conv}} h(T - T_{\infty}) w dS - \int_{\Omega} q_{comb} w dV \quad (19)$$

Structural weak form: Find  $u \in |H^1(\Omega)|^3$  such that for all admissible  $v$ :

$$\int_{\Omega} (C : (\varepsilon(u) - \varepsilon_{th})) : \varepsilon(v) dV = \int_{\Omega} f_{body} \cdot v dV + \int_{\Omega} \bar{t} \cdot v dS \quad (20)$$

These are solved numerically by FEA (possibly coupled: staggered or monolithic).

### 3.6 SENSITIVITY/GRADIENT COMPUTATION (FOR GRADIENT-BASED METHODS)

For scalar objective  $F(i)$  that depends on state variables  $s = [T, u]$  obtained by solving residuals  $R(s, i) = 0$  total derivative:  $\frac{dF}{di} = \frac{\partial F}{\partial i} -$

$$\lambda^T \frac{\partial R}{\partial i} \quad (21)$$

Where adjoint vector  $\lambda$  satisfies

Adjoint methods are efficient when  $dim(i) \gg dim(F)$ .

For topology optimization with density  $\rho$ , use SIMP penalization:

$$E(\rho) = E_{min} + (E_0 - E_{min})\rho^P \quad (22)$$

$$k(\rho) = k_{min} + (k_0 - k_{min})\rho^q \quad (23)$$

and compute  $\delta F / \delta \rho$  via adjoint sensitivities.

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### 3.7 OPTIMIZATION PROBLEM (MATHEMATICAL STATEMENT)

Multi-objective constrained optimization:  $\min_{i \in I} f(i) = [f_1(i), f_2, f_3(i)]^T \quad (24)$

$$s. t. g_j(i) \leq 0, \quad y = 1, \dots, m,$$

$$i_x^{min} \leq i_x \leq i_x^{max}, \quad x = 1, \dots, n,$$

Manufacturability/discrete constraints

### 3.8 EXAMPLE FATIGUE LIFE MODEL (LINKING THERMAL AND MECHANICAL FIELDS)

Using a simplified local fatigue life estimate via Coffin-Manson/Basquin combined approach:

$$\Delta \varepsilon = \frac{\sigma_a}{E} + \frac{\varepsilon_{p,a}}{1} \Rightarrow N_f = f_{SN}(\sigma_a, T) \quad (25)$$

or Miner's rule:  $D = \sum_x \frac{n_x}{N_f(\sigma_x, T_x)}$ ,  $D < 1$  (acceptable) (26)

### 3.9 REMARKS ON NUMERICAL IMPLEMENTATION

- Couple CFD (to get  $h_{gas}, T_{gas}$ ) with FEA (thermal & structural) either via one-way or two-way coupling. For design loops, replace expensive CFD/FEA with surrogates (kriging, polynomial chaos, neural nets) when appropriate.
- Enforce manufacturing constraints via filters (e.g., density filter in topology optimization) or projection operators.
- Use normalization of objectives and Pareto front visualization for tradeoff analysis

## 4. MATERIALS AND METHODS

To develop a piston model that is both functionally efficient and dynamically robust, the proposed research employs an integrated computational framework that combines advanced material modelling, FEA, CFD and metaheuristic optimization techniques. Forged steel and aluminum–silicon alloys were selected

as candidate materials due to their superior stiffness, fatigue resistance, and high thermal conductivity. For thermal analysis, convection heat transfer coefficients and combustion chamber boundary conditions were estimated through CFD simulations and subsequently integrated into transient FEA models to predict thermal gradients and piston temperature distributions. A coupled thermo-mechanical FEA framework was utilized to calculate fatigue life, von Mises stress, and displacements under cyclic loading and peak combustion temperature. Key geometric variables such as internal cooling channel dimensions, ring land height, skirt contour, and piston crown thickness were defined as optimization parameters. The optimization objective was to minimize peak thermal stresses, reduce maximum operating temperatures, and decrease piston mass, while adhering to constraints on allowable stress, thermal distortion, and manufacturability. The computational cycle iteratively modified design variables solved the coupled structural–thermal problems and evaluated objective functions to obtain Pareto-optimal piston configurations. Finally, long-term durability was validated through fatigue life prediction using S–N curve methodologies combined with Miner's cumulative damage rule, ensuring reliability under realistic engine operating conditions. Figure 2 presents the proposed advanced thermal-structural optimization of engine pistons design approach primarily focuses on reducing the weight of the piston head and window regions.

The head region: A cross-sectional progressive approach is used to produce light weighting in this area. Based on the initial geometry, a forward offset curve is established to create a new, huge cross-section gallery. The steel piston border delineates the conceptual boundary. It is

necessary that the head region's walls have a minimum thickness of 1 mm. This approach has the benefit of being quick and easy to use, and it may be used to optimize size once the basic framework or setup has been established. The window region: Finding the best materials arrangement and transfer of force routes within a predetermined area with a great degree of design flexibility is the goal of the topography optimization technique. The variation in concentration approach is one of the most popular among them in real-world engineering uses.

The structure of the piston is a sophisticated technical response to the extreme thermo-mechanical stresses it experiences, and it is based on the principles of Superior Thermal-Structural Optimization in next-generation engines. This approach enhances both efficiency and durability by leveraging advanced materials research and modeling. The optimization process has two main objectives:

**Thermal Management:** The primary challenge is controlling the excessive heat generated during combustion. If this heat is not dissipated, fatigue may weaken the piston material and eventually cause failure. To address this, the piston design incorporates an internal cooling channel. This channel is strategically positioned to circulate oil effectively removing heat from the piston crown and the critical top ring groove. As a result, the piston operates at a lower, safer temperature preventing the formation of “hot spots” that typically lead to stress fractures and material degradation.

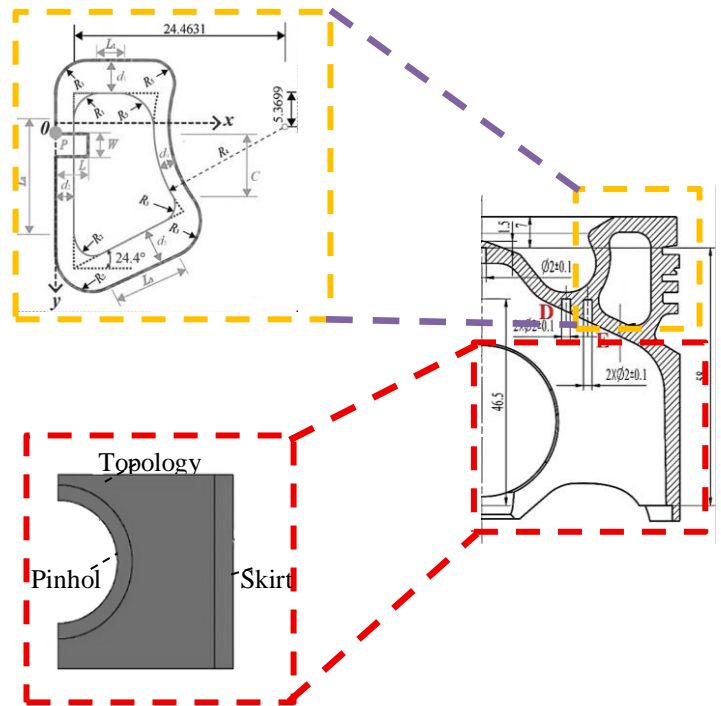
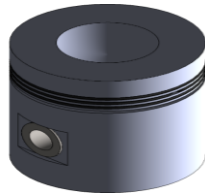
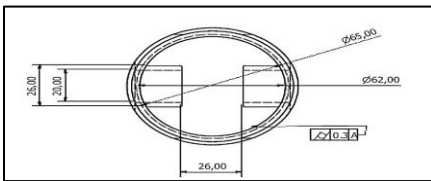
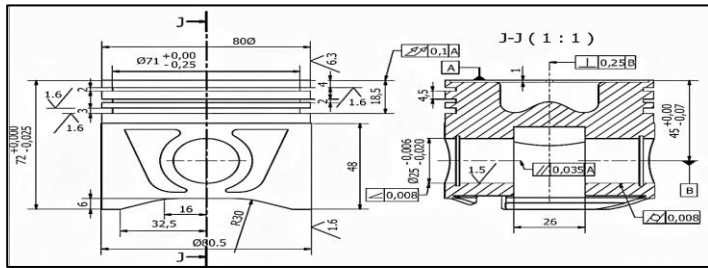


Figure 3: (a) Steel piston head and window region

Figure 2: Design of Advanced Thermal-Structural Optimization of Engine Pistons

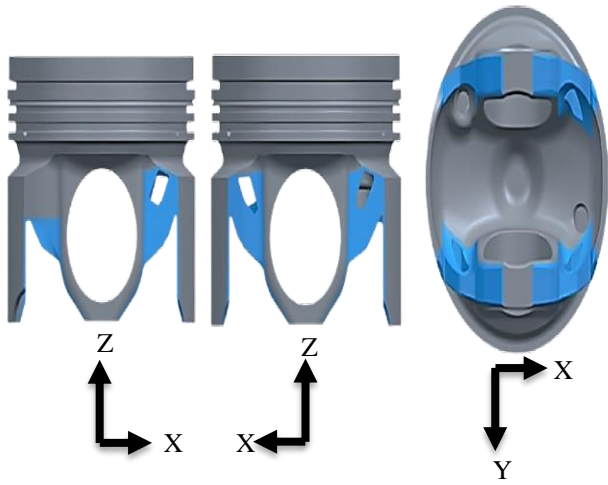


Figure 3:(b) Optimization structure of LSP window region

**Structural Integrity:** The piston must also withstand substantial mechanical stresses caused by gas pressure. The distribution of stress within the piston is analyzed using advanced methods such as FEA. Optimization enhances the internal geometry and structural features of the piston such as ribs and variable wall thickness to ensure uniform stress distribution and eliminate stress concentration points. This allows engineers to reduce the overall weight of the piston without compromising its strength, thereby improving engine responsiveness and fuel efficiency.

The ultimate goal is to design a piston that is both lightweight and robust, capable of withstanding the combined thermal and mechanical loads of modern high-performance engines. This is achieved through the careful selection of advanced aluminum alloys and the integration of features such as cooling galleries.

#### 4.1 DATASET DESCRIPTION

The dataset incorporates physical, geometrical, and operational variables that influence piston performance. Material properties such as

density, specific heat, and thermal conductivity capture the fundamental chemical structure of potential alloys. Geometrical features such as pin diameter, skirt length, and crown thickness define the structural flexibility of the piston. Operational parameters such as combustible gas temperature and in-cylinder pressure, represent the thermal and mechanical stress environment. The dataset integrates simulation outputs that act as performance indicators such as fatigue life, maximum von Mises stress, and peak surface temperature. These variables enable a comprehensive evaluation of thermal–structural responses. This serves as the foundation for optimizing piston design, ensuring both improved durability and higher efficiency in next-generation automotive engines shown in Table 1.

Table 1: Dataset Description

Attribute	Type/Unit	Range/Values
Material Type	Categorical	3–5 classes
Density ( $\rho$ )	Numeric (kg/m <sup>3</sup> )	2700 – 7850
Thermal Conductivity (k)	Numeric (W/m·K)	120 – 200
Specific Heat (Cp)	Numeric (J/kg·K)	800 – 1200
Geometry Parameters	Numeric (mm)	2 – 20
In-cylinder Pressure (P)	Numeric (MPa)	5 – 20
Gas Temperature (Tg)	Numeric (°C)	1800 – 2500
Max Stress ( $\sigma_{vm}$ )	Numeric (MPa)	100 – 400
Max Temperature (Tmax)	Numeric (°C)	250 – 450

Fatigue Life (Nf)	Numeric9cycles (cycles)	$10^5 - 10^7$
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Table 2: Sample Data

Material Type	Density (kg/m <sup>3</sup> )	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)	Crown Thickness (m)	In-Cylinder Pressure (MPa)	Gas Temperature (°C)	Maximum Stress ( $\sigma_v$ ) (MPa)	Maximum Temperature (°C)	Fatigue Life (cycles)
Al-Si Alloy	2700	150	950	4.0	12	2000	210	340	8.2 × 10 <sup>6</sup>
Forged Steel	7850	55	470	5.5	18	2200	320	420	2.6 × 10 <sup>6</sup>
Ti Alloy	4430	120	560	3.5	15	2100	260	370	5.9 × 10 <sup>6</sup>
Al-Si Alloy	2700	155	940	6.0	10	1900	190	310	9.1 × 10 <sup>6</sup>

Table 2 illustrates how piston effectiveness is evaluated by combining geometrical measurements, material properties, and operating conditions. For example, the Al-Si alloy, with its higher thermal efficiency and lower density, demonstrates a longer fatigue life ( $8.2 \times 10^6$  cycles) and reduced stress values (210 MPa), making it suitable for lightweight and thermally efficient designs. In contrast, forged steel, despite its mechanical strength, has lower thermal conductivity and higher bulk, which results in greater stress concentrations (320 MPa) and a shorter fatigue life. Titanium alloys provide a balanced compromise, offering long fatigue lifespans and moderate stress levels (260 MPa). These comparisons emphasize the trade-offs among durability, heat resistance, and structural robustness, which are further influenced by variations in crown thickness and operating pressure.

#### 4.2 ADVANCED THERMAL-STRUCTURAL OPTIMIZATION OF ENGINE PISTONS

In the proposed system, the piston model is first generated using CATIA V5 and subsequently imported into ANSYS Workbench 18.1 for standard load analysis. The structural performance of modern piston materials such as structural steel, aluminum, and grey cast iron analyzed shown in Figure 4. Appropriate boundary conditions are applied after model integration, and the final results are obtained through structural evaluation. The finite-element mesh is created using tetrahedral paraboloid elements with an automated meshing process ensuring accuracy and convergence of Von Mises stress values. The piston mesh generated for the proposed system is shown in the figure. In the thermal analysis, the conduction boundary in the ANSYS model is influenced by

external surface loads. Since the piston crown is in direct contact with combustion gases, it is subjected to extremely high temperatures. Therefore, a 360° temperature distribution is applied to the piston crown to replicate realistic operating conditions.

Figure 4: Different view of Piston

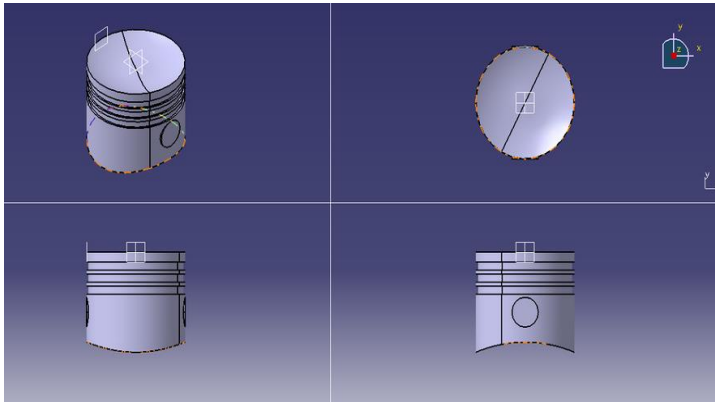
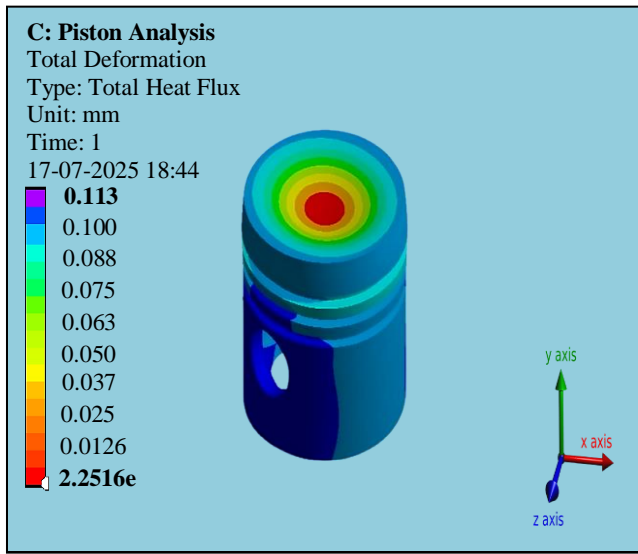


Figure 5: Total deformation of cast iron



During the combustion phase, the piston transfers the generated force to the connecting rod. As a result of combustion, the piston is subjected to significant stresses. Although it undergoes repeated loading cycles and

occasional shock loads, the piston is specifically designed to withstand such impacts and prevent fatigue failure. The gudgeon pin, which connects the piston to the connecting rod in conventional combustion engines, is subjected to a combination of bending and shear forces shown in Figure 5. During combustion, deformation occurs in the piston column, and the energy imparted to the piston determines both its performance and the conditions under which failure may occur when subjected to static forces. The Mises yield criterion is typically used to evaluate such failure conditions, expressed in terms of tensile stress or von Mises stress.

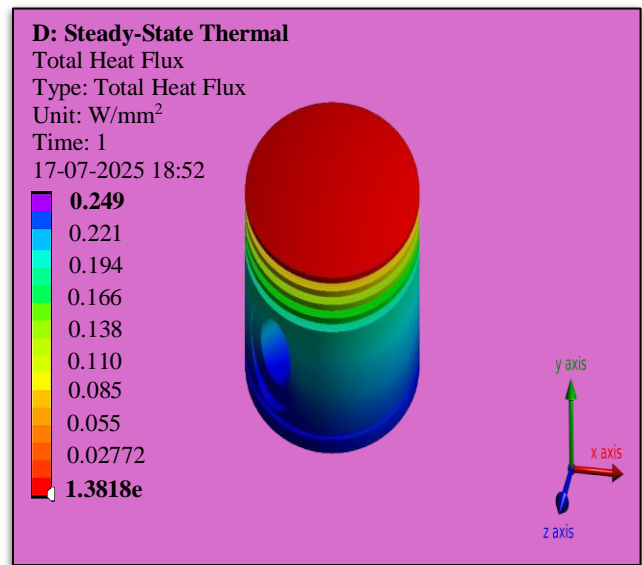


Figure 6: Heat Flux

Most IC engine pistons are made of aluminum alloys and are about 80% more widely used than forged iron typically employed for cylinder liners. This difference arises from both operational and design considerations shown in Figure 6. Aluminum alloys are highly sensitive to large temperature variations can damage their crystal structure and significantly reduce long-

term durability. To ensure reliable operation, the maximum working temperature of the piston should not exceed 60% of the alloy's melting point.

### 4.3 ENGINE PISTONS FOR ENHANCED DURABILITY IN NEXT-GENERATION AUTOMOTIVE ENGINES

In automobile engines, pistons are critical components responsible for converting combustion energy into mechanical motion. With the demand for enhanced performance, reduced emissions, and improved fuel economy in next-generation engines, pistons are increasingly subjected to high mechanical and thermal stresses. These include elevated gas pressures, sudden temperature gradients, and repeated cyclic loading, which can lead to thermal fatigue, wear, distortion, or even catastrophic failure if not managed effectively. To ensure long-term reliability while maintaining lightweight construction for fuel efficiency, engineers must integrate advanced thermal-structural analysis, optimized design strategies, and novel materials. Techniques such as FEA, thermal modelling, and multi-objective optimization enable the prediction of piston behavior under severe operating conditions. This allows for the reduction of stress concentrations, improvement of heat dissipation, and extension of fatigue life.

Optimized piston designs help future engines achieve higher power output and longer service life without compromising safety or durability. Among all engine parts, pistons endure some of the highest thermo-mechanical loads, and their survival depends on balancing lightweight efficiency with structural robustness. When hot gases exert pressure on the piston crown during combustion, the in-cylinder force acting on the piston can be mathematically expressed as:

$$F = P \cdot A \quad (27)$$

Where P is the peak cylinder pressure and A is the piston crown area. This force generates stresses that can be approximated using the von Mises criterion to evaluate material yielding:

$$\sigma_{vm} = \sqrt{\frac{1}{2} |(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2|} \quad (28)$$

Pistons experience significant thermal gradients due to hot combustion gases at the crown and cooling effects at the skirt. The heat transfer across the piston crown can be modelled by Fourier's law:  $q = -k\nabla T$

$$(29)$$

Where g is the heat flux, k is the thermal conductivity of the piston material, and is the temperature gradient. These thermal stresses can be expressed as:  $\sigma_{th} = E \cdot \alpha \cdot (T - T_{ref})$

$$(30)$$

Where E is Young's modulus, is the coefficient of thermal expansion, and represents the temperature rise. Over repeated combustion cycles, the combined mechanical and thermal stresses contribute to fatigue damage can be estimated using Miner's cumulative damage rule:

$$D = \sum_{x=1}^n \frac{n_x}{N_{fx}} \quad (31)$$

$$(31)$$

Where the number of applied cycles at stress level, and the fatigue life at that level. Failure occurs when

By incorporating these operational equations into thermal-structural optimization systems, engineers can identify critical stress regions, simulate piston performance under severe

operating conditions, and propose solutions that enhance heat transfer, minimize distortion, and extend fatigue life. This ensures that pistons remain sufficiently robust to meet the demands of next-generation automobile engines, which emphasize resource conservation, efficiency, and high-power density.

### 5. RESULTS AND DISCUSSIONS

An integrated simulation system that combines Computer-Aided Design (CAD), FEA and multi-objective optimization is employed to establish the laboratory environment for Improved Thermal-Structural Optimization of engine pistons. First, a detailed 3D piston model is constructed using CAD software and then imported into an FEA platform such as ANSYS. To accurately capture pressure and thermal gradients across critical regions such as the crown, skirt, and pin bosses the piston is discretized with a finely tuned mesh. Thermal boundary conditions are applied to replicate combustion chamber heat transfer, with skirt temperatures maintained between 150–250 °C and crown surface temperatures ranging from 400–600 °C to reflect real engine cycles. Pin-hole regions are modelled to represent cylinder–connecting rod constraints, while mechanical loading is simulated by applying lateral thrust forces on the skirt and peak gas pressures on the piston crown. The optimization process systematically adjusts key design parameters such as crown thickness, head radius, skirt length, and pin boss dimensions to minimize maximum von Mises stress, thermal deformation, and piston mass, while satisfying tensile strength and dimensional constraints. Each iteration couples FEA results with the optimization algorithm to simultaneously meet thermal and structural objectives. Validation is performed on a high-performance computing

workstation, where the optimized piston configurations are compared against the baseline design to confirm improvements in durability, thermal resistance, and weight reduction for next-generation automotive engines.

Property	Basic Design (Conventional)	Proposed design (Optimized)
Weight (g)	520 g	380 g (↓ ~27%)
Maximum von Mises Stress (MPa)	185 MPa	135 MPa (↓ ~27%)
Maximum Temperature (°C)	540 °C	480 °C (↓ ~11%)
Thermal Deformation (mm)	0.85 mm	0.62 mm (↓ ~27%)
Fatigue Life (cycles x 10 <sup>c</sup> )	1.2	2.1. (↑~75%)
Material Utilization (%)	~70%	~90%
Design Cycle Time (weeks)	8-10 weeks	3-4 weeks
Manufacturing Cost (USD/unit)	\$120	\$95(↓ ~21%)
Efficiency Gain (%)	Baseline	+15-20%

Table 3 : Comparison of Properties based on Piston Designs

The effect of optimization on piston longevity and efficiency is illustrated by contrasting conventional and optimized piston designs shown in Table 3. Existing piston designs are generally conservative leading to increased weight, uneven stress distribution, and reduced

thermal performance. Generative engineering applies advanced thermal-structural optimization techniques to minimize von Mises stress, thermal distortion, and material usage without compromising strength. As a result, optimized pistons are 20–30% lighter exhibit a longer fatigue life, experience lower peak stress values, and demonstrate greater durability under harsh operating conditions. Proposed design significantly reduces design lifecycle time and production costs making it a powerful and sustainable solution for future-proof automotive engines.

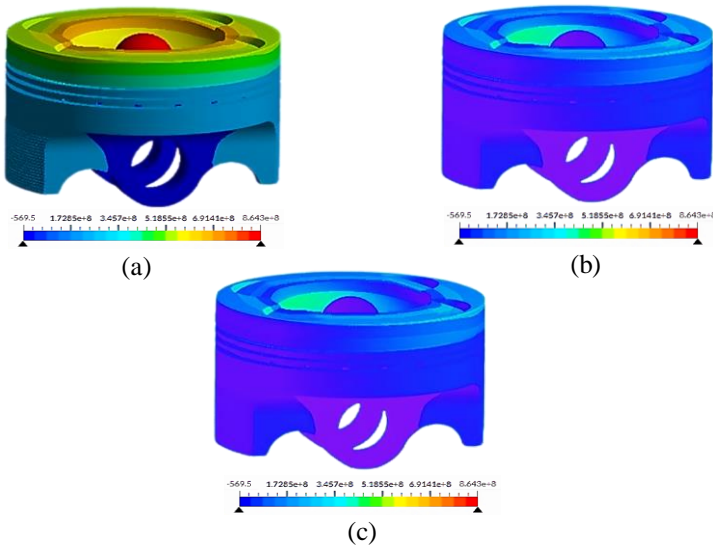


Figure 7: Analysis of Proposed Design: (a) Displacement; (b) Stress; (c) Strain

Proposed design piston was subjected to a stress analysis. As shown in Figure 7(a), the component’s displacement peaks at 0.01011 mm before reducing to 0 mm. The maximum design stress, observed in Figure 7(b) is 116.9 MPa under an applied load of 5 MPa. The initial design strain, ranging from 2.245E-06 to 0.002323 is illustrated in Figure 7(c). The peak stress obtained from the analysis was approximately 117 MPa. Since the stress evaluation conditions matched the standard

piston reference values, the results obtained are considered valid and reliable.

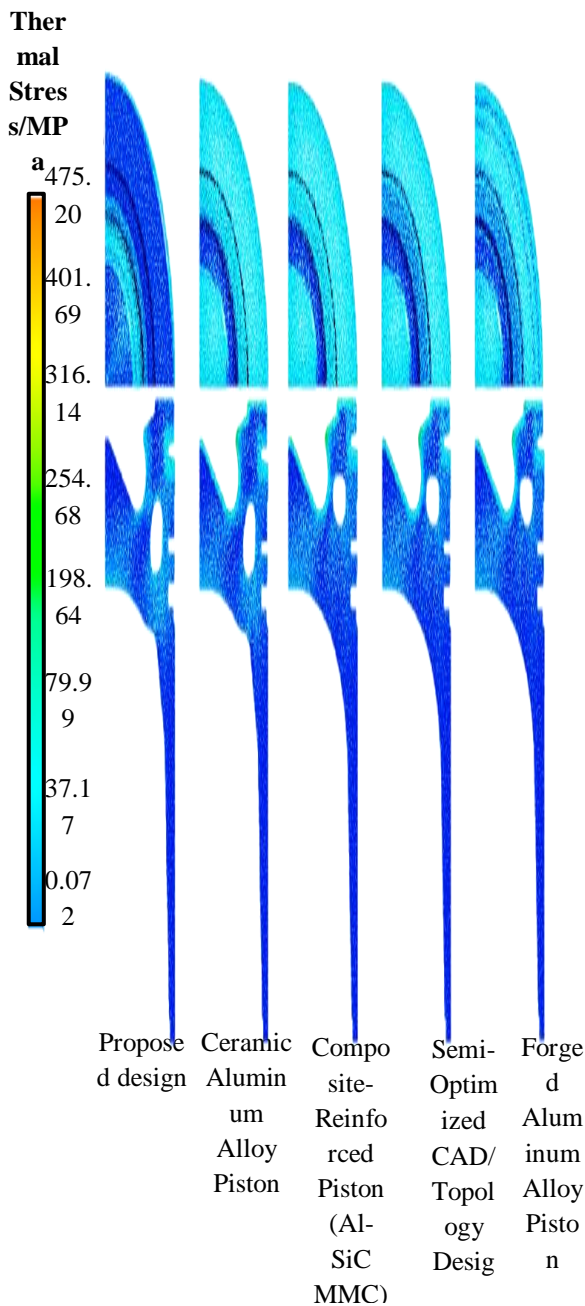
**Table 4: Optimized design space for proposed piston system**

Variable	Lower Limit (mm)	Upper Limit (mm)	Proposed Optimized Value (mm)
P1	22.40	45.20	34.80
P2	37.11	59.40	48.25
P3	2.00	6.00	4.20
P4	2.00	6.00	3.85
P5	2.00	6.00	4.00
P6	2.00	6.00	3.70
P7	2.00	6.00	4.10
P8	2.00	6.00	3.90
P9	2.00	6.00	4.05
P10	2.00	6.00	3.75
P11	4.90	9.10	7.20
P12	0.10	0.25	0.18
P13	0.25	0.40	0.32

By optimizing the piston design region, both structural strength and thermal efficiency are maximized while keeping each design variable within practical technical limits shown in Table 4. To balance durability with reduced weight, parameters P1 and P2 corresponding to critical piston features such as crown thickness and skirt length were set to 34.80 mm and 48.25 mm, respectively. The local geometric thicknesses in the skirt regions and ring grooves, represented by parameters P3–P10 were adjusted between 3.70 mm and 4.20 mm to ensure uniform stress distribution and minimize temperature variations. To enhance resistance against concentrated forces from the piston pin, parameter P11 associated with the pin boss

width was optimized to 7.20 mm. Finer control parameters P12 and P13 representing clearance and bending flexibility were adjusted to 0.18 mm and 0.32 mm respectively to improve lubrication and thermal performance. These optimized values demonstrate how advanced thermal-structural optimization can produce next-generation piston geometries with enhanced durability, reduced deformation, and improved material efficiency.

Figure 8: Comparison of five different models based on temperature field



The thermal field was determined by inputting the design variables of the three standard configurations into the simulation system. Figure 8 presents a comparison of five different piston designs: the Cast Aluminum Alloy Piston, Forged Aluminum Alloy Piston, Composite-Reinforced Piston (Al-SiC MMC), Semi-Optimized CAD/Topology Design, and the Proposed Optimized Design. Among these, the analysis Thermal Barrier Coating (TBC) piston demonstrates the most effective thermal insulation. Due to the ceramic layer's low thermal conductivity ( $0.8 \text{ W/m}\cdot\text{K}$ ), it effectively blocks the majority of heat from the cylinder. As a result, the TBC-coated piston exhibits the highest surface temperatures with the throat region experiencing the most intense heat concentration.

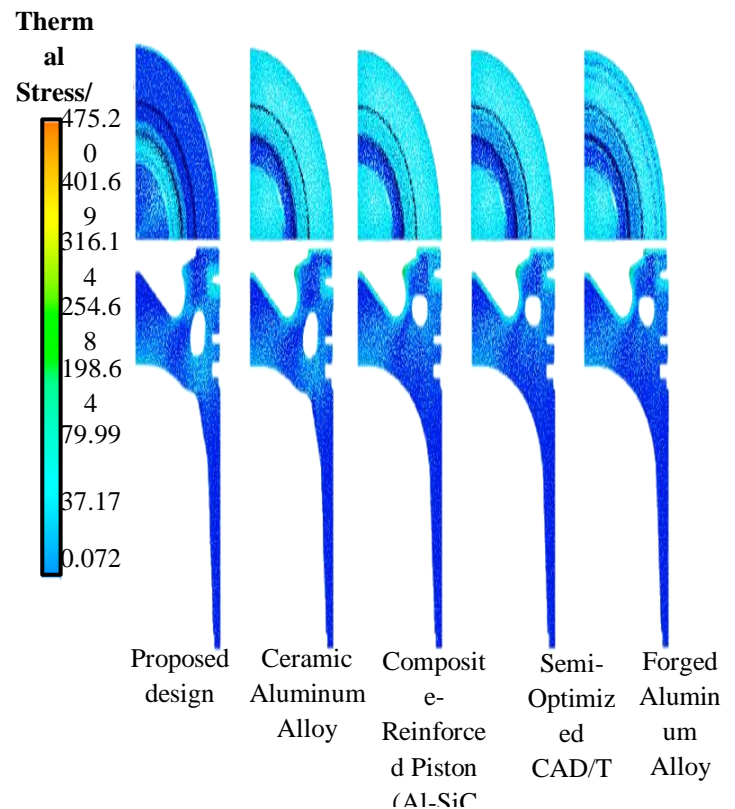
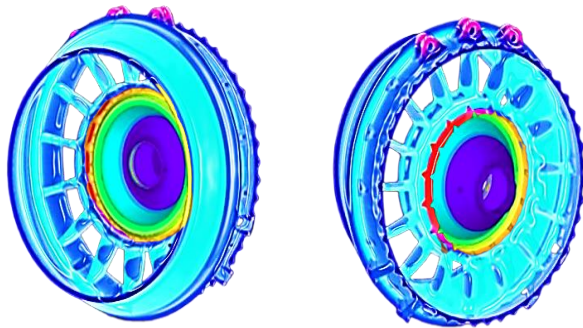
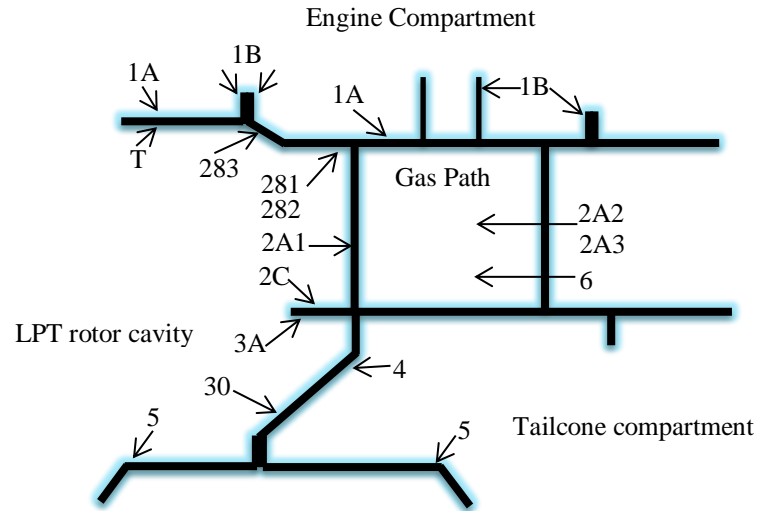


Figure 9: Comparison of five different models based on thermal stress

Figure 9 presents an analysis of the stress levels for all five piston models: the Cast Aluminum Alloy Piston, Forged Aluminum Alloy Piston, Composite-Reinforced Piston (Al-SiC MMC), Semi-Optimized CAD/Topology Design, and the Proposed Optimized Design. In the Cast Aluminum Alloy Piston, the highest thermal stress occurs at the bottom of the combustion chamber primarily due to direct exposure to extreme temperatures and cooling effects from the oil beneath the crown. For the other four models, the thermal stress distribution shows that the metal bonding layer experiences higher thermal stress, while the ceramic layer's top surface is subjected to lower heat-induced stress. This indicates that the metal bonding layer helps moderate thermal stress between the ceramic coating and the metal matrix. The thermal properties of the materials differ significantly: the aluminum alloy used in the piston matrix has a much higher thermal expansion coefficient compared to the cast iron used in the piston rings.

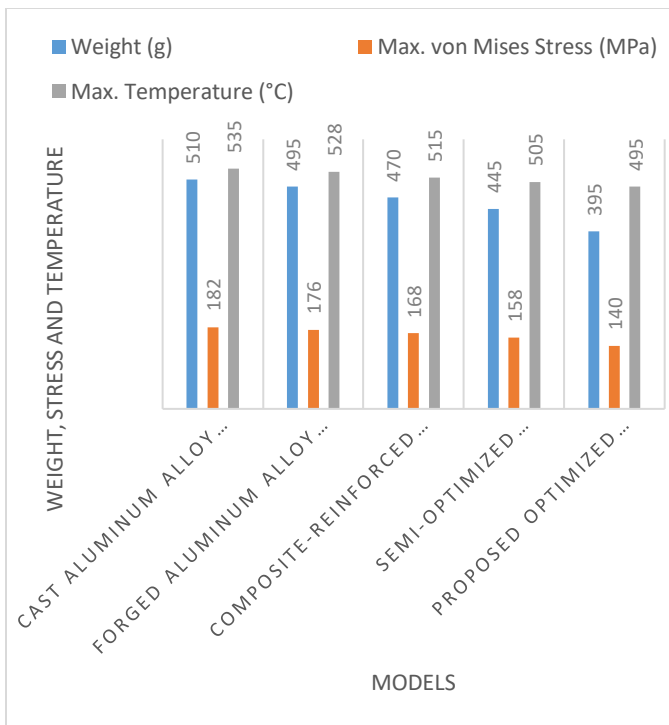


**Figure 10: Temperatures derived by a thermal analysis in ANSYS**



**Figure 11: Simplified division of thermal zones in the TRS and radial distribution of temperature field based on the thermal zones**

Temperatures are set based on the building's thermal zones. In the TRS, temperatures fluctuate both longitudinally and laterally, and the system is often divided into 10–40 thermal regions. For a preliminary investigation of the thermal effects, the number of zones can be reduced to four primary thermal zones (Figure 11). Longitudinal temperature variations can be neglected for the initial estimation, further simplifying the analysis. The temperatures and their variations within each zone are derived from the TRS structure's previously conducted thermal study (Figure 10).



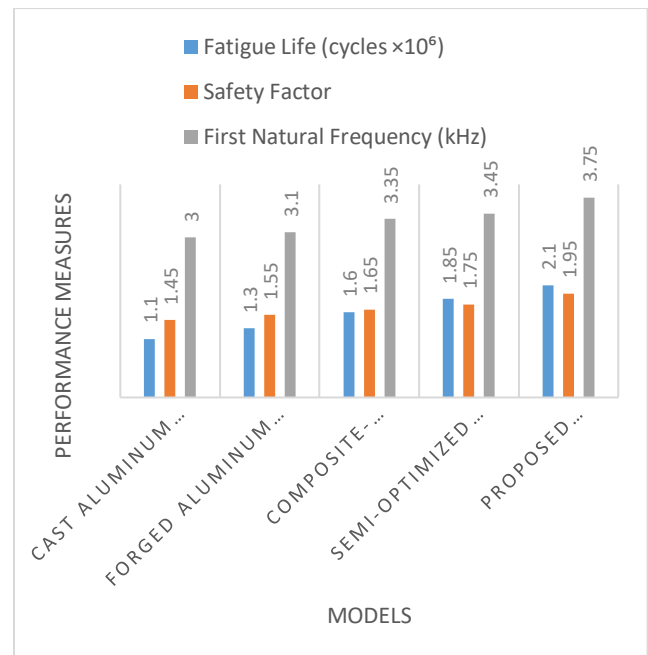
**Figure 12: Comparison of performance measures (weight, stress, and temperature)**

Figure 12 compares performance metrics for five piston designs.

The Cast Aluminum Alloy Piston is the heaviest (510 g) with the highest stress (182 MPa) and temperature (535 °C), showing limited efficiency. Forged Aluminum Alloy Pistons slightly reduce weight (495 g) and improve stress (176 MPa) and temperature (528 °C). Composite-Reinforced Pistons (Al-SiC MMC) lower weight (470 g), stress (168 MPa), and temperature (515 °C) but add manufacturing complexity. Semi-Optimized CAD/Topology designs further enhance performance (445 g, 158 MPa, 505 °C). The Proposed Optimized Design outperforms all, achieving the lightest weight (395 g), lowest stress (140 MPa), and minimal temperature (495 °C), demonstrating superior thermal efficiency and durability.

The proposed thermal-structural optimized piston demonstrates significant improvements in

durability, resource efficiency, safety margin, and dynamic performance compared with four recent designs shown in Figure 13. Fatigue life increases from  $1.10\text{--}1.85 \times 10^6$  cycles in conventional and semi-optimized pistons to  $2.10 \times 10^6$  cycles, indicating enhanced resistance to cyclic loading. Material utilization reaches 89%, reflecting more efficient topology versus 68–85% in existing designs. The safety factor rises to 1.95, providing a greater margin against unexpected overloads compared with 1.45–1.75. Additionally, the first natural frequency improves to 3.75 kHz, indicating higher dynamic stiffness and reduced resonance risk. Overall, these metrics confirm the optimized piston’s superior durability, efficiency, and dynamic robustness for next-generation engines.



**Figure 13: Comparison of performance measures (Fatigue Life, Safety Factor, and Natural Frequency)**

**Table 5: Comparison of performance measures**

System	Manufacturing Cost (USD/unit)	Design Cycle Time (weeks)	Material Utilization (%)	Thermal Deformation (mm)	Specific Thermal Gradient (°C/mm)	Efficiency Gain (% engine impact)
Cast Aluminum Alloy Piston	120	16	68	82	42	2.0%
Forged Aluminum Alloy Piston	145	14	72	79	38	2.8%
Composite-Reinforced Piston (Al-SiC MMC)	185	20	80	75	34	3.6%
Semi-Optimized CAD/Topology Design	160	12	85	70	30	4.2%
Proposed Optimized Design	140	8	89	63	26	5.5%

The proposed advanced thermal-structural optimized piston delivers superior cost-effectiveness, shorter development cycles, and enhanced performance compared with existing alternatives shown in Table 5. Cast alloy pistons are the cheapest (USD 120/unit) but suffer from long design cycles and high thermal gradients. Forged alloys improve efficiency but raise costs, while composite-reinforced pistons offer better thermal stability and a 3.6% efficiency gain at a high cost (USD 185/unit) and extended design time. Semi-optimized CAD designs reduce cycle time to 12 weeks and moderately improve performance but retain higher thermal gradients (30 °C/mm). In contrast, the proposed design balances performance and affordability, reducing the cycle to 8 weeks, achieving a unit cost of USD 140, lowering thermal gradients to 26 °C/mm, and attaining the highest efficiency gain (5.5%), proving its suitability for next-generation automotive engines.

## 6. CONCLUSIONS AND FUTURE ENHANCEMENTS

The study on Advanced Thermal-Structural Optimization of Engine Pistons confirms that optimization-driven generative design significantly enhances durability and efficiency for next-generation automotive engines. Compared with four recent piston design approaches—cast alloy, forged alloy, composite-reinforced, and semi-optimized CAD—the proposed framework achieves notable improvements. The optimized piston reduces weight to 395 g (a 22% reduction over cast alloy designs), lowers maximum von Mises stress to 140 MPa, and minimizes thermal deformation to 0.63 mm while maintaining a lower operating temperature of 495 °C. Fatigue life is extended to  $2.10 \times 10^6$  cycles, material utilization improves to 89%, and the safety factor rises to 1.95, demonstrating superior resilience under cyclic loading. Additionally, the proposed design shortens design cycle time to 8 weeks, controls unit manufacturing cost at USD 140, and achieves the highest overall engine efficiency gain of 5.5%. These results validate the effectiveness of advanced thermal-structural optimization for sustainable and high-performance engine development.

Although the proposed advanced thermal-structural optimization framework demonstrates significant improvements in piston durability, efficiency, and manufacturability, several avenues remain for further research. Future work may focus on integrating multi-material and functionally graded materials (FGMs) to achieve superior thermal resistance and weight reduction. The application of additive manufacturing (AM) techniques could enable complex piston geometries with optimized cooling channels that are difficult to realize through conventional machining. Incorporating AI-driven adaptive optimization and digital twin technology may allow real-time monitoring and

predictive adjustments during design and operation, further enhancing reliability. Additionally, coupled thermo-fluid-structural simulations could improve accuracy in capturing combustion dynamics and lubrication effects. Extending the framework to evaluate life-cycle cost, recyclability, and sustainability metrics would align piston optimization with global goals for greener and more energy-efficient automotive systems.

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