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Thermo-Mechanical Analysis and Durability Optimization of the Piston

Mothanna Taha Mohammed Fattah Agha*

Department of Soil Sciences and Water Resources, College of Agriculture, Al-Qasim Green University, Babel, Iraq

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*Correspondence: Mothanna Taha Mohammed Fattah Agha
Email: mothanna@agre.uoqasim.edu.iq

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Abstract: *This study evaluated both the thermal and mechanical performance of an internal combustion engine piston in different operating conditions. A comprehensive thermo-mechanical analysis was performed to evaluate temperature distribution, heat transfer behavior, pressure accumulation and visco-plastic stress in various parts of the piston. The results show that there is considerable thermal influence on the flame face, first ring groove and crown underside of the oil area for different operating conditions, i.e., rated vs. idle conditions. Thermal and visco-plastic strain concentrations are illustrated as being a result of cyclically increasing temperatures in the stabilized 5th cycle examination; however, visco-plastic stresses remained well below maximum allowable values. Additionally, the TMF-based life prediction indicated that the piston design is capable of withstanding more than 3000 cycles and will not fail with reasonable probability. The study also indicates the need for understanding thermal boundary conditions within ring grooves and how heat transfer coefficient (HTC) values may be used to regulate piston surface temperature, which will lead to better engine reliability and efficiency by providing an optimized material selection and thermal management strategy for the piston.*

Keywords: *"Thermal-Mechanical Fatigue (TMF)", "mechanics of structural", "Finite Element" and "fatigue_durability".*

Introduction

The piston is an element that operates beneath extreme thermal loads and is a major contributor to the total performance and longevity of an internal combustion engine. The piston is one of the most critical moving components and undergoes severe temperature fluctuations, high levels of mechanical stress and friction as it performs during operation. All of these factors can contribute to reduced structural integrity, thermal efficiency and general life span of the piston (Elhadi et al. 2021).

Significant amounts of research have been completed to assess materials used to create pistons, develop surfaces and new manufacturing methods to increase the durability of pistons. Pistons today are generally made from aluminum alloys due to their low weight and improved thermal conduction. However, high running temperatures and combustion pressures in engines can also lead to thermal expansion, increased wear and tear, and eventual fatigue failure of the piston (Amroune et al. 2019; Mohamad et al., 2020; Mohamad et al., 2021). Therefore, both computational and experimental testing and analysis is required to optimize the configuration of pistons, reduce thermal stresses and improve cooling of the piston.

Kumar and Kumar (2022) investigated and extensively examined the piston failure in Internal Combustion Engines, illustrating how mechanical and thermal stresses result in fatigue and seizure from the piston's interaction with the piston rings, grooves and cylinder liner. This research is a study of major failure modes of the piston device; and provides a review of how various coatings can be used to prevent or at least reduce failures. It includes a detailed description of the tribological and mechanical properties of different coatings including but not limited to: hardness, elastic modulus, coefficient of friction, surface roughness and wear rates. This study also provides information about the selection of optimal coating material, method, and factors for increasing the durability of piston devices, while reducing the risk of damage from fatigue, stress, wear, and friction.

Kuttin et al. (2024) evaluated the structural performance of piston devices to improve their durability and efficiency. In this study, fatigue damage was demonstrated based on cyclic gas force stress developed by the cyclic gas force pressure and inertial stress. An attempt was made to use a composite matrix of aluminum and silicon carbide (AlSiC-12), to increase the wear resistance of the piston devices. So the stress analyses, strain, temperature distribution, and deformation was performed by using FEA In the Results, the AlSiC-12 showed better wear resistance compared with the Al-6061. This phenomenon is attributed to its lower density and higher strength.

In a report from Soni (2023), the design and analysis of a piston used in an internal combustion engine, which is designed to transfer the forces produced by the combustion of gas to the connecting rod were discussed. A computer model of the piston was developed in Fusion 360, and subsequently evaluated using ANSYS software. In this research, the combined effects of the thrust and thermal loads are being studied for an aluminum alloy piston; these studies eliminate the complexity of thermal loading. The results of the structural and thermal analyses performed with ANSYS will provide the data required to identify the critical values associated with the behavior of the piston, as well as information regarding its potential performance and longevity due to operational conditions. Lee and Ku (2021), studied the effect of the geometric design of the piston head, stress, temperature, and deformation on the performance of the piston. The study evaluated four different piston head designs – flat-top, bowl, square bowl, and dome pistons, which were designed with SolidWorks. Static structural and steady-state thermal analyses in ANSYS Workbench were used to determine the stress, deformation, and temperature distributions across each of the four pistons. Topology optimization was employed to eliminate excess material, and as a result, the total weight of the piston was reduced by about 5%. The results of this research indicate that the bowl piston exhibited the least amount of stress, deformation and temperature among all of the pistons examined, whereas the optimized piston performed superiorly in all of the measured parameters compared to the original piston. Delprete et al. (2018), reviewed the mechanical energy losses due to friction between lubricated bearings and internal combustion engines, and emphasized the benefits of reducing friction through the use of a cost effective means to reduce emission levels and improve efficiency. It was important for the authors to focus on the role of the piston secondary motion. Secondary motion occurs due to an imbalance of forces and moments experienced by the piston and generates a small degree of movement (both translationally and rotationally) within the limits of the clearances of the piston. As stated above, these movements are also capable of generating power losses through the mechanical friction of the lubricants used as well as providing better or worse lubrication of the skirt/piston liner interface, depending upon the nature of their movements. Also, they generate noise in the engine. Authors combined and evaluated those factors that were most influential upon the tribological and lubricating performance of the piston based on the parameters of the piston design, the rheology of the lubricant, the mechanisms of the oil cycle, and the operating conditions of the engine. This study is primarily concerned with assessing the structural and thermal performance of the piston body when operated under actual conditions. This will be accomplished by employing FEA and experimental methods to measure the stresses developed within the body, its deformation and the temperature gradients within it. with this information, practical design changes can be made to improve durability & performance. Additionally, future advancements in coating technology and opportunity substances are mentioned to in addition improve piston reliability in high-overall performance applications.

Workflow for Piston Structure Analysis

The Finite Element Analysis (FEA) methodology is a computational method that uses a series of steps to determine the structural and thermal performance of a system, most likely an engine component. In the first step (pre-processing), the FEA methodology breaks down the problem into individual ranges, including determining all of the advanced fabric model (AMM) parameters necessary to run the simulation and developing a discrete mesh to allow for numerical modeling. In this same step, boundary conditions are established for both the mechanical and heat transfer (HT) portions of the system. Using these conditions, the FEM solver performs the computational analysis to evaluate heat flow within the jacket.

As mentioned above, the FEA process can be broken down into two phases. Phase one includes assigning global material properties; completing a steady-state heat transfer analysis; validating the results of the heat transfer analysis through establishment of a heat balance and comparison of the FEA results with experimental test data; and if necessary, iterating to obtain an acceptable set of results from the FEA simulation model.

The second step in the FEA process will be to assess the Transient Thermal & Mechanical Response of the Component. The process will also include establishing a Thermo-Mechanical Fatigue (TMF) cycle as well as Simulate the transient Heat Transfer Effects. Lastly, the AMM will be utilized to determine the transient Stress/Strain responses of the Material under several Operating Conditions.

In the last phase of the FEA Process (Post-Processing), the Results from the Simulation will be analyzed to predict the Life of the Component using Stress, Strain, & Fatigue Calculations. Therefore, this iterative approach allows the FEA Analyst to Validate the simulation Results with Actual Test Data and provide an accurate assessment of Engine Component Durability.

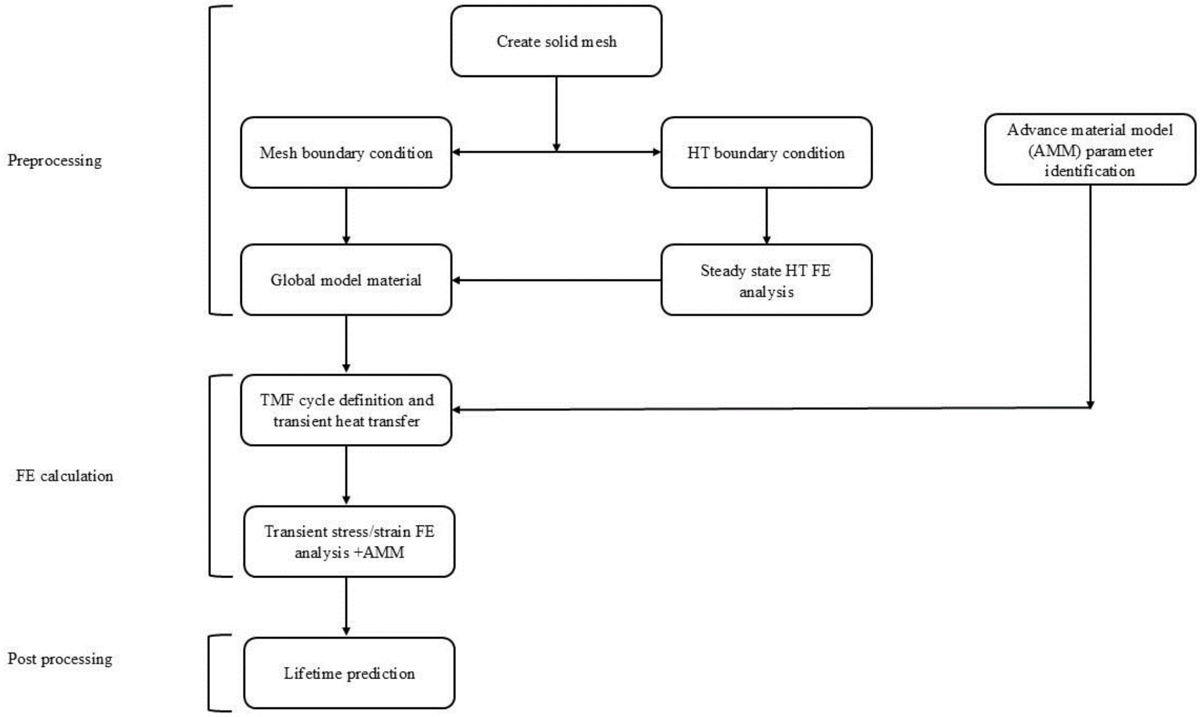


Figure 1. The Analysis Workflow for Piston Structure

As shown in Figure 2, the model meshing is used as an extremely fine array of types of elements to perform a computational method for simulating structural and thermal behaviors. The various colorations depict separate materials/components; the blue area depicts the piston body, the red area indicates the piston pin and other structural elements are depicted in differing hues. The meshing implies that a high-resolution simulation will be employed to assess stress distribution, thermal expansion, and fatigue behavior when the piston is subjected to the conditions of engine operation. A cut-section perspective provides the ability to visually examine in detail the internal configuration of the structure.

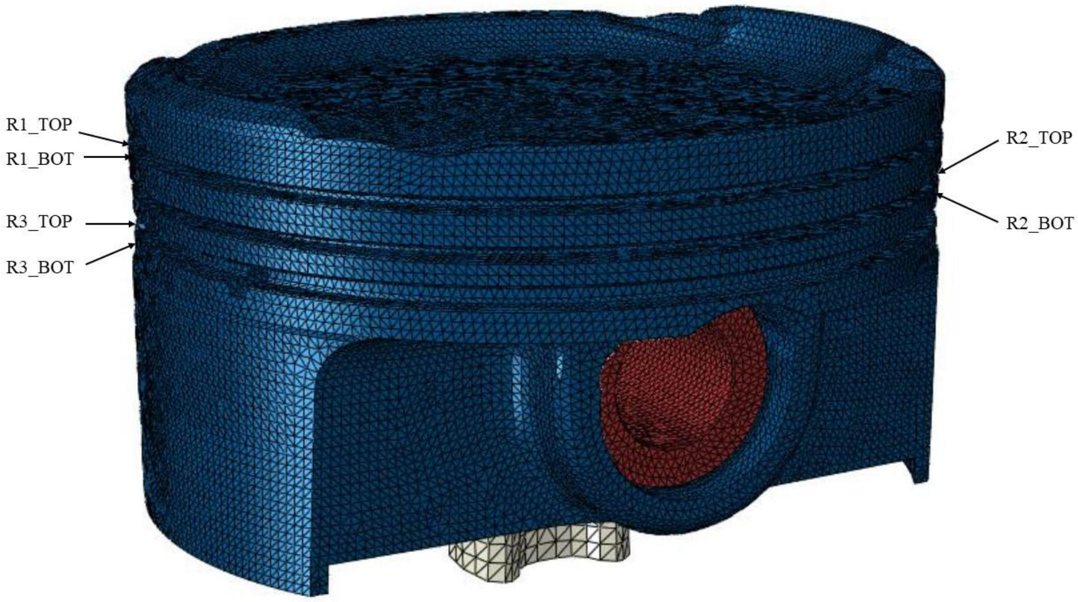
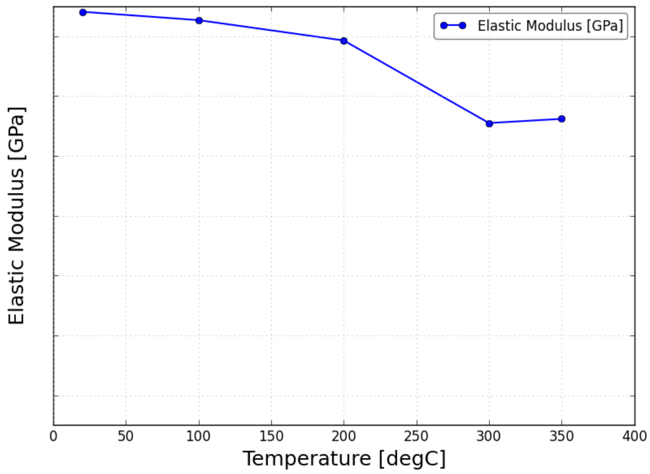


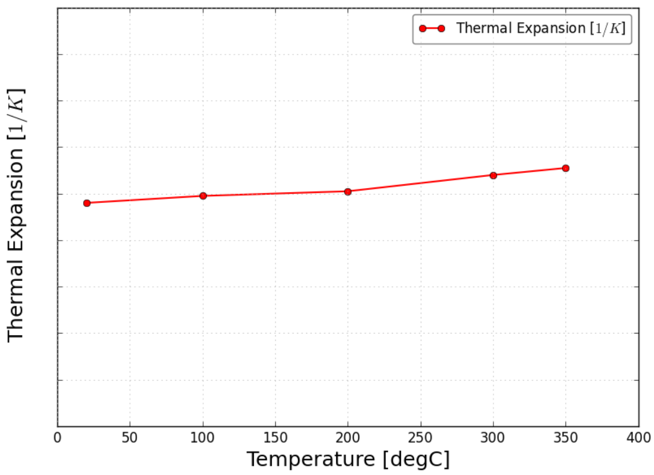
Figure 2: Geometry of Piston model

Finite Element Model and Results

Materials' thermal and mechanical functionality under operating conditions provide insight into developing thermal resistance and robotic strength in additive manufacturing. As illustrated in Figure Three (A), the elastic modulus (GPa) is plotted against temperature (°C). There was a small decrease in elastic modulus due to temperature increase; however, there was a much greater decrease after 200°C and then a slight stabilization in the elastic modulus at elevated temperatures. This behavior indicates a discount in the cloth's stiffness with growing temperature, which is common for metals and alloys utilized in high-temperature programs, together with engine additives. Figure (b) displays the thermal growth coefficient (1/K) as a function of temperature. The statistics indicate a gradual increase in thermal growth with rising temperature, indicating that the cloth expands more at higher temperatures.



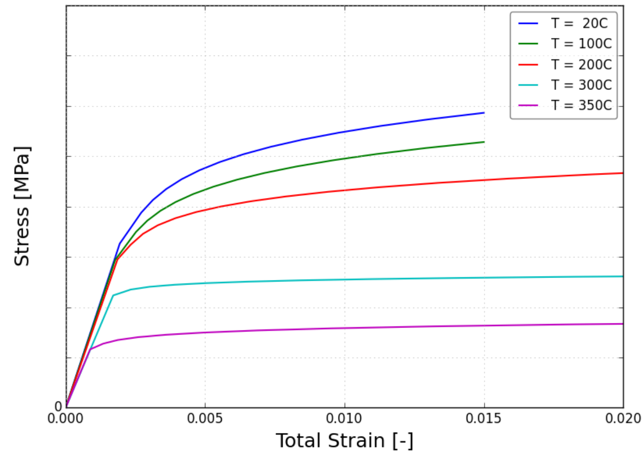
(a)



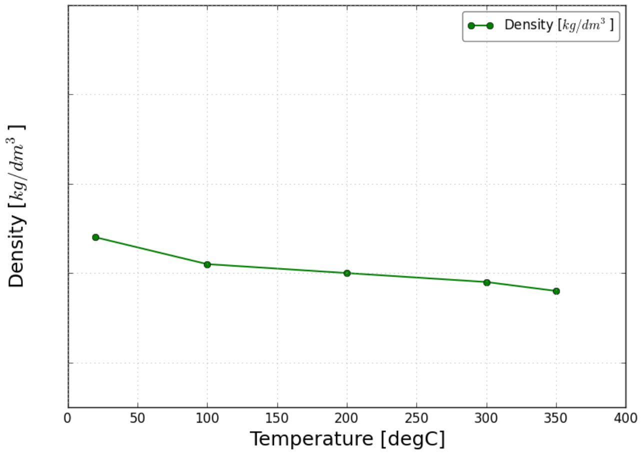
(b)

Figure 3(c)

Illustrates the relation between stress (in MPa) and strain for exclusive temperatures starting from 20°C to 350°C. The curves display a decreasing trend in stress with increasing temperature, indicating a decrease in the strength of the material, strain, and stiffness at elevated temperatures. At high value of temperatures, the material is well-known to show extra strain for a given stress. Figure 3(d) represents the variant of density (kg/m³) with temperature. The trend suggests a slow lowering in density as temperature increases; that is expected due to the material's thermal expansion. As temperature rises, the volume of materials already increases while their mass remains steady, leading to a reduction in density.



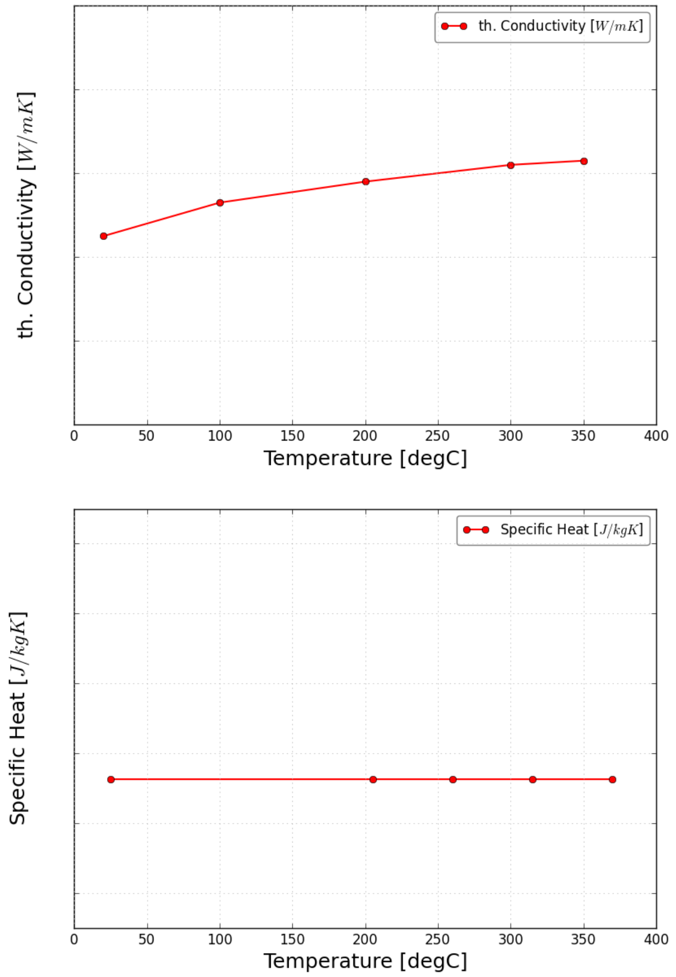
(c)



(d)

Figure 4.

Thermal Conductivity (in W/m·K) as a function of Temperature (in °C) is illustrated in Fig. 3(e), which illustrates an increase in thermal conductivity with increasing temperatures, and thus demonstrates an increased efficiency in the transfer of heat when there are rapid changes in temperature. This type of behavior is typical for metals, which exhibit an increase in lattice vibrations with temperature, and therefore an enhancement in heat transfer. In contrast, fig. 3(f) illustrates Specific Heat Capacity (in J/kg·K) as a function of temperature, and indicates that the Specific Heat Capacity exhibits little change over varying temperatures, and therefore, the amount of energy stored by the material will also remain largely unchanged with temperature variations.



(e)

(f)

Figure 3, "a, b, c, d, e, f" Piston material properties

Heat transfer

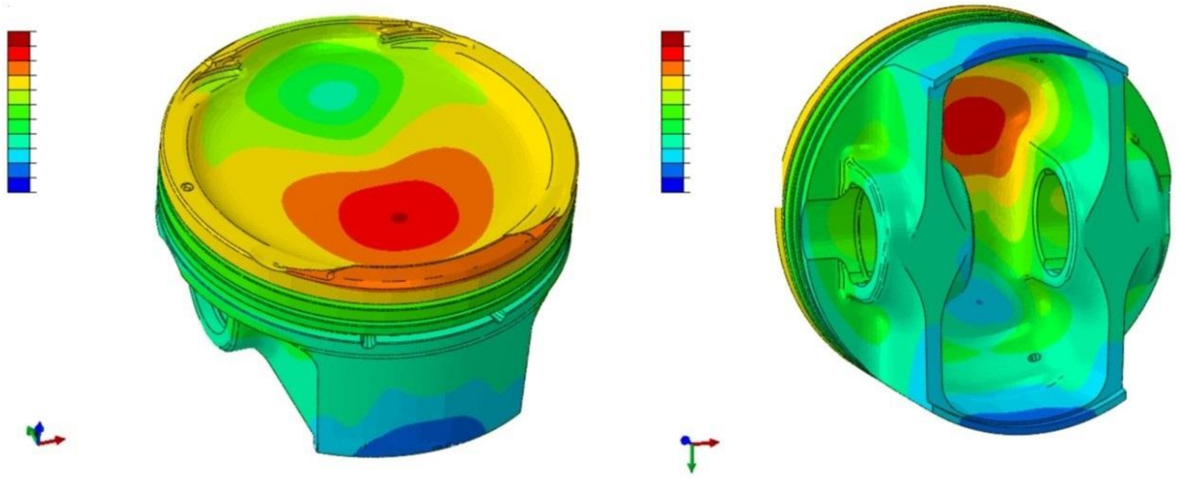
Boundary conditions for thermal effects in the grooves of the rings on a piston with the heat transfer coefficient (Htc), temperatures (T), and the location (R1_top, R1_bot, R2_top, etc.), and the number of simulations (loops). This is to help in understanding thermal load and thermal heat loss as the simulation loop progresses as it impacts the thermal behavior of the piston, as shown in table 1.

Table 1 Thermal boundary – Ring grooves

	Loop					
Parameter	Initial		1		2	
	HTC W/(m².k)	T (˚C)	HTC W/(m².k)	T (˚C)	HTC W/(m².k)	T (˚C)
R1_TOP	3060	103.4	2720	96.4	3000	93
R1_BOT	14270	103.4	14550	96.4	14520	93
R2_TOP	3160	90.7	1260	84.4	710	79.3
R2_BOT	5050	90.7	5780	84.4	6170	79.3
R3_TOP	90	88.9	90	88.9	90	87.1
R3_BOT	18640	88.9	18640	88.9	18640	87.1

Thermal Loading of Piston Under Rated and Idle Conditions is shown in Figure 4. Temperature distributions across the piston are highlighted as well as temperature distribution differences by area of the piston, including highest temperatures on the flame side, first ring groove and under the oil side or crown of the piston. The analysis shows that the thermal load varies significantly between operating conditions and thus impacts the stress to materials and ultimately durability. Thermal gradient profiles along the axial direction were also identified which show significant areas of thermal gradients.

Rated



Idle

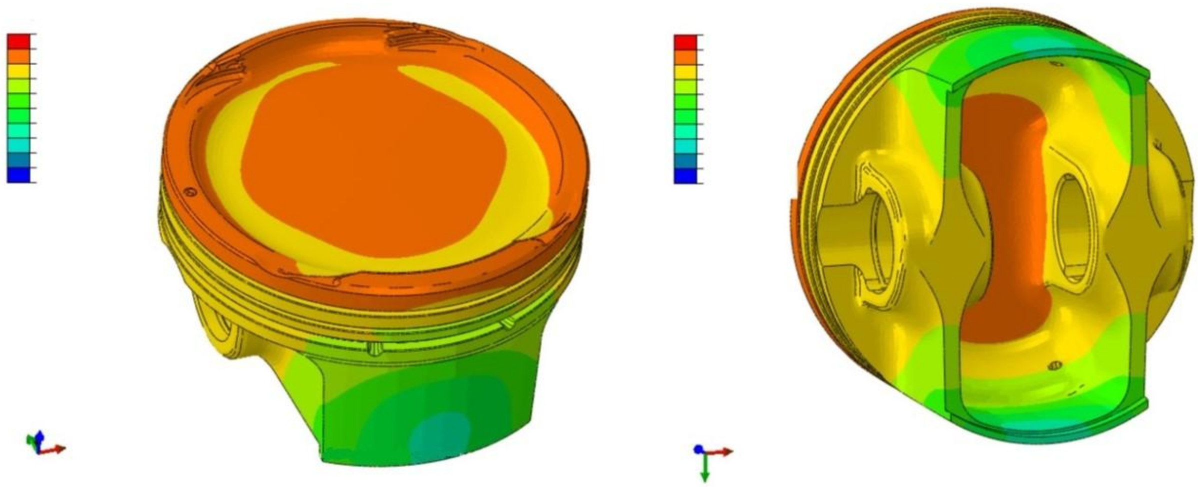


Figure 4. Heat transfer analysis of a piston under rated and idle conditions.

Thermal – Mechanical Fatigue

Each cycle in Figure 5 includes both hot and cold cycles; however, gas (red) and oil (blue) are treated as separate operating condition states. The hot cycle has the engine running at rated conditions, but with the gas being held at a constant rated condition and the oil being increased from idle until it reaches a steady state rate. Following the hot cycle is the cold cycle, which is when the gas is returned to idle conditions and the oil is decreased back down to its idle conditions as well. These cycles repeat continuously, and by approximately the fifth TMF cycle, an equilibrium or stabilization phase occurs that signifies that the thermal and mechanical responses of the material have reached a stable condition.

In addition to the repetition of these cycles, there is also a 30 hour "aging" period included between the cycles to represent the effects of long term operation and material degradation. The cycles in this study were defined using TMF test data from a similar engine to ensure that the cycles represented realistic engine operating conditions for the fatigue analysis.

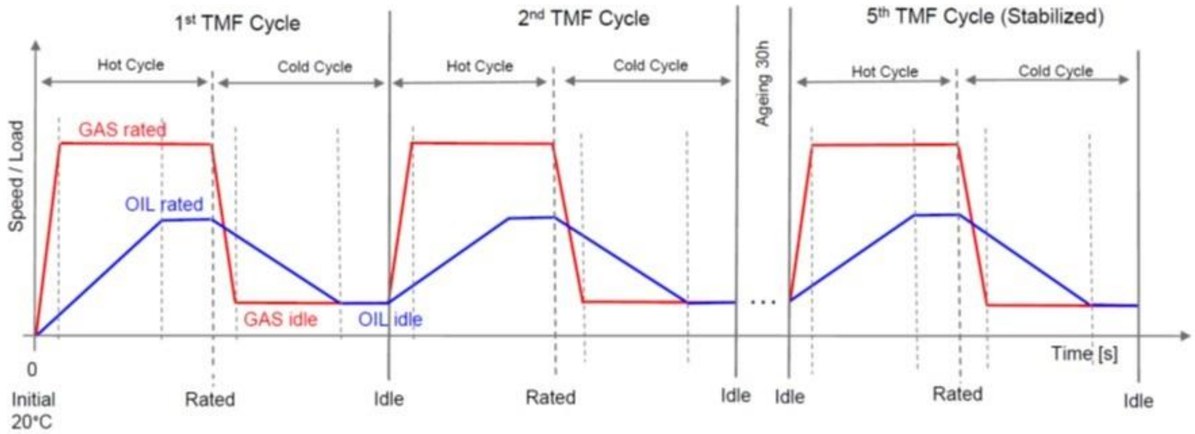
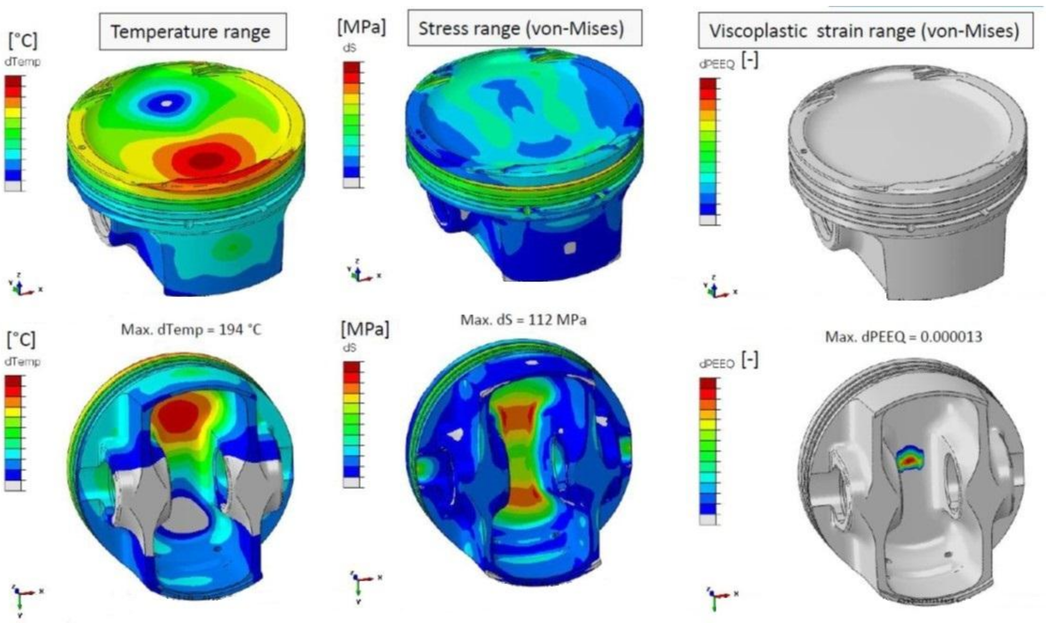


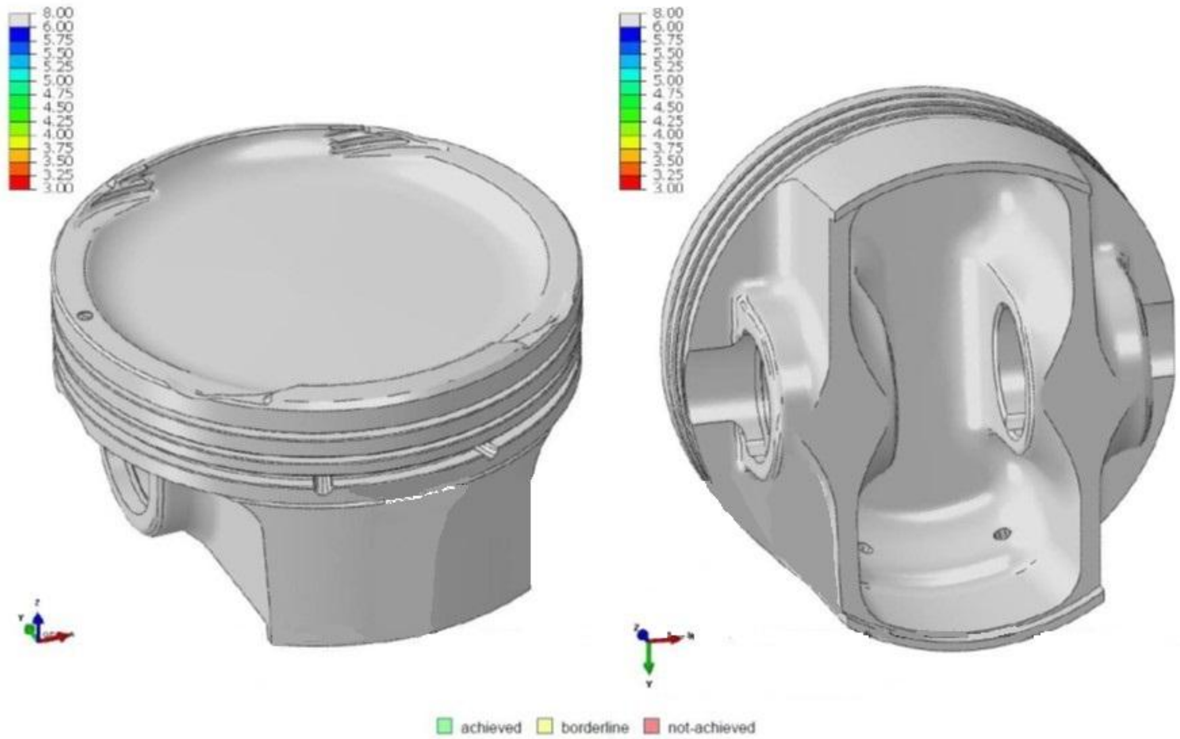
Figure 5. TMF cycle definition for an engine test, illustrating variations in speed/load over time for gas and oil conditions across multiple cycles.

Range of the stabilized 5th cycle

TMF life assessment of a piston based on an analysis model and results for the stabilized 5th cycle of a piston under TMF conditions has been shown in figure 6 (a). Temperature, stress, and viscoplastic strain distributions have been presented along with the temperature, stress, and viscoplastic strain ranges of the most stressed areas of the piston under the thermal and mechanical constraints due to the material behavior as a result of temperature changes. The left side of this figure contains a temperature distribution map for the piston and the maximum ΔT is 194°C. On the right-hand side of this map, a distribution map of von Mises stress is given. Viscoplastic strain range maps are also included to show the minimal strain accumulation of the piston materials after the last cycle. Therefore, the main effects of the geometric stiffness of the piston on the variation of stresses and strains in the piston can be seen in these results. In contrast, figure 6 (b) addresses the lifetime estimation of the piston. Based on the calculation of the number of cycles to crack initiation in all piston regions, it was concluded that the number of cycles exceeds 3000 cycles and this is significantly higher than the specified value by Society of Automotive Standards for this type of material. Hence, it can be said that there is no danger of TMF failure in the piston design and therefore the design satisfies the necessary durability requirements. Overall, the evaluations provided in this study confirm the structural integrity of the piston under high-temperature engine conditions, hence contributing to the long-term operational reliability of the piston.



(a)



(b)

Figure 6 (a, b) Temperature, stress and viscoelastic Strain range of the stabilized 5th cycle.

Conclusion

The comprehensive investigation of the TMF behavior in engine pistons has been focused on the thermal, mechanical and viscoelastic stresses at multi-cycles; the results show that the variability of temperature, distribution of stresses and accumulation of viscoelastic strain are within acceptable limits and thus ensure the structural stability; and the life time estimation analysis shows that the piston can endure more than 3000 cycles before crack appearance. Therefore, these data confirm that the durability of the piston under a real engine operation condition is confirmed and provide an opportunity to optimize the choice of materials, design of pistons and the predictive repair methods. Also, future investigations may be focused on new types of surface coating (advanced), alternative alloys or more precise TMF models to further improve the resistance and performance of pistons in high-performance engines.

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