



Topology Optimisation of an Internal Combustion Engine Piston

Roland Magyar

Andrew Noble

Wales Institute for Science & Art
MSc Motorsport Engineering

Introduction

The piston is one of the most highly stressed components in an engine, exposed to steep thermal gradients and cyclic pressures (Heywood, 2018). This project applies density-based topology optimisation (SIMP) to reduce mass while maintaining durability. By combining finite element analysis with realistic thermo-mechanical loads (Zhu et al., 2021) and manufacturability constraints (Alrashdan & Alhakeem, 2025), the study demonstrates an approach that is both technically credible and industrially relevant.

$$F_g(\theta) = p(\theta) A_p$$

Equation used in MATLAB to work out the loads applied to the piston

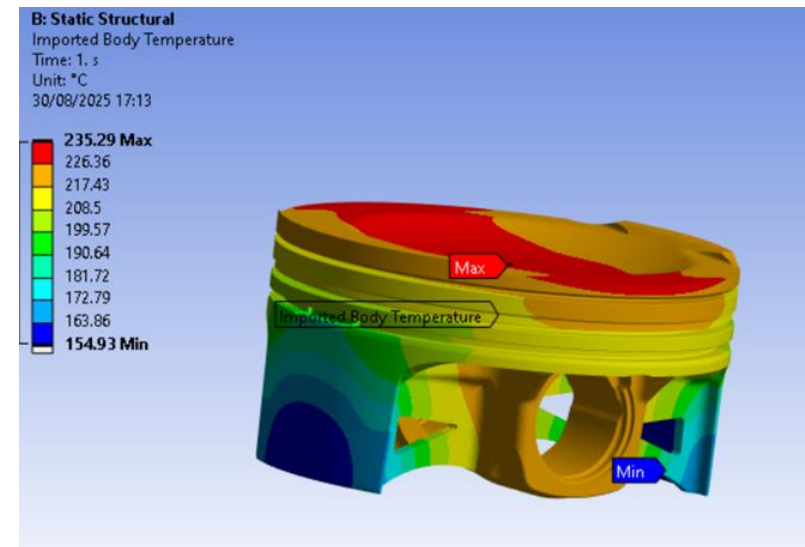
Literature Review

Recent studies highlight the potential of topology optimisation (TO) for lightweighting pistons without sacrificing durability. Barbieri et al. (2017) applied density-based TO to additively manufactured pistons and achieved a 12.6% mass reduction, while maintaining structural performance. Lee and Ku (2021) showed that crown geometry strongly influences thermo-mechanical behaviour, with bowl designs reducing stress concentrations. Giacomini et al. (2014) demonstrated that non-uniform thermal gradients drive fatigue at the crown rim and ring grooves, emphasising the need for coupled thermal–mechanical modelling. More recent work by Zhang et al. (2024) introduced meshless optimisation with neural networks, showing promise for faster design iterations, though industrial readiness remains limited. Together, these studies show that credible piston optimisation depends on realistic boundary conditions, accurate thermal representation and manufacturability constraints.

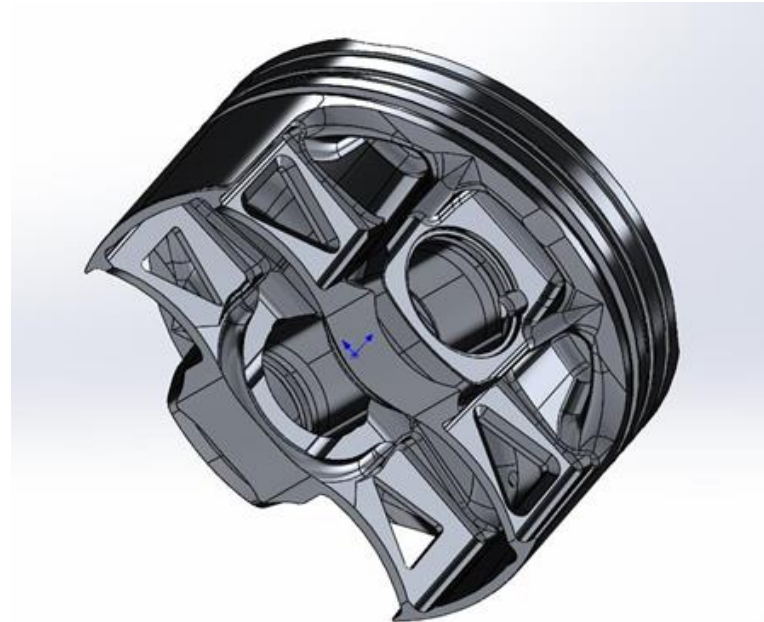


The figure shows how the mesh looked on the piston for the program to work

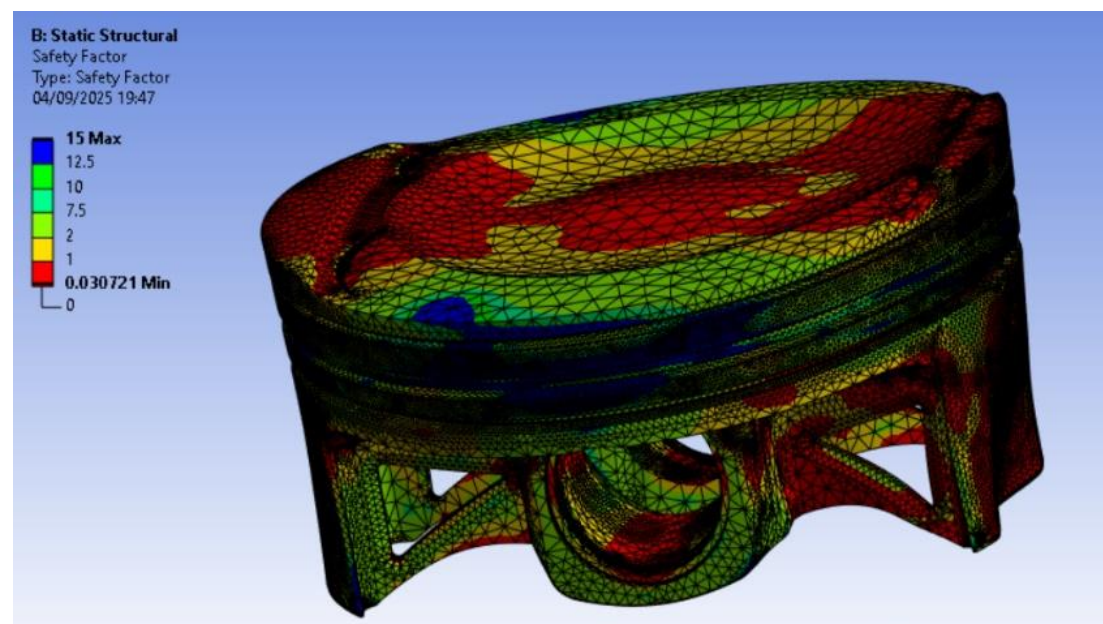
The figure shows the temperature spread across the piston, which was applied for the thermal conditions



The Figure shows the underside of the piston before any changes were made.



The image shown is the final result after the optimisation process was repeated multiple times



The image shown above shows the safety factor across the piston after the forces were applied to it.

References

- Heywood, J.B. (2018) *Internal Combustion Engine Fundamentals*, 2nd edn.
- Zhu, X. et al. (2021) Thermal gradients and crown surface temperatures in pistons.
- Moser, D. et al. (2021) Coupled CFD–FEA piston thermal boundary validation.
- Giacomini, M. et al. (2014) Thermomechanical fatigue in diesel pistons.
- Alrashdan, A. & Alhakeem, A. (2025) Topology optimisation with casting constraints.

Methodology

A piston model was built in ANSYS with mesh refinement at the crown rim, ring belt and pin-boss fillets, following meshing strategies outlined by Moser et al. (2021). The Al-Si4032 alloy was chosen for its balance of stiffness and thermal stability (Marklund, 2013). Thermal conditions represented a 450 °C to 120 °C crown-to-skirt gradient (Liu et al., 2022), while structural loading included peak firing pressures and pin-boss reactions (Ali et al., 2020). Optimisation was performed with the SIMP algorithm (Bendsøe & Sigmund, 2003) under 30% volume retention and casting constraints, before re-analysis confirmed stresses and deformation.

Result

The piston mass was reduced from 352.25 g to 334.83 g, a saving of 4.9%, aligning with published ranges of 3–6% from density-based studies (Lee et al., 2016; Huo et al., 2018). The optimised piston displayed a more uniform safety factor field of 1.2–2.0, consistent with findings that redistribution improves fatigue predictability (Strzelecki et al., 2020). The rib lattice beneath the crown improved stiffness-to-mass, while preserving conduction paths through the rim, in line with observations from Zhu et al. (2021) that crown rims act as critical thermal conduits.

Conclusion

Validated thermo-mechanical optimisation achieved weight savings without compromising safety, echoing the conservative but robust outcomes of industry-calibrated studies (MAHLE, 2024). The optimised piston improved stiffness and redistributed stresses, confirming that SIMP-based topology optimisation is a practical tool for lightweight yet durable piston design (Gao et al., 2016).

Acknowledgements

I would like to thank my friends and family for all the support along the way