Thermo-transient and thermo-mechanical finite element modeling of a diesel four-stroke engine piston for variable engine speed conditions

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Abstract

Diesel pistons work with very high temperatures, especially in the region of the bowl rim. Nowadays, with the use of the high speed diesel engines the resulting temperatures are even higher. For these components the thermal loading is extremely important. In general, steady state thermal analyses are used to obtain the temperature distribution of the piston for each engine speed condition and these results are used as boundary conditions for the thermo-mechanical analysis. A substantial amount of experimental observations in engine tests show that important phenomena occur during the transitions of engine speed which may cause considerable damage accumulation. Of course, such phenomena can not be captured by models that consider only steady state boundary conditions. In this work we report the thermo-mechanical modeling of a high speed diesel aluminum alloy piston developing a methodology to model the thermo-transient conditions which allows to obtain the induced stresses that occur when the engine speed changes.

Keywords: Modeling; Diesel piston; ADINA; Thermo-transient analysis; Variable engine speed conditions; Thermo-mechanical analysis; Thermo-elastic constitutive model; Thermo-elasto-plastic constitutive model

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1. Introduction

Nowadays finite element modeling of pistons is routinely used in industry. The procedures used have already attained a considerable degree of sophistication since the models already take into account some of the complexity of the physical problem. The evolution of computer hardware and software makes it possible to solve models that consider the load history and use very refined finite element meshes. The objective of this work is to present the modeling of the thermo-transient analysis of a high speed aluminum alloy piston considering the thermal load history from room temperature to low idle engine condition (900 rpm) and then to rated power engine condition (3500 rpm). The analysis includes the periods required to obtain a stabilized temperature distribution in low idle and in the rated power conditions.

As modeling enhancements, the piston's material was described as an isotropic conduction material whose conduction properties are temperature dependent, and with constant specific heat. The thermal loads are applied as convection loads using convection surface elements of constant heat transfer film coefficient and convection nodal temperatures.

The study of the temperature evolution in different piston regions was performed to evaluate the time necessary to get the stabilized condition. In particular, the most important regions to obtain the history of temperatures are the bowl rim and bowl bottom regions because the first presents the highest temperature levels of the piston and the second presents structural damage that is not explained using the traditional steady-state thermal analyses.

2. Modeling of the thermo-transient conditions

The thermal boundary conditions on the piston's

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surfaces are very complex because there are several different mechanisms of heat transfer involved and the most important heat source is the gas at high temperatures that results from the diesel combustion cycle. Some simplifications are introduced to model the piston thermal behavior. In fact, although a combustion cycle simulation allows the variation of the convection coefficient and the gas temperature during the cycle to be obtained, average values were used since there are too many cycles in the transient time period of the analysis. Therefore the thermal boundary conditions are assumed to be constant during each engine condition. In the model, the piston initially at room temperature was submitted to the low idle thermal conditions until the stabilization of the temperature distribution, and then the thermal loading is changed to the rated power condition. In Fig. 1 we show the load function of the effective gas temperature during the analysis. A similar curve was used for the effective heat coefficient.

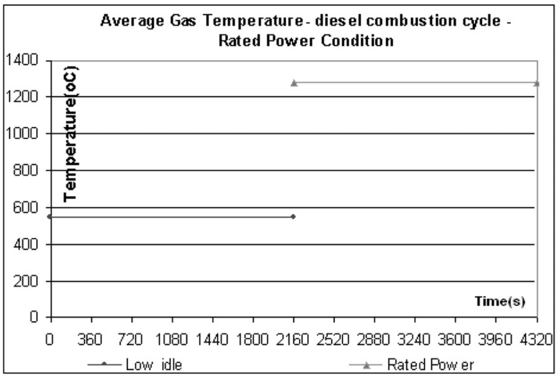

Fig. 1. Load function of the effective gas temperature during the analysis.

In Fig. 2 the finite element model used in the analysis is shown. Model I uses 10-node tetrahedral conduction elements with quadratic convection surfaces elements [1]. The constitutive law used to represent the piston's aluminum alloy is the isotropic variable conduction temperature constitutive model. The thermal load was applied using surface convection elements on all the surfaces of the piston. The constitutive model of these convection elements are characterized by a value of heat transfer film coefficient that is variable according to the load condition and convection nodal temperatures at the exterior piston nodes. In Fig. 2, the greyscale is associated to different values of heat transfer film coefficient. The finite element solutions were obtained with ADINA [2].

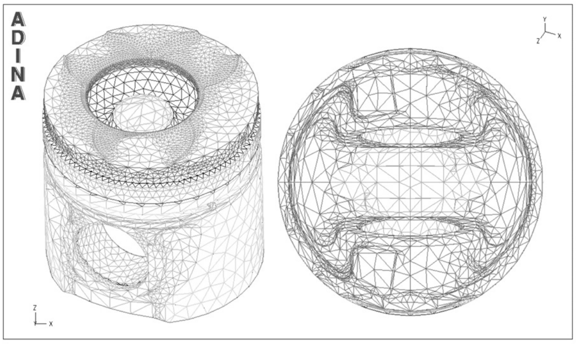

Fig. 2. Thermal finite element model of the piston – conduction and surface convection elements (Model I).

At the beginning of the analysis, we assume a uniform temperature of 20 °C for the piston. When the analysis starts the thermal load of low idle condition is applied for 2160 seconds, and then the boundary conditions of the rated power are imposed.

3. Numerical results

Some points located at important regions of the pistons have been chosen to monitor the evolution of temperatures during the transient analysis. Figure 3 shows the location of these points and in Fig. 4 the temperature history during the analysis. The temperature results show that the stabilization is reached after 120 s of the beginning of each new thermal load boundary condition. The predicted time for temperature stabilization agrees well with experimental observations.

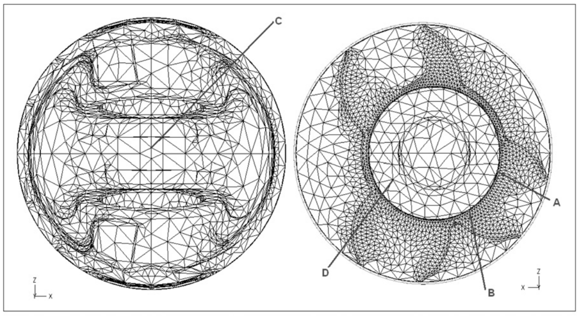

Fig. 3. Location of points A, B, C and D (Model II).

The most important motivation for modeling the thermo-transient conditions is to obtain the stresses that are induced by strong temperature gradients developed due to the change of the engine speed. In this analysis the temperature nodal history from the thermo-transient

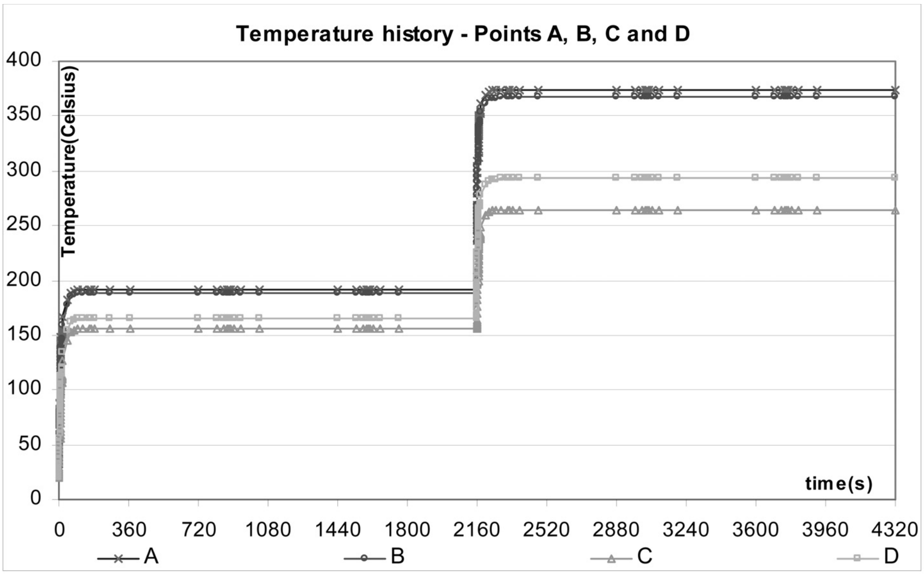

Fig. 4. Temperature history of points A, B, C and D (Model I).

analysis was applied as a boundary condition to Model I.

Both thermo-elastic and a thermo-elasto-plastic analyses were undertaken. A thermo-elasto-plastic multilinear kinematic hardening model was adopted. The constitutive model parameters were obtained from experimental low fatigue cycle tests, using a methodology described in [3]. The analyses time periods were considered to be the same as for the thermo-transient analyses described in Section 2.

In Fig. 5 we present the elastic and elasto-plastic effective stress history for point A. The results show that, just after the change of the engine speed, severe stress peaks occur at the bowl rim nodes, since point A is a sample point for this region.

Also we note that the consideration of the plastic behavior of the material substantially diminishes the

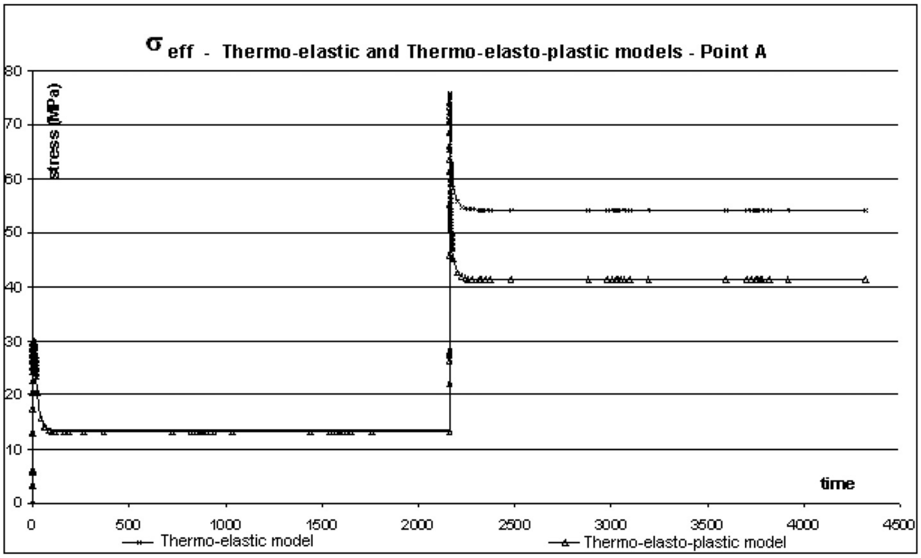

Fig. 5. Effective stress history of point A (Model I).

stress peaks and stress stabilized values when compared with the elastic results.

4. Concluding remarks

The methodology for modeling the thermo-transient condition of a piston submitted to different engine speeds showed good results. The instantaneous change of the mean temperature and mean heat transfer coefficient is a simple and effective way of representing the change of thermal load that occurs when the engine condition changes. The time periods required for the stabilization of the temperature agree well with the experimental observations.

A most important result was obtained through the thermo-mechanical analyses. The modeling of the thermo-transient condition between low idle and rated power condition leads to induced stress peaks just after the change of the engine speed. Note that the traditional methodology of considering the steady state conditions for each engine speed would not capture such a peak and would lead to significantly lower stress difference predictions.

Acknowledgment

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References

[1] Bathe KJ. Finite Element Procedures, Englewood Cliffs, NJ: Prentice Hall, 1996.

[2] ADINA R&D, Inc. Automatic Dynamic Incremental Nonlinear Analysis. ADINA System, 2004.

[3] Bueno EMR, Bucalem ML, Furukawa C, Zabeu CB, LOPEZ LMV. Thermo-elasto-plastic finite element modeling of an Otto four stroke engine piston for consecutive load cycles. In: Proc of the 2nd MIT Conference on Computational and Solid Mechanics, Cambridge, MA, 17–20 June, 2003, pp. 149–153.