# Thermo-Mechanical Coupling Analysis of a Diesel Engine Piston

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**Abstract.** As the research object to a certain type of diesel engine pistons, a three-dimensional finite element analysis model is established. Piston stress is calculated under the conditions of thermal load, mechanical load and coupled load. Results show that, the main cause of the piston safety, the piston deformation and the great stress is the temperature, so it is feasible to further decrease the piston temperature with structure optimization.

## 1. Introduction

As the main heated part of the engine, the piston has to bear the complicated mechanical load and thermal load subjected to periodical change. An analysis to the stress and the deformation condition under the mechanical load or the thermal load only is far from enough to reflect the actual working condition of the piston. A reference can only be provided for the piston design with factors influencing the thermal load found out, taking into overall consideration the piston intensity under the coupling effect of the thermal load and mechanical load.

Nowadays, thermo-mechanical coupling analysis work includes: Bao-Lin Wang, Yiu-Wing Mai [1] establishes a solution method for the one-dimensional (1D) transient temperature and thermal stress fields in non-homogeneous materials. Douglas M. Baker, Dennis N. Assanis [2] present a methodology for a coupled thermodynamic and heat transfer analysis of diesel engine combustion chambers. P. O'Hara [3] analyzed heat transfer problems exhibiting sharp thermal gradients using the classical and generalized finite element methods. U. A. Benz, J. J. Rencis [4] a dual reciprocity boundary element formulation using quadratic elements is presented for coupling two-dimensional and axisymmetric zones for transient heat transfer applications. Sook-Ying Ho, Allan Paull [5] describes a relatively simple and quick method for implementing aerodynamic heating models into a finite element code for non-linear transient thermal-structural and thermal-structural-vibrational analyses of a Mach 10 generic HyShot scramjet engine. Elisa Carvajal Trujillo [6] proposes a methodology for the estimation of the mean temperature of the cylinder inner surface in an air-cooled internal combustion engine.

Based on the fundamental of thermal analysis, this paper analyzes the stress of the piston under the conditions of thermal load, mechanical load and coupled load. Respectively and compares it to the stress and deformation condition under the coupling effect of the thermal load and mechanical load. Through the analysis, it is concluded that the main factor influencing the piston intensity is the temperature, thus providing basis for the optimization design of the piston.

## 2. Finite Element Model

Establish reasonable and accurate finite element model is the most important part of the piston finite element analysis, thus carrying out analysis by marking element grids to obtain the accurate results finally. According to the structural symmetry of the piston, in order to be convenient for calculation and decrease workload, cut the established piston model to maintain 1/4 and then import the model to

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the finite element software for the finite element analysis to the piston according to the fine interface between the modeling software and the finite element analysis software. During the importing process, some details have been omitted, such as the chamfer and the snap ring of the piston pin etc. The geometrical model for the piston is as shown in figure 1. Overall, the element division is smaller, calculation more accurate, but needs more time. During the mesh generation for the piston model, based on experiences and with several trials, the eight-node hexahedron cell SOLID70 is selected in this paper. Physical Properties of the Material is as shown in table 1.

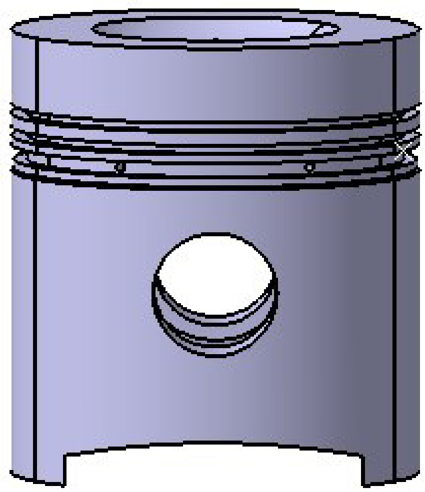

**Figure 1.** Geometrical model for the piston.

**Table 1.** Parameters of the piston material

| Parameters | Values of the parameters |
|---|---|
| Piston material | Aluminum alloy |
| Poisson ratio | 0.32 |
| Elastic modulus of the piston | 70GPa |
| Material density | $2700 kg/m^3$ |
| Conductivity factor | $160 w/(m^2 \cdot K)$ |
| Coefficient of thermal expansion | $21\times10^{-6} m/K$ |

**3. Basic Theory for Thermal Analysis**

To solve the temperature field of an object is the precondition necessary for the calculation of the thermal stress, thus obtaining the thermal strain and then carrying out the accumulation with the positive strain and shearing strain of the mechanical load.

Based on the basic theory for heat transmission, we can deduce the differential equation of the heat transmission for the object with the internal heat source and the transient temperature field:

$$\rho c\frac{\partial T}{\partial t}=k\left[\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}\right]+q_V \tag{1}$$

where, $T$ is the transient temperature value of the object, $t$ is the time, $k$ is the conductivity factor of the material, $\rho$ is the material density, $c$ is the specific heat capacity of the material and is the internal heat source intensity of the material. Usually, $k$, $\rho$, $c$ and are treated as constants, while the stable thermal analysis has nothing to do with the time variable t, and no internal heat source has to be taken into consideration for the finite element analysis to the piston. So we can get

$$\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}=0 \tag{2}$$

Besides, to get the unique solution for the aforesaid differential equation, the initial condition and the boundary condition should be added, which are collectively called the definite condition. Then we get coupling solution for the differential equation. In this paper, the third boundary condition is applied for solving and analyzing the temperature field for the piston, which means that the temperature $T_f$ and the heat exchange coefficient h of the fluid medium contacting the object is treated as the variables whose constants have been known. We can express in the equation as follows:

$$-k\frac{\partial T}{\partial n}=h(T-T_f) \tag{3}$$

where, $n$ is the exterior normal vector for the object boundary, $h$ is the convection heat exchange coefficient and $T_f$ is the temperature of the surrounding medium.

The finite element analysis for the temperature field of the piston is to get the extreme value the functional of the differential equation with the variation principle, based on the principle of the functional of the differential equation, thus solving the equation set with the node temperature as the unknown variable. Based on the variation principle, the functional equation for solving the node temperature is

$$I(T)=\frac{k}{2}\iiint_V\left[\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}+\rho C\frac{\partial T}{\partial t}T\right]dxdydz-\iint_S h(T^2-T_fT)ds \tag{4}$$

where, $S$ is the piston boundary and $V$ is the solution zone for the piston body.

The temperature function $T(x,y,z,t)$ of the piston temperature field meeting the boundary condition is obtained by carrying out variation to the aforesaid functional and obtaining the minimum solution as follows

$$\delta I=0 \tag{5}$$

After discrete the piston body with the finite element method, every element can be considered as the sub-domain of the integral computational domain, thus obtaining $I(T)=\sum I^e(T)$, where $I^e(T)$ is the sub-domain for every cell.

While the functional equation for the cells within the sub-domain can be expressed as:

$$I^e(T)=\frac{k}{2}\iiint_V\left[\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}+\rho C\frac{\partial T}{\partial t}T\right]dxdydz-\iint_S h(T^2-T_fT)ds \tag{6}$$

The temperature value of any point within the cell applies the node temperature of the cell to carry out interpolation function and obtain with calculation:

$$T(x,y,z,t)=\sum_i^m N_iT_i \tag{7}$$

where, $N_i$ and $T_i$ are the shape function and the of the temperature cell node respectively and m is the number of cell nodes.

## 4. Thermo-mechanical coupling analysis to the piston

### *4.1. Mechanical load analysis to the piston*

Select the maximum explosion pressure conditions as the calculation condition, Select the load of the gas pressure inside the cylinder is pressure, make the top of piston to receive the high pressure.

From Figure 2, the stress concentration parts of the piston are distributed within the piston pin boss and the point where the pin boss contacts the inner cylinder, with the maximum stress in the forward direction is 18.9MPa. The stress concentration occurs because displacement constraint is applied to this part, thus the stress is changed sharply and in the meantime, no rounded corner treatment is carried out during the import procedure of the model; in the actual condition, the stress within the piston structure will be smaller, thus the piston is safe.

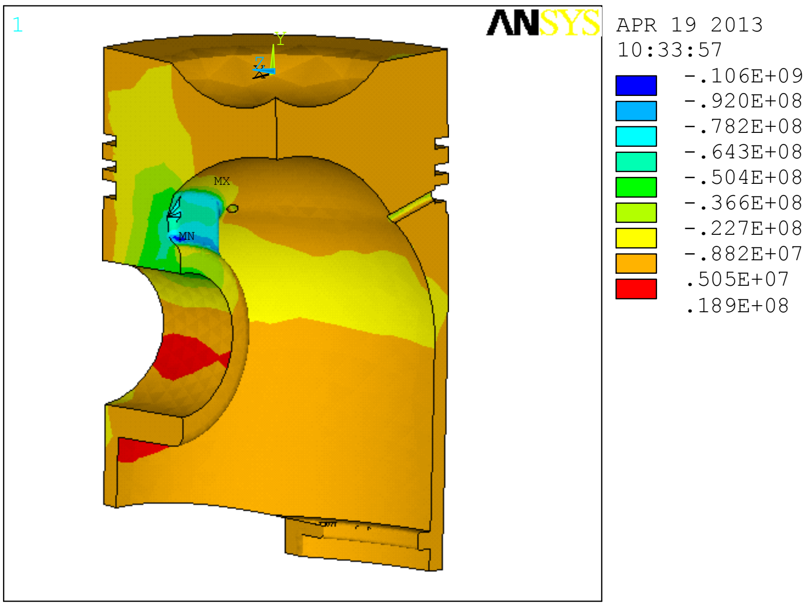


**Figure 2.** Mechanical stress nephogram.

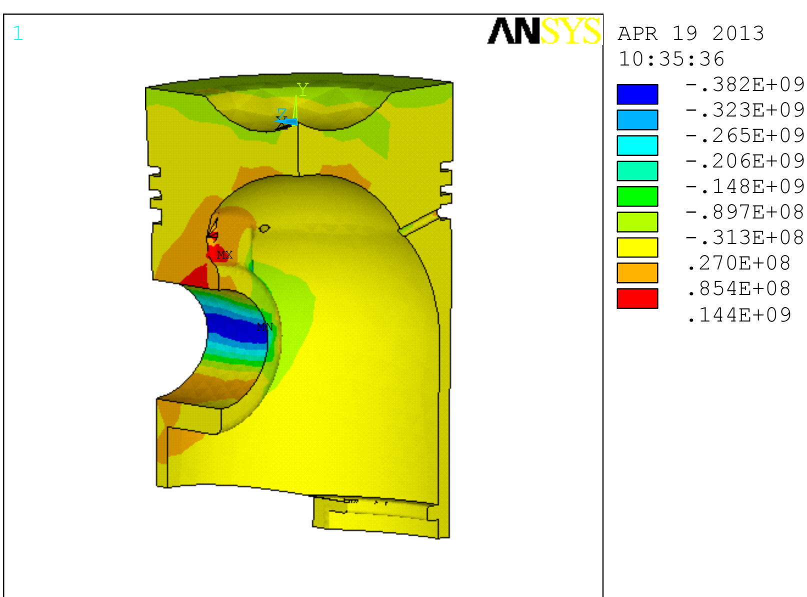


**Figure 3.** Thermo-mechanical coupling stress nephogram.

*4.2. Coupling Analysis to the Piston*

Piston bear the coupling effect of the high-temperature gas and mechanical pressure, in the same plane of symmetry constraints, and is constrained at the bottom of link. Piston brings about the coupled stress. Although the thermal load and mechanical load are two kinds of different loads acting on the piston, they will both affect the reliability and endurance of the operation of the piston. Deformation occurs to the piston under the effect of the thermal load and the piston deformation will affect the transfer of heat, the thermal stress and the mechanical stress, so it is necessary to integrate the dual function of the thermal stress and the mechanical stress of the piston to carry out coupling analysis and solve so as to better reflect the stress field distribution and deformation condition of the piston in the operation condition.

From figure 3, we can get the thermo-mechanical coupling condition of the piston and that the stress concentration occurs at the piston pin boss and the ribbed plate, with the maximum value in the forward direction of 144MPa, which is 250MPa smaller than the allowable stress of the piston, so the piston is safe. But with the combined effect of the thermal load and mechanical load, the thermal load plays the main role.

## 5. Conclusion

By thermo-mechanical coupling analysis, we can get the stress distribution and the deformation condition for each part of the piston. The maximum thermal stress of the piston is 250MPa and the maximum mechanical stress is 18.9MPa. The maximum deformation under the effect of the thermal stress is 0.402mm. With the thermo-mechanical coupling analysis, we can get that the maximum of the stress to the piston is 144MPa, the stress value within the allowable range, so the piston is safe. The maximum stress value appears in the vicinity of the pin boss, so in this region must have the right Chamfer, to prevent stress concentration. Thermal stress dominates in this piston, temperature is the main reason for thermal stress is generated in the piston, so to try to reduce the temperature, the stress below the tensile strength of the piston, so the piston safety.

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