Computational and Experimental Method for Assessing the Thermal Strength of High-Loaded Diesel Engines

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Abstract: The article discusses the reasons of fatigue failure of pistons of high-loaded diesel engines. A deformation-kinetic criterion is proposed, generalized to non-isothermal loading, which allows more correct calculation of the number of thermal loading cycles before the appearance of fatigue damage. For a specific implementation of the proposed criterion, a calculated assessment of the piston stress-strain rate was carried out using the FEM. The boundary conditions for the calculation were obtained by thermometry of the piston head on a non-motorized thermal stand (TS). Comparison of the calculated and experimental values of the number of thermal cycles before the appearance of cracks on the edge of the combustion chamber (CC) of pistons made by casting and isothermal stamping is given.

1. Introduction
One of the reasons leading to the premature replacement of pistons in operation is the formation and development of cracks on the edges of their combustion chambers (CC) [1-3]. Analysis of currently published theoretical [4-6] and experimental [7-9] studies gives reason to believe that the appearance of fatigue damage on the edges of the combustion chamber is a consequence of a high level of stress-strain state of the piston caused by the combined effect of non-stationary thermal and mechanical loads.

2. The purpose of the study
The main goal of this study is to develop a method for the computational and experimental evaluation of the thermal cyclic resistance of the edges of the combustion chamber of pistons of high-loaded diesel engines under sharply changing operating modes.

Damage $d_n$ in transient (sharply changing) modes occurs under conditions of developed cyclic plastic deformations on the edge of the combustion chamber. Therefore, for assessing damage from low-cycle fatigue, the most universal can be considered the deformation-kinetic criterion, developed by a team of authors from the Institute of Mechanical Engineering. A.A. Blagonravova [10]. This criterion is based on the linear summation of fatigue $d_f$ and quasi-static $d_s$ damages, which in our case can be determined from the following expression

$$d_n = d_f + d_s$$

It is believed that destruction occurs if the total damage reaches the limit value.
The number of cycles to failure, depending on the range of plastic deformation, is determined by the well-known Coffin low-cycle fatigue equation [10]:

\[
N_s = \frac{\varepsilon_p(T)}{2 \cdot \Delta e^p}
\]  

(2)

where:
\( \varepsilon_p(T) \) - the ultimate plasticity of the material (elongation at break);
\( \Delta e^p = \varepsilon_p^{n-1} - \varepsilon_p^0 \) - the width of the elastic-plastic hysteresis loop.

Quasi-static damage can be defined by the expression:

\[
d_s = \frac{\Delta e^p \cdot N}{\varepsilon_p(T)}
\]  

(3)

where:
\( \Delta e^p = |\varepsilon_p^{n-1} - \varepsilon_p^0| \) - one-sided displacement of the elastic-plastic hysteresis loop in one cycle.

Then the number of cycles before destruction will have the form:

\[
N = \left[ \left( \frac{2\Delta e^p}{\varepsilon_p(T)} \right)^2 + \frac{\Delta e^p}{\varepsilon_p(T)} \right]^{-1}
\]  

(4)

A preliminary calculation according to this criterion at the minimum and maximum values of the ultimate plasticity of the material showed that the number of cycles before destruction was 400 and 4900, respectively. This difference is due to the non-isothermal nature of the process and a significant dependence on temperature.

3. Research methods and tools

To carry out a correct calculation, a criterion generalized to non-isothermal loading is proposed below. In this case, fatigue damage is determined by the following equation

\[
d_f = n_n \left\{ \frac{\Delta e^{p}}{0} 2 \frac{\Delta e^{p}}{0} \frac{d(\Delta e^{p})}{\varepsilon_p(T_{n-1})^2} + \frac{\Delta e^{p}}{0} \frac{d(\Delta e^{p})}{\varepsilon_p(T_{n})^2} \right\}
\]  

(5)

where:
\( n_n \) - the number of transition modes (transitions from idle to rated load and back);
\( T_{n-1}, T_n \) - temperatures on \((n-1)^{M}\) and \(n^{-M}\) half cycles. Quasi-static damage under non-isothermal loading is determined by the dependence

\[
d_s = n_n \left\{ \frac{\Delta e^{p}}{0} \frac{d(\Delta e^{p})}{\varepsilon_p(T_{n})} \right\}
\]  

(6)

Thus, to assess the damage to the material of the CC edge from the influence of transient modes, it is necessary to have the following data: \( \Delta e^{p}_{n-1}; \Delta e^{p}_n, \Delta e^{p}, T_{n-1}, T_n \) - as a function of time (loading parameter), and also - as a function of temperature.

For an experimental assessment of the number of cycles to failure (the appearance of a macrocrack) under the conditions of thermocyclic tests of pistons on a non-motorized thermal stand (TS) [11], a thermal loading cycle was developed. This cycle, by the nature of the temperature distribution in the piston head, was as close as possible to their real distribution in the diesel piston with a sharp drop and load surge. The duration of the thermal loading cycle on the TS was 72 s (36 s - heating, 36 s - cool-
ing). The maximum radial temperature difference along the bottom of the piston head from the edge of the combustion chamber to the periphery was \( \Delta T = 65^\circ C \).

In order to obtain the initial data for the specific implementation of the proposed criterion, at the second stage of the research by the finite element method (FEM), a computational assessment of the stress-strain state of the piston head with a combustion chamber of the "CNIDI" type of the D-245 tractor diesel engine was carried out [7, 15, 17-21].

The temperature values at points on the surface of the piston head during its thermometry on the TS according to a given thermal loading cycle were used as boundary conditions (Fig. 1).

![Diagram showing temperature change at characteristic points of the piston head within one thermal loading cycle lasting 72 s.](image)

**Figure 1.** Temperature change at characteristic points of the piston head within one thermal loading cycle lasting 72 s.

The calculation was carried out according to the following algorithm. The entire thermal cycling process was divided into time layers with a constant interval \( \Delta t = 6c \).

For the current time layer \( t_i \), the problem of thermal conductivity and thermoplasticity was solved taking into account the dependences of the thermophysical and mechanical characteristics of the material on temperature [12, 13].

4. **Computational analysis of the piston stress-strain rate**

The first stage of the research was to calculate the temperature fields in the piston head.

At the second stage of the research, the calculation of the stress-strain state of the piston head was carried out, the main tasks of which were:

- determination of the general nature of the stress-strain state of the piston head, and in particular, the edge of the combustion chamber;
- study of the kinetics of stress-strain state under thermal cyclic loading;
- analysis of the non-isothermal process of changing plastic deformations in order to predict the thermal fatigue strength of the head [16].

According to the results of the performed calculation, it was found that the defining stresses in the zone of the edge of the combustion chamber are ring stresses. The maximum value of stresses reaches 52.3 MPa, while the radial, axial and shear stresses, respectively, are 2.0, 1.1, and 0.8 MPa. Consequently, practically simple (radiation) loading is realized on the edge of the combustion chamber, which corresponds to the conditions of applicability of the proposed criterion.

In fig. 2 shows the kinetics of the elastoplastic stress-strain state of the combustion chamber edge in coordinates \((\sigma_y - \varepsilon)\).
As follows from the shown dependence in Fig. 2, the stabilization of the elastoplastic hysteresis loop occurs practically from the second loading cycle. The maximum compressive ring deformations, equal to 0.115%, are achieved at the end of the heating half-cycle at the maximum temperature. Subsequent cooling leads to a decrease in the level of compressive deformations, which turn into tensile deformations at the end of the cooling cycle, reaching their maximum value of 0.005% at the minimum cycle temperature. The range of "force" deformation is 0.124%, and the range of plastic deformation, as follows from the calculation, is 0.056%. Therefore, the calculation method, which used a model of the elasticplastic behavior of the material, allowed us to estimate the stress-strain state of the combustion chamber edge and identify the amount of plastic deformation in its zone.

The performed calculation of the stress-strain state of the piston head under cyclic exposure to temperature loads, similar to the transient operation of a diesel engine, provides the necessary information for determining the number of cycles to failure using the developed criterion. This number was estimated for both cast and stamped pistons of the D-245 diesel engine. Ultimate plastic deformation of the material [10, 12, 14] in both cases depends on temperature (Fig. 3a, 3b) and increases significantly starting from 270-300 °C.

Figure 3. Change in the increment of plastic deformation, temperature and ultimate plasticity: a) on the half-cycle "heating"; b) on the half-cycle "cooling".
The change in the zone of the combustion chamber edge of the increments of plastic deformation, temperature, limiting plasticity of cast and stamped pistons for \((n-1)\) a half-cycle (cooling) and \((n)\) a half-cycle (heating) is shown.

Using the curves shown in Fig. 3a and 3b, the values of the integrand were obtained (Figs. 4a and 4b), which is included in the equation for assessing damage and characterizing the rate of damage change on the corresponding half-cycles.

![Figure 4](image)

Figure 4. Dependence of the rate of damage accumulation for cast and stamped pistons on the increment of plastic deformation: a) on the half-cycle "heating"; b) on the half-cycle "cooling".

The area under these curves is the damage values on \((n-1)\) and \((n)\) half cycles. Damage on half-cycles of cooling and heating, obtained from the maximum and minimum values of the ultimate plastic deformation at the corresponding temperature, for the material of the cast piston varies from \(2.8 \times 10^{-4}\) to \(5.7 \times 10^{-4}\), and for the stamped piston \(-4.4 \times 10^{-5}\) to \(11.75 \times 10^{-5}\).

The corresponding values of the number of cycles before destruction vary from 1750 to 3550 and from 8500 to 20750. Since for our case the limiting plastic deformation of the material of the cast and stamped pistons corresponded to the spreading minimum value (Fig. 3a and 3b), then, consequently, the number of cycles before destruction will be: 1750 for a cast piston, and 8500 for a stamped piston.

5. Conclusion
The given comparison of the calculated and experimental (on a non-motorized thermal stand) values of the number of thermal cycles before the destruction of the combustion chamber edge showed their satisfactory correspondence: 1. for cast: calculation - 1750; experiment - 1400 ... 2000; 2. for stamped: calculation - 8500; experiment – 5850 ... 6400.

Thus, the proposed deformation-kinetic criterion, generalized to non-isothermal loading, allows, in combination with the calculation by the finite element method of the stress-strain state of the piston in the elastoplastic formulation, to evaluate the thermal stability of the combustion chamber edge under non-stationary thermal loading modes.

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