Topology-Optimized Piston Head Design Using Metal Additive Manufacturing for Porsche's 6-Stroke Engine

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Abstract
Porsche's innovative 6-stroke engine design introduces a second power stroke per cycle, generating significantly more heat than traditional 4-stroke engines. This necessitates advancement in piston thermal management solutions. This study investigates the application of metal additive manufacturing and topology optimization to develop lightweight, thermally efficient piston designs capable of withstanding the increased thermal loads. Using nTopology software, a control piston geometry was topologically optimized with a volume fraction constraint of 0.2, aiming for maximum stiffness while minimizing mass. Both the baseline and optimized designs were tested using finite element analysis in ANSYS, simulating peak combustion conditions with 20MPa pressure and a surface temperature of 1273.2K. The optimization achieved a 20.4% mass reduction (from 1.254kg to 0.999kg) and demonstrated significantly improved thermal performance, with the minimum temperature at the piston pin boss reduced by 109.4K. However, structural analysis revealed excess stress in the optimized design, with maximum von Mises stress reaching 1318.6MPa compared to 375.73MPa in the control design. These results demonstrate that while topology optimization has significant potential for addressing thermal challenges through weight reduction and improved heat dissipation, the optimization parameters require refinement.

Introduction
Porsche's innovative 6-stroke engine introduces a second power stroke to a traditional 4-stroke engine. This is anticipated to generate significantly more heat, and pistons will require further optimization to maximize efficiency and performance. Piston heads are central to an engine's thermal and mechanical performance. While traditional manufacturing methods are reliable, they limit the complexity and efficiency of piston designs. The overall goal is to balance thermal management with structural integrity and weight reduction. Metal additive manufacturing provides an opportunity to overcome these limitations by allowing for complex geometries to reduce their weight and allow for greater heat dissipation. Porsche and MAHLE have already tested this manufacturing technology in creating additive manufactured piston heads in a Porsche 911 GT2 RS. These piston heads were topologically optimized to reduce their weight by 10% and included integrated cooling channels to reduce piston ring temperatures by over 20 degrees [4].

The goal of this paper is to quantify how well traditional piston heads perform within the new Porsche 6-stroke engine and investigate how metal additive manufacturing can be used to optimize these piston heads for maximum heat dissipation, structural integrity, and weight reduction.

Background
In an internal combustion engine, pistons convert chemical energy from fuel into mechanical energy. In Figure 1, the piston oscillates vertically between top dead center, labeled TDC, and bottom dead center, labeled BDC. The connecting rod transfers this motion into the crankshaft as rotational energy. During each cycle, the piston is pushed down to BDC from a power stroke

in another piston. Air and fuel from the intake valve and injector, respectively, rush to fill this space. The piston then compresses this mixture within the combustion chamber, and the combustion pushes the piston back to BDC, which continues the crankshaft rotation. Due to the motion of other pistons, the piston returns to TDC and expels exhaust gasses through the exhaust valve. A piston's performance is directly correlated to engine performance.

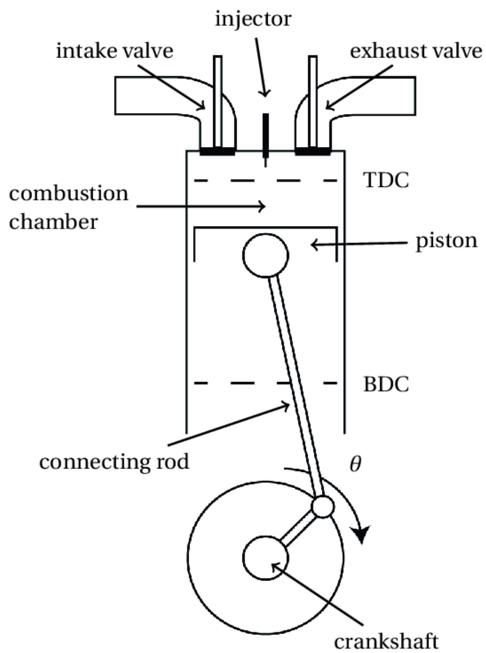

Figure 1: Piston Motion During Power Cycle Schematic [3]

Pistons are manufactured through casting and forging, more commonly casting. Casting involves pouring molten metal into a mold to form the piston's general shape. Forging uses high pressure and heat to form a solid piece of metal into its desired shape. Casting is preferred as it is cost effective with minimal waste and easy to mass produce. Although forged pistons are more expensive and harder to shape precisely, they are much stronger and used in heavy duty applications. After this initial shaping, pistons are machined and finished to meet the tight tolerances of modern engines. This precise machining ensures a perfect fit within the cylinder maximizing efficiency and minimizing friction. Surface finishing further reduces friction and wear.

Historically, pistons were made from cast iron into crude shapes with poor quality. These early designs were heavy and inefficient, contributing to higher fuel consumption, increased wear, and limited performance. Advances in materials and manufacturing technologies have led to the use of aluminum alloys which are significantly lighter and have better thermal conductivity. This allows for higher engine speeds and better fuel efficiency. Modern pistons also have features such as grooves to accommodate piston rings which help to maintain a seal within the cylinder. Some designs also include thermal barriers and advanced coatings to improve heat and wear resistance. However, with rapid advancements in technology, modern piston designs require further innovation.

Methodology

Geometry Generation

Control

The geometry for the control piston was obtained from GrabCad. The specific model is titled “Piston SubAssembly,” created by Narendra Naidu and uploaded on June 23rd, 2025 [2]. This specific model was chosen as it represents a conventional piston design that would typically be manufactured through casting or forging processes, allowing it to serve as a realistic control piston to be tested against its optimized counterpart.

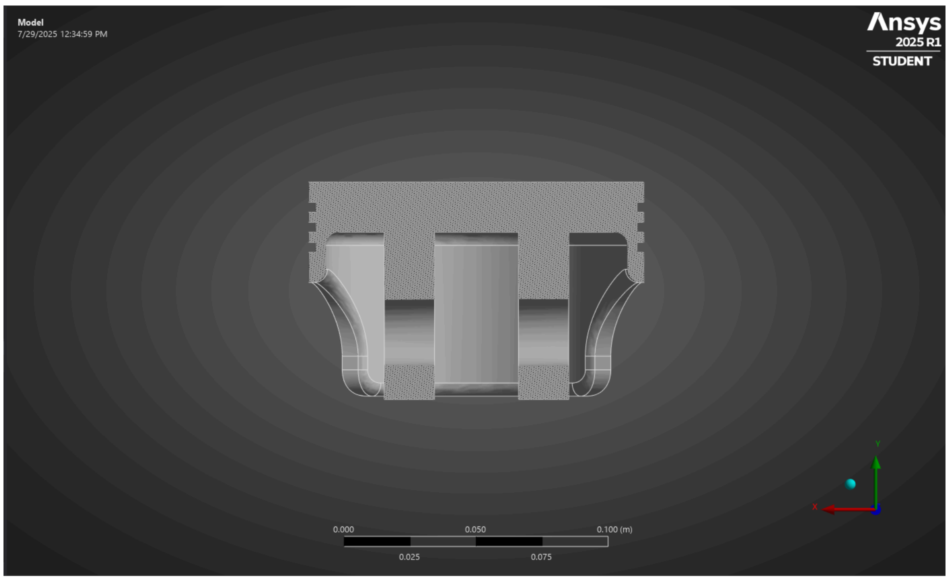

Figure 2: Section View of Control Geometry

Optimized

The geometry for the optimized piston was generated using the nTopology software, following their topology optimization workflow guide “How to run a topology optimization” [1].

The first step involved importing the control geometry and defining the design space. The optimization region was established by isolating the entire model, the constant bodies, and the bodies to be optimized each as their own variable.

The next step was to define the material properties using an Isotropic Elastic Property block with a Young’s modulus of 69GPa and a Poisson’s Ratio of 0.33 to approximate the behavior of the aluminum alloys typically used in performance engines.

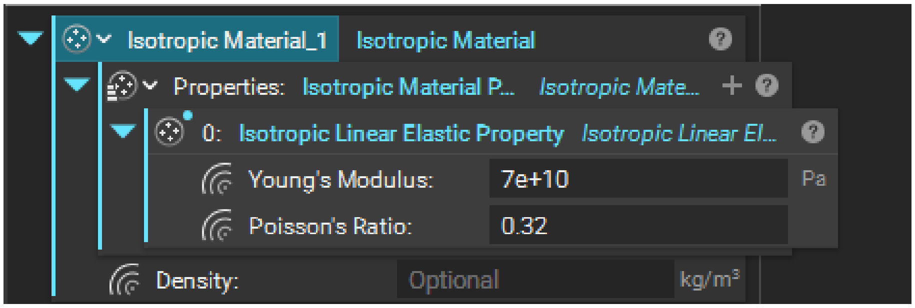

Figure 3: Material Properties

After this, a FE Volume Mesh was created from the design space by plugging it into a Mesh from CAD Body block, adding a Remesh block with an edge length of 3mm, a Volume Mesh block with an edge length of 3mm and the shape set to triangles. Finally, the volume mesh must be inserted into an FE Volume Mesh block.

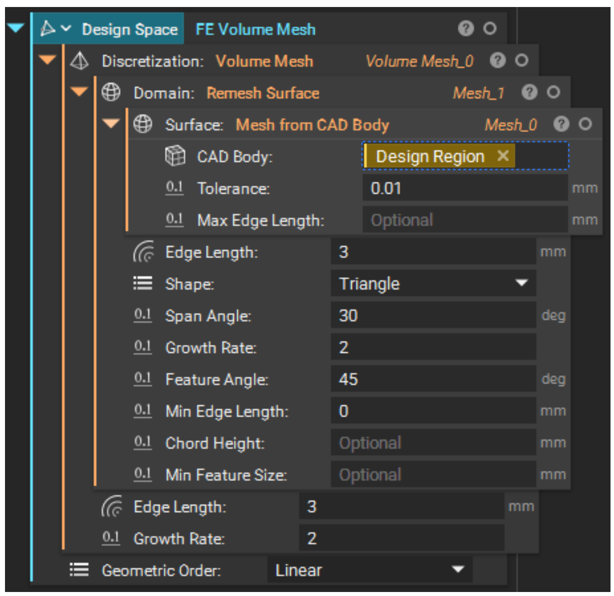

Figure 4: Design Space & Mesh Control

The Displacement Restraint block was used to simulate the fixed constraints at the piston pin bosses. The Force block applied a downward load of 100N representing pressure from combustion. Both boundary conditions referenced an FE Face Boundary, created from the piston's CAD surfaces and the FE mesh. These inputs were used to define a structural compliance design response, with the objective set to minimize compliance, maximizing stiffness. The response was stored as a variable and linked into the topology optimization block.

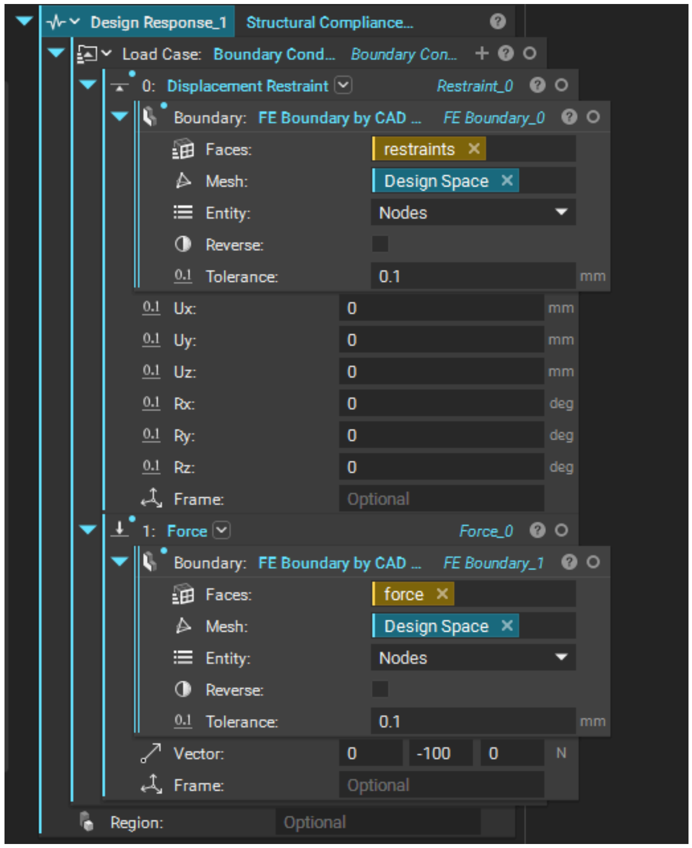

Figure 5: Boundary Conditions

To control the amount of material retained in the final design, a Volume Fraction Constraint was used. A constraint value of 0.2 was applied, ensuring that the final piston head retained no more than 20% of the original design space volume.

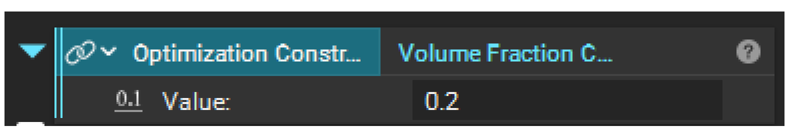

Figure 6: Optimization Constraints by Volume Fraction Method

Next, the raw result from the optimization must be smoothed using the Construct Optimized Body block.

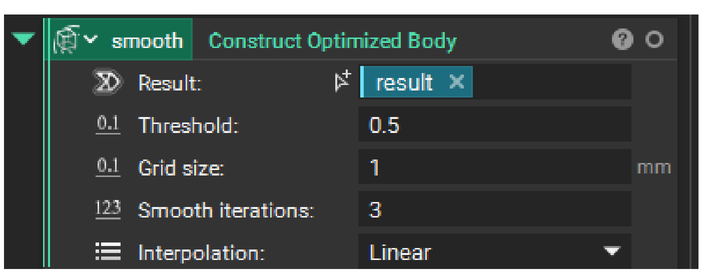

Figure 7: Construct Optimized Body Menu

After this the model was converted to an implicit body using the Implicit Body from CAD Body block, thickened by 4mm with the Thicken Body block, and joined with the Boolean Union block.

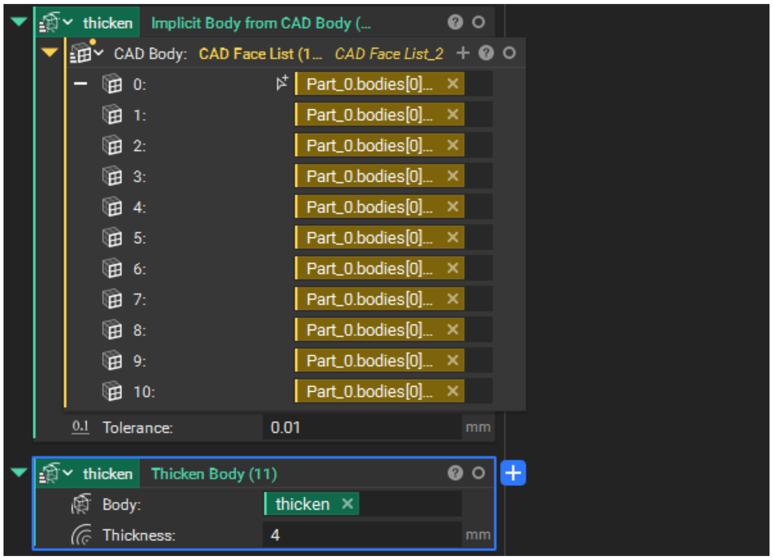

Figure 8: Thicken Body Menu

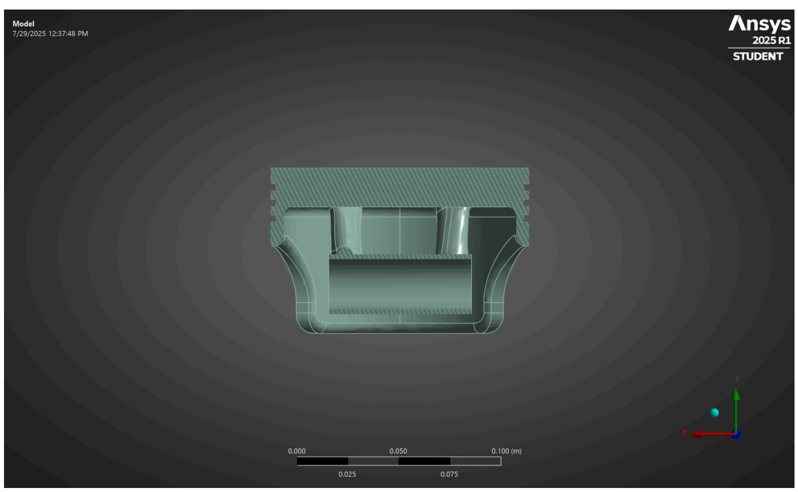

Figure 9: Section View of Optimized Geometry

Structural Simulation

1. The first step in the structural simulation was dragging a static structural block into the Ansys workbench.
2. Next, the piston head geometry was imported.
3. After this, the model was opened in Ansys mechanical, and the part was assigned an aluminum alloy material.
4. Next, the reference center of the mesh was set to fine, and the mesh was generated.
5. Downward pressure of 20MPa was assigned to the top face of the piston head.

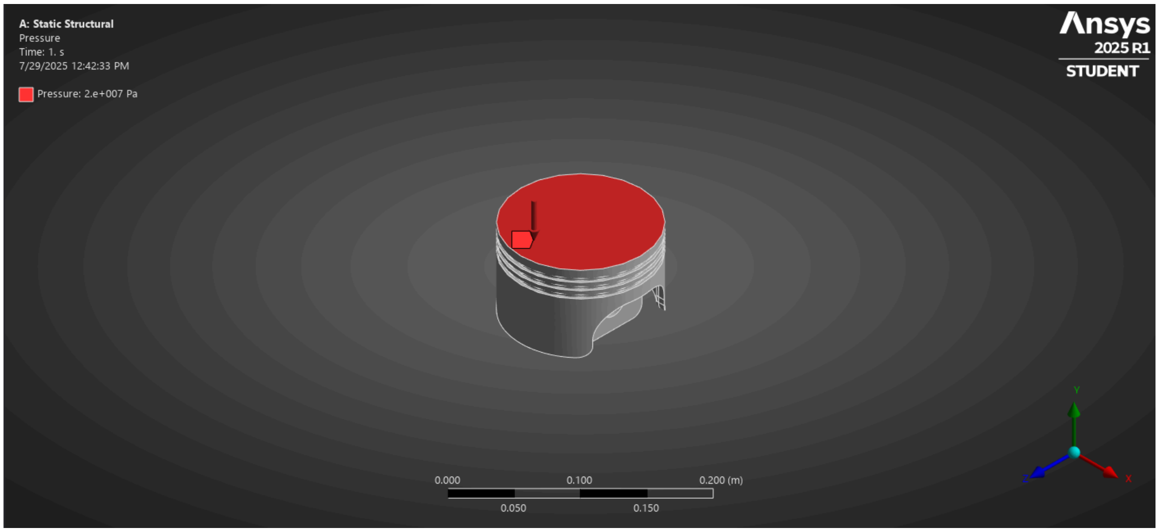

Figure 10: Applied Pressure on Control Geometry

6. The internal faces of the piston pin bosses were defined as fixed supports.

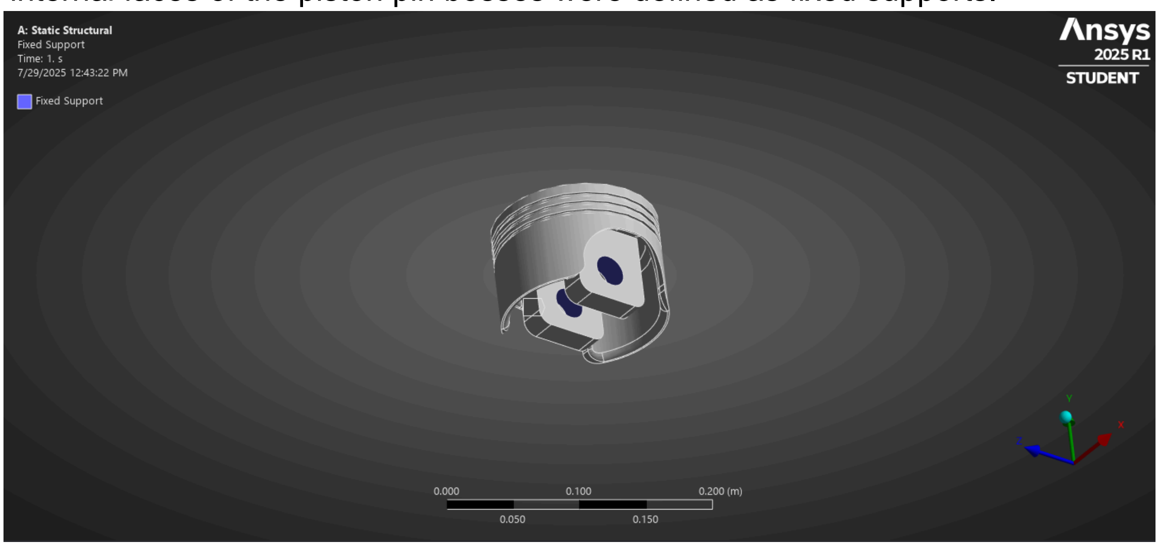

Figure 11: Fixed Support for Control Geometry

7. The solution was set to output the total deformation, as well as the equivalent von-Mises stress.
8. After this, the model was solved and outputted the simulation results.

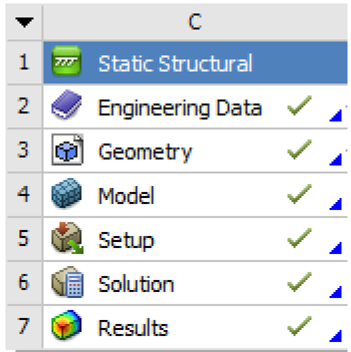

Figure 12: Static Structural Setup

Thermal Simulation

1. The first step in the thermal simulation was dragging a steady-state thermal block into the Ansys workbench.
2. Next, the piston head geometry was imported.
3. After this, the model was opened in Ansys mechanical, and the part was assigned an aluminum alloy material.
4. Next, the reference center of the mesh was set to fine, and the mesh was generated.
5. The model's initial temperature was set to 298.15K.
6. A temperature of 1273.2K was assigned to the top face of the piston head.

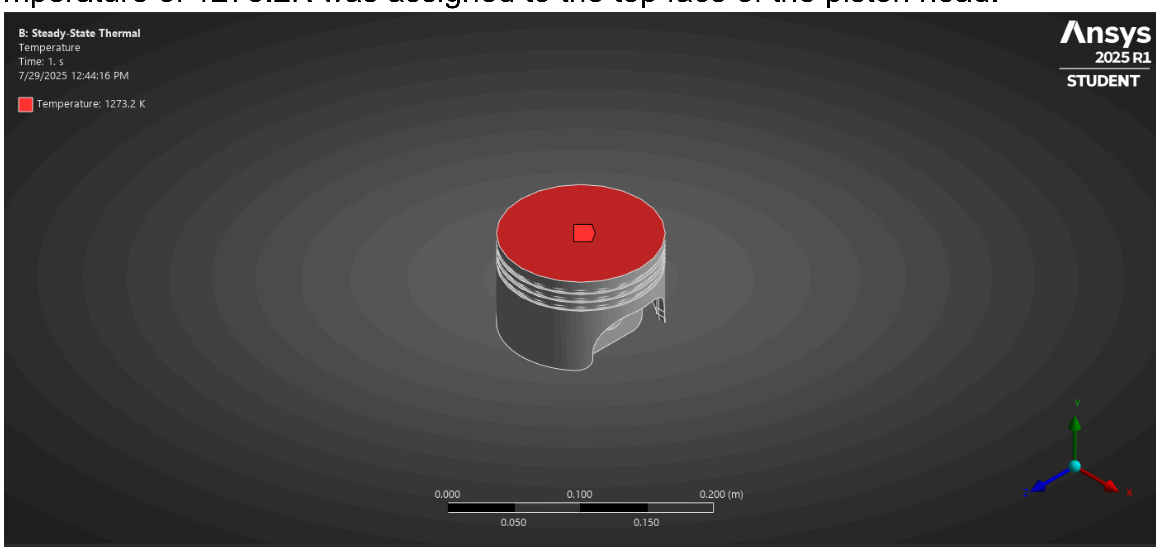

Figure 13: Temperature Boundary Condition on Control Geometry

7. Convection was assigned to all the inner faces with a Film Coefficient of 25 W/m^2*K

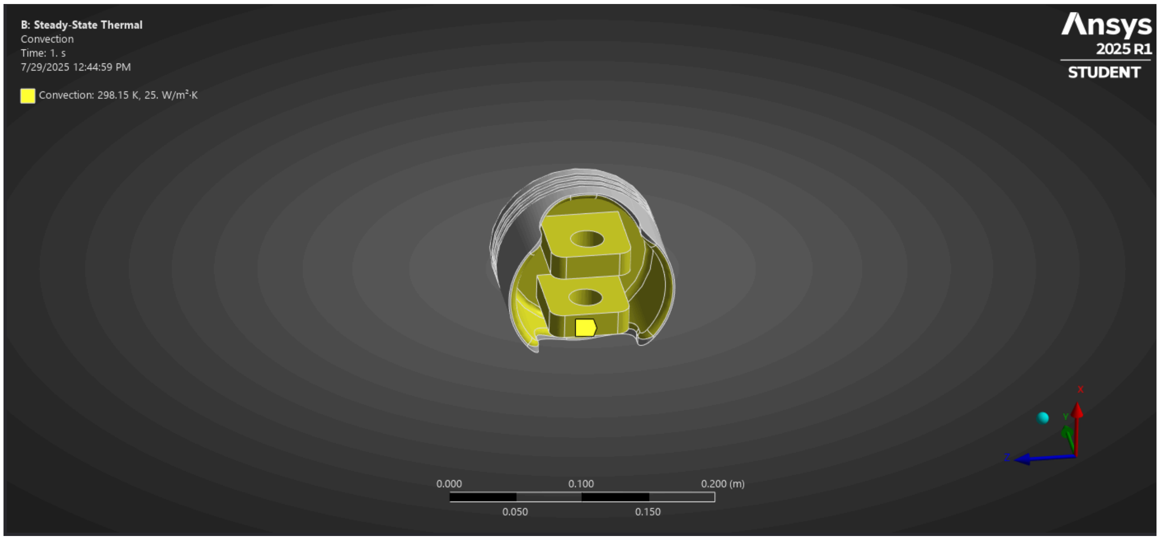

Figure 14: Convection Boundary Condition on Control Geometry

8. The solution was set to output the final temperature of the part.
9. After this, the model was solved and outputted the simulation results.

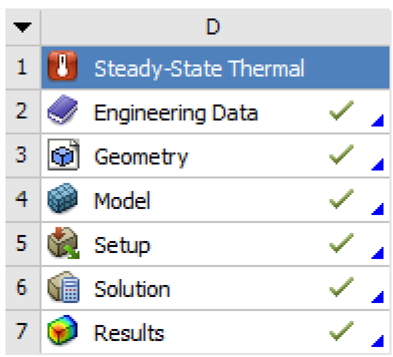

Figure 15: Steady State Thermal Setup

Results & Discussion

The performance comparison between the control piston and the topology-optimized piston was evaluated through separate thermal and structural simulations ANSYS. Both designs were subjected to identical boundary conditions representing peak operating conditions in the 6-stroke engine cycle. The optimization achieved a 20.4% mass reduction (from 1.254 kg to 0.999 kg) while demonstrating superior thermal performance, though with increased stress requiring further optimization.

Control - Static Structural

Total Deformation

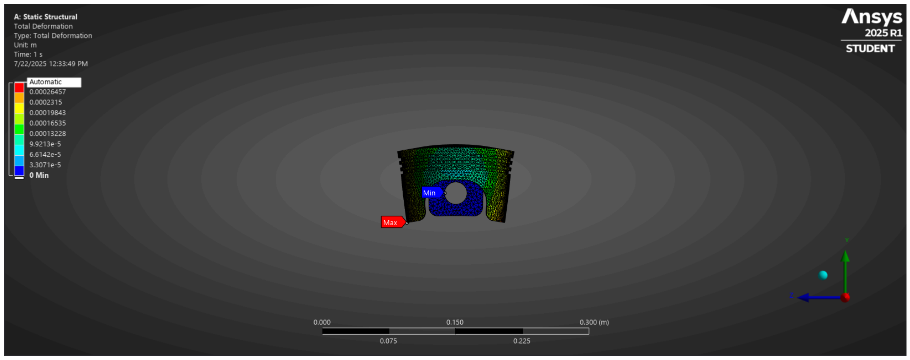

Figure 16: Control Geometry Total Deformation

Equivalent Stress

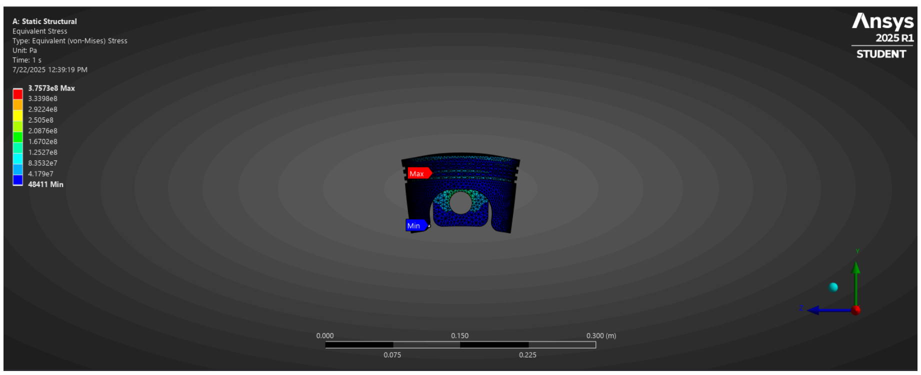

Figure 17: Control Geometry Equivalent Stress

Under peak combustion pressure of 20 MPa, the control piston head with a weight of 1.254kg showed:

Maximum Deformation at the edges of the piston skirt of 0.26mm
Maximum von Mises Stress of 375.73MPa at the piston ring lands

The relatively high mass of the control design provides structural robustness but increases reciprocating forces during engine operation.

Optimized - Static Structural

Total Deformation

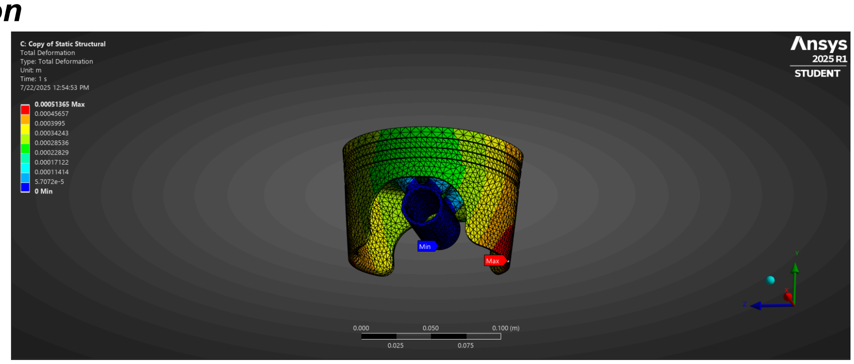

Figure 18: Optimized Geometry Total Deformation

Equivalent Stress

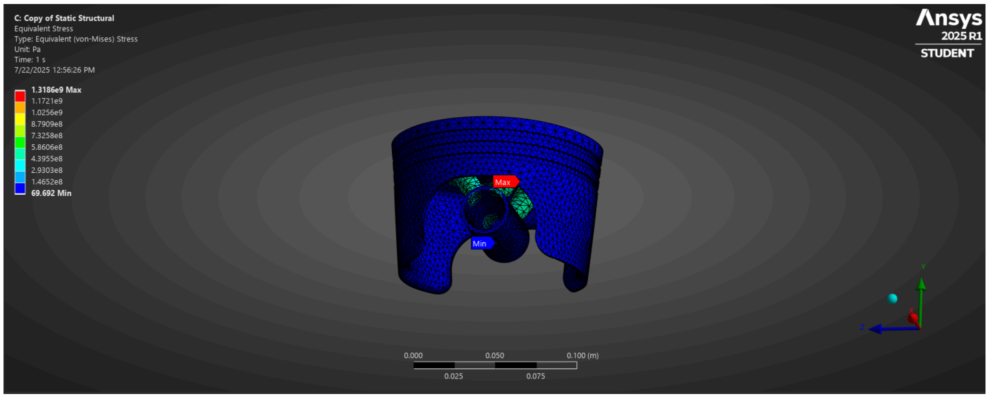

Figure 19: Optimized Geometry Equivalent Stress

Under the same 20 MPa of pressure, the optimized piston head with a weight of 0.999kg showed:

Maximum Deformation at the edges of the piston skirt of 0.51mm
Maximum von Mises Stress of 1318.6MPa at the piston pin boss

The optimized design achieved significant mass reduction but exhibited higher stress levels. This demonstrates the challenge of balancing mass reduction with structural integrity. While the 20.4% mass reduction exceeds the target inspired by the Porsche/MAHLE study (10%), the stress levels indicate over-optimization [4]. The volume fraction constraint of 0.2 (retaining only 20% of original volume) was too aggressive for this application.

Control - Temperature

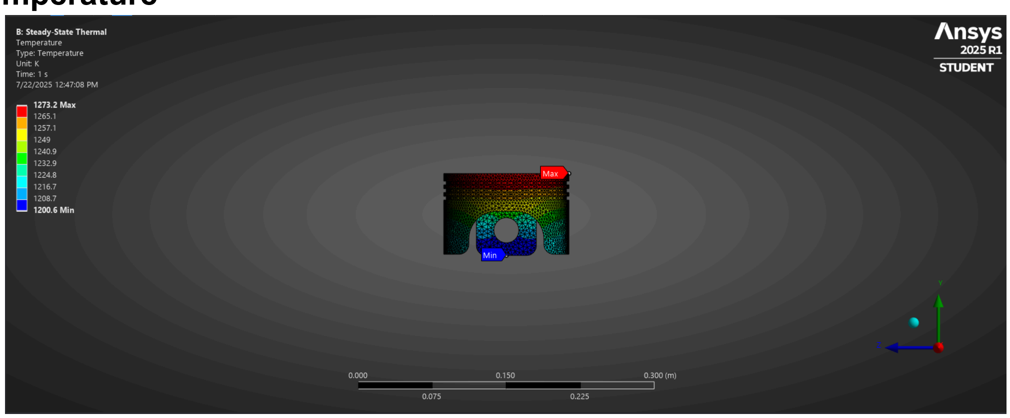

Figure 20: Control Geometry Temperature Profile

The final maximum temperature of the control piston head at the crown was 1273.2K.
The minimum temperature at the piston pin bosses was 1200.6K

Optimized - Temperature

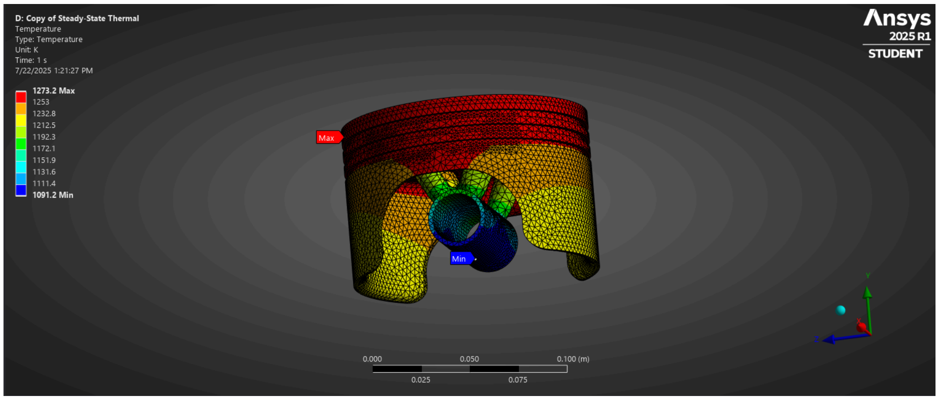

Figure 21: Optimized Geometry Temperature Profile

The final maximum temperature of the control piston head at the crown was 1273.2K.
The minimum temperature at the piston pin boss was 1091.2K

The 109.4K reduction in minimum temperature at the piston pin boss demonstrates that the optimization created more surface area and allowed for more efficient heat dissipation cooling paths, despite the absence of dedicated cooling channels in this design.

Table 1: Performance Comparison Between Control and Optimized Piston Designs

Parameter	**Control**	**Optimized**	**Change**	**Implication**
Mass (kg)	1.254	0.999	-20.4%	**Reduced reciprocating forces**
Max von Mises Stress (MPa)	375.73	1318.6	+251%	**Exceeds material limits**
Max Deformation (mm)	0.26	0.51	+96%	**Within operational tolerance**
Min Temperature (K)	1200.6	1091.2	-109.4 K	**Improved heat dissipation**

Conclusion

This study investigated the application of metal additive manufacturing and topology optimization to enhance piston design for Porsche's innovative 6-stroke engine. The research demonstrates both the significant potential and current challenges of using additive manufacturing technologies to address the increased thermal and mechanical demands of modern engine designs. The topology optimization process successfully achieved a 20.4%

mass reduction while improving thermal performance, with the minimum temperature at the piston pin boss reduced by 109.4 K compared to the control design. This enhanced heat dissipation capability directly addresses the primary challenge of 6-stroke engine’s additional heat. The reduced reciprocating mass also offers benefits for engine dynamics and efficiency. However, the structural analysis revealed that aggressive material removal led to stress concentrations exceeding acceptable limits, with the maximum von Mises stress increasing to 1318.6 MPa at the piston pin boss. This demonstrates how topology optimization for engine components requires a careful balance between strength and weight. The volume fraction constraint of 0.2 proved to be too aggressive for maintaining structural integrity under combustion loads.

References

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[2] N. Naidu, "Piston SubAssembly," *Grabcad.com*, Jun. 23, 2025. https://grabcad.com/library/piston-subassembly-2/details?folder_id=14137594 (accessed Jul. 22, 2025).

[3] G. Turesson, "Figure 1," *ResearchGate*, Jun. 2018. https://www.researchgate.net/figure/The-basic-geometry-of-an-engine-cylinder-Combustion-of-fuel-and-air-in-the-combustion_fig1_325086523

[4] M. Team, "Porsche Develops 3D Printed Pistons For The Powerful 911 GT2 RS With Help From Mahle, Trumpf And Zeiss | Manufactur3D," *Manufactur3D Magazine*, Jul. 16, 2020. https://manufactur3dmag.com/porsche-develops-3d-printed-pistons-for-the-powerful-911-gt2-rs-with-help-from-mahle-trumpf-and-zeiss/ (accessed Jul. 22, 2025).