Causes of cracks on the edges of the combustion chamber of the diesel engine piston

A N Gots and V S Klevtsov*

Vladimir State University named after Alexander Grigorjevich and Nikolay Grigorjevich Stoletovs (VlSU), Department of mechanical engineering and automobile transport, 600000 Vladimir Gorky Street 87, Russian Federation

*Ehanic2221@rambler.ru

Abstract. Internal combustion engines operate in non-stationary operating modes, when the crankshaft rotational speed changes over wide ranges, not only the torque but also the angular speed changes. While transients occurring in the cylinder of an internal combustion engine during operating modes, especially for tractor diesels, are the most unfavorable for parts of the cylinder-piston group. Long cycle changes during which pressure, temperature, piston speed and heat transfer surface are constantly changing creates very difficult loading conditions. Moreover, the peak values of thermal powers through the heat exchange surfaces of the piston bottom in unsteady modes are 2 ... 2.5 times higher than the values at steady modes. High values of thermal and mechanical loads on the piston lead to cracks on the edge of the combustion chamber and premature destruction. Failure in pistons can be caused by mechanical and thermal loading, but thermal loads make the greatest contribution to the value of equivalent stresses. Therefore, cracks gradually develop, which often leads to a deterioration of the working process, and then to the destruction of the piston.

1. Introduction
The current stage of development of internal combustion piston engines (ICPE) is characterized by high growth rates of their specific indicators, for example, liter and piston capacity, while ensuring economic and environmental indicators, which leads to a significant increase in the thermal and mechanical loading of parts that form the combustion chamber (CS) such as the piston, sleeve, cylinder head. Note that the increase in the economic parameters of engines with compression ignition (diesels) contributed to a significant boost in their performance indicators and the speed of rotation of the crankshaft. Analysis of statistical data on the production of foreign-made piston engines for various purposes shows that the capacity of new modifications produced increases by an average of 60 ... 80 % for every 10 years [1]. Heat-stressed engine parts, especially the piston and cylinder head, usually have a complex geometric shape, and their individual elements, such as the piston, are in thermal, power and kinematic interaction with other parts. Therefore, when designing, calculating and fine-tuning the engine to the specified parameters in the technical specification, a more complete and accurate account of all the values that determine reliability and resource is required.

The development of methods for assessing the durability of internal combustion engine pistons (ICEP) involves the study of conditions for loading engine parts and finding out the reasons for their failures in operation. As you know, tractor diesels are operated most of the time in non-stable modes,
the reason for which is a change in the position of the control body and the moment of resistance when the machine-tractor unit performs agricultural, skidding and other types of work. Fluctuations in the load on the shaft of the tractor engine is caused by various factors: the area of operation of the units and its type of work, the properties of the unit and its power plant, production technology, season, climatic conditions and soil, safety requirements and the environment in general, subjective factors of the operator, etc. Since the engines are operated under unsteady operating conditions and in a wide range of crankshaft speed shaft, then the angular velocity and moment on the motor shaft all the time change in time [2-4]. Transients occurring in the cylinder of a diesel engine during operational modes of operation, in particular tractor diesel engines, are the most unfavorable loads for parts of the cylinder-piston group (CPG). In unsteady conditions, the stress-strain state of the piston changes over time, which leads to the appearance of fatigue cracks on the edge of its combustion chamber. First of all, this refers to a semi-open type CC. The appearance of a crack and its growth to a critical length often leads to the destruction of the CC edge. This circumstance makes it necessary to clarify existing methods for calculating the residual life, as well as to develop new ones, taking into account the possibility of predicting the durability in the presence of cracks [7-9].

Long cycle changes during which pressure, temperature, piston speed and heat transfer surface are constantly changing creates very difficult loading conditions. For example, experimental studies carried out at the Department of ICE of the Leningrad Polytechnic Institute (LPI) in the 80-ies of the engine YAMZ-238, showed that the maximum value of the heat flux through the surface of the piston, which perceive the heat under transient conditions is 2.5 times higher than the value of their steady state. The temperature gradients and stresses were changed similar to the changes of heat flux [10].

2. Purpose of research
The purpose of the article is to review the research on the regularity of changes in the rate of development of fatigue cracks depending on operational and structural factors.

3. Analysis of causes of piston failure
We will analyze the causes of piston failure during engine operation based on our own research, as well as materials published in the literature. When forcing a diesel engine, for example, due to turbocharging, the power and torque increase, and, therefore, the thermal and mechanical loads acting on the piston, which leads to its premature destruction. Thus, after increasing the power by 30% of YAMZ-240 diesels, failures were recorded in operation due to the appearance of cracks on the edge of the combustion chamber with a length from 5 to 18 mm [3]. The combustion chamber of diesels is located in the piston head and when changing the operating modes of the diesel engine, the temperature gradient in the sections of the piston changes, which leads to an increase in temperature stresses. According to our calculations, the results of which are consistent with other data [10-12], the distribution of temperatures and stresses in the 4chn11/12.5 (D-240) diesel piston in the nominal mode (figure 1) differ in large differences, especially at the edge of the CC.
Figure 1. The temperature distribution (t°C) (a) and stresses (MPa) (b) the piston of a diesel engine 4CHN 11/12.5 in the rated power mode.

Thus, the temperature difference with a large gradient leads to the appearance of cracks, especially in thin-walled sections, for example, on the edge of the CS (region B, see figure 1-b). Cyclic thermal loading of the piston leads to the growth of the crack and its destruction. Almost always, failures caused by the destruction of the piston in diesels with an open combustion chamber in the bottom were caused by the appearance of cracks on the edge of the CS. The nature of crack development is shown in figure 2 [5, 6].

Figure 2. The location of the cracks in the edge of the combustion chamber of the piston of a tractor diesel.

Thus, when testing the MD-5 engine after running for 840 hours, the pistons were destroyed precisely because of cracks. Since the piston is loaded not only by thermal loads, but also by gas pressure, it is shown in figure 1, b that a crack may appear in the region A (see figure 2, b).

Let's analyze the main causes of cracks on the edges of the combustion chamber:

- cyclic pressure change in the CS volume caused not only by the working process, but also by changes in the diesel operating modes;
- temperature fluctuation in the piston when changing operating modes, which are attributed to low-frequency fluctuations;
- temperature fluctuations in the piston cross sections during each operating cycle, which are attributed to high-frequency fluctuations.

Note that the temperature stress is several times higher than the stress from gas pressure and inertial loads [5, 6, 7]. In this case, the maximum pressure and maximum temperature appear at different angles of rotation of the crankshaft (about 5...20° degree of turn of crankshaft (CD)). This is due to the
different nature of the flow of the dependence of the heat release characteristic, which is shown in figure 3.

During the working cycle, the pressure in the CC increases when the piston approaches the dead point and the combustion of the working mixture. The maximum value of the pressure reaches after the passage of the piston through the dead point and only after that there is an extreme temperature in the CS. We have calculated the stresses from the action of temperature and the action of gases in the piston of a d-240 diesel engine with a half-open combustion chamber when operating at the nominal mode. The results of calculations are shown in figure 4 and 5, from which it follows that the stress intensity at the edges of the CC is 2.3...2.5.

A similar result was obtained when calculating the TNDS of the piston of a high-powered diesel 21/21, conducted at the Department of internal combustion engines of the Leningrad Polytechnic Institute [2]: temperature stresses exceed the stresses from gas forces by 2..2.5 times. The same results were obtained in the studies of N. D. Chaynov, N. A. Ivashchenko, A.V. Timokhin, A. B Ivanchenko, E. A. Lazarev [8-10], which showed that the CS edge is a constructive stress concentrator. Therefore cyclic loading at changing temperatures can lead to elastic plastic deformations [11-15].
Note that a change in temperature affects the mechanical properties of the aluminum alloy from which the piston is made. According to [16] when heating samples from aluminum alloys to 350° C, the yield strength is reduced by almost 7 times, and the modulus of elasticity is 1.8...2 times.

The main temperature load comes from low-frequency temperature fluctuations, with which temperature differences can occur over 150° C [6-8]. as for high-frequency temperature fluctuations in the diesel cycle, they affect the local heating of the CC edge [14-17].

Based on numerous studies [18-21], it was proved that at high-frequency temperature fluctuations, its amplitude reaches only 5 ... 20 °C at a depth of no more than 0...1 mm from the surface. Therefore, the assessment of its impact on TNDS is quite difficult due to the difficulties with measuring the temperature with high-speed sensors. It is believed that not taking into account the influence of high-frequency temperature fluctuations can lead to an error of no more than 10-12% in the final results [15].

It is known that the engine operates in transient modes, the duration is from 5 to 15 seconds [5]. In this case, the temperature of the piston is stabilized within 3...4 minutes after entering a certain mode.

Note that when cracks from variable thermal loads appear on the surfaces of the pistons, they may stop developing due to an increase in the cross-sectional area at the edge (for example, for a d-240 diesel piston). However, most often, together with cyclic heat transfers, even a small mechanical load leads to the deepening of cracks up to through destruction. In other words, after the appearance of cracks from temperature stress, stress from the action of gases completes the destruction process.

The development of cracks from temperature stresses can start not only from the surface, but also inside the piston section in the presence of any structural imperfections (for example, in the manufacture of the piston) [20, 21].

Thus, it can be noted that it is the operation of the diesel engine in non-stationary modes that leads to the appearance of cracks on the edges of the CC. This is due to the fact that when the diesel engine is switched from one mode to another (for example, from idle to nominal), the gas temperature and thermal processes in the CC volume change. Due to uneven heating of the piston, temperature stresses occur with a large difference. As mentioned above, when the piston is operating in this mode, the temperature field of the piston is equalized. However, when switching from nominal mode to idle mode, other processes and stresses occur. At the same time, taking into account the cross sections of the CC edge, it can be noted that plastic deformations may occur just in these cross sections. At the same time, their accumulation occurs over time.

As the material in the surface layers are expanding more intensively than the material thickness of the piston, the edge of the combustion chamber is experiencing compressive stresses. In the further operation of the engine the magnitude of these stresses decreases as temperature field of the piston is aligned. During the transition from nominal mode to idle mode, in the edge of the combustion chamber, the reverse processes take place. Stresses arise in the edge of the combustion chamber with a sharp change of load generally exceed the yield strength of the material of the piston.

The reasons for the formation of cracks on the edge of the CC piston can be the result of deterioration of the working process due to changes in the design parameters of the diesel engine. For example, when the rings wear out, there is an increase in the gaps in the CPG, which inevitably worsens the heat transfer to the cooling system. This can significantly increase the temperature of the piston and the likelihood of cracks on the edge of the CC. Thus, when CHN26/26 diesel engine [14] is running in the nominal mode, even a slight increase in the gaps in the CPG for the uncooled piston led to an increase in the temperature of the piston from 232° to 250° C, and above the compression ring from 185° to 225° C (figure 6). Similarly, when the fuel advance angle changes, which determines the nature of heat release during fuel combustion, the temperature of the piston changes [14]
4. The results of the study and their discussion

All failures that occur during engine operation due to piston failure can be divided into the following groups [14]:

- failures caused by imperfect design, when the design did not take into account the possibility of failure due to local stress concentrators;
- failures due to poor technological process: appearance of shrinkage shells, porosity of the structure, crack, etc. [14, 19];
- failures in operation, for example, the operation of a diesel engine with incorrect adjustment of the fuel equipment, irrational choice of the injection advance angle, etc.

Operational failures can be caused by quite a large list of factors [15]. All this will definitely affect the reliability of the piston.

So, for example, failure of the temperature control system of tractor diesel air-cooled 8DWT-330 led to the melting of the piston head and scuffing the side of the surface through 550 hours [14, 15]. Note that the service life of the piston depends on number and length of cracks. In table 1 shows for comparison the average service life time of parts of the cylinder group [15]

| Detail of the cylinder group | \( T_{av} \cdot 10^{-3} \) h (average value in hours) |
|-----------------------------|---------------------------------|
| Piston                      | 0.8...4.0                       |
| Piston rings                | 0.5...2.0                       |
| Piston pin                  | 1.0...5.0                       |

Having analyzed the main reasons for the appearance of cracks and their destruction, we will consider methods for increasing the temperature resistance of pistons, which will affect their durability. A review of a number of measures aimed at reducing the thermal state of the piston and extending the service life of the pistons showed that the temperature of the piston head can be reduced by using the so-called thermal protection.

The term "thermal protection" should be understood as a set of actions that reduce the temperature on the surface of the piston in any mode of operation of the diesel engine. Research work on the so-called "adiabatic engine", which was widely carried out in the 80 years, showed that the working process is significantly affected by the thermal insulation of the COP [15]. Note also that the piston made of aluminum alloy can work without failure at a temperature not higher than 300 ... 375 °C [15, 17]. If the temperatures exceed these values, then there may be a melting of the CC edge, burning of the piston bottom, and rings deposition. Therefore, most often use a whole set of design and other measures that together increase the temperature resistance of the pistons. These include:
• reducing the stress concentration coefficient by increasing the radius of rounding the edge of the CC;
• use for thin sections of the edge: reinforcement with heat-resistant materials (for example, ceramics);
• construction of the piston head from other heat-resistant materials, i.e. development of composite pistons;
• applying protective coatings to the piston, which reduces the heat input; – using gallery jet cooling with oil.

The last mentioned method of reducing the temperature of the piston is widely used. According to the research that we conducted in NICTID [14], the shape and orientation of the cooling cavity in the piston should be such that it is possible to ensure a uniform flow of heat into the cooling cavity.

It is cooling piston by Oil gallery with the correct design of the cooling cavity can reduce the temperature of the edge of the combustion chamber to 25°C, in the area of the upper compression ring - up to 30°C, the bottom of the CS-by 27°C. The disadvantages of such cooling include the following. In the absence of oil in the cooling cavity, the temperature in the CS increases, which also increases the temperature stress. In addition, increased temperatures lead to aging of the engine oil, which will require replacing it more often.

The most promising is the use of heat-protective coatings, which are applied to the bottom of the piston using laser coatings, gas-plasma and electric arc methods [15]. Materials that are applied to the piston must have good heat resistance, as well as the ability to adhere to the material of the piston. In this regard, laser coating provides a good connection between the base material and the surfacing. The surfacing must withstand mechanical loads and a sharp temperature drop.

The efficiency of heat-conducting coatings was studied at the Department of internal combustion engines of LPI using CNIDI technology and the UMP4-64 plasma unit. Even with a coating thickness of only 0.5 mm, the temperature in the piston head was lowered by 10%.

The main problem with this method is the difficulty of ensuring strong adhesion of the thermal insulation material to the piston material. In addition, at elevated temperatures in the CS, nitrogen oxide emissions increase, which worsens the environmental performance of diesel [18].

5. Conclusions

Analysis of the causes of cracks in edge of the combustion chamber piston tractor diesel shows that in the assessment of the durability of the piston it is necessary to consider a range of indicators and parameters of the motor: the level crossing at the liter or the power piston; piston design and single-action combustion therein, the working conditions of the power plant, which installed a diesel; cooling is available (inkjet or gallery); change the properties of the aluminum alloy, which made the piston etc.

Analysis of the causes of cracks in edge of CC piston of a tractor diesel shows that in the assessment of the durability of the piston it is necessary to consider a range of indicators and parameters of the motor: the level increase power at the liter volume engine or area the piston; piston design and combustion chamber therein, the working conditions of the power plant, which installed a diesel; cooling is available (inkjet or gallery); change the properties of the aluminum alloy, which made the piston etc.

The strength properties of aluminum alloys for internal combustion engine pistons can be improved by cyclic temperature treatment [8, 9, 15]. This treatment is a quenching process in which high-temperature exposure is replaced by cyclic heating and cooling at a certain temperature range. In this way, you can achieve a significant increase in the number of cycles before cracks appear. Manufacturing technology largely determines the physical and mechanical properties of materials, so when selecting materials for pistons under the appropriate working conditions, it is necessary to take into account the manufacturing method.

References
[1] Bruk M A, Viksman A S and Levin G.Kh. 1981 Work of diesel is in non-stationary modes
(Leningrad: Engineering Publ.) p 208

[2] Ivanchenko A B 1995 *Methodology of estimation of tireless durability at the thermal loading of pistons of force diesels* (Moscow: Diss. for the degree of cand. of tech. sciences) p 174

[3] Kolmakov V I 1986 *Increase of reliability of diesels force a supercharge* (Moscow: Diss. for the degree of cand. of tech. sciences) p 244

[4] Ivanchenko A B and Glinkin S A 2005 Analysis of durability of piston of perspective diesel of type of CHN 10,5/12 *Materials of the International scientific and practical conference “Fundamental problems of perfection of piston engines”* ed V V Efros and A N Gots (Vladimir) pp 73-74

[5] Shalay A N 1996 How to promote longevity of a piston? *Engine Building* 2 51-52

[6] Dyachenko N Kh, Dashkov S N, Kostin A K and Burin M M 1969 *Heat exchange in engines and thermal tension of their details* (Kharkov: Engineering Publ.) p 248

[7] Lazarev E A, Ivashchenko N A and Perlov M L 1988 Features of the thermal and stress-deformed condition of tractor diesel engine pistons *Engine Building* 7 3-5

[8] Lazarev E A, Ivashchenko N A, Perlov M L and Bondarev A A 1989 Stress-deformed and thermal condition of tractor diesel engine cooled piston at the different location of cross-sectional of cooling cavity *Engine Building* 2 7-10

[9] Donchenko A S, Morganyuk V S, Averchenkov E A, Kharchenko V K and Isaev E V 1983 Calculation the stress-deformed condition of tractor diesel engine piston at a cyclic loading. *Problems of Strength* 3 39-44

[10] Shekhovtsov A F, Abramchuk F I and Pylev V A 1986 Creep and relaxation at tension of aluminium alloy of AL25 *Engine Building* 11 45-47

[11] Chaynov N D 1986 Model of calculation of the temperature field of axisymmetrical details of diesels engine cylinder and piston *University News. Engineering* 9 77-91

[12] Shekhovtsov A F 1978 *A mathematical design of heat transfer is in high-speed diesels* (Kharkov: Higher School Publ.) p 153

[13] Ivanchenko N N, Semenov B N and Sokolov V S 1972 *Working process of diesels engine with a chamber in a piston* (Leningrad: Engineering Publ.) p 232

[14] Gots A N, Fomin V K, Paponov S V and Balyuk B K 1988 Improved diesel engine piston reliability, air-cooled *Engine Building* 10 40-43

[15] Gots A N and Glinkin S A 2017 *Forecasting the durability of internal combustion engine pistons: a monograph* (Saarbrucken: LAPLAMBERT Academic Publ) p149

[16] Libovits G 1977 *Calculation of constructions on fragile durability* (Moscow: Engineering Publ.) vol 5 p 452

[17] Semenov B N and Ivanchenko N N 1990 Tasks of increase of fuel economy *Engine Building* 11 3-7

[18] Chaynov N D, Timokhin A V and Ivanchenko A B 1990 Evaluation of the fatigue life of the piston tractor diesel engine under cyclic loading *Engine Building* 11 14-15.

[19] Chaynov N D, Batanova O A and Cherneva G E 1989 Features of the calculation of the stress and strain in the piston internal combustion engine, made of fragile materials *University News. Engineering* 6 61-65

[20] Birger I A, Shorr B F and Iosilevich G B 1993 *Calculation of the strength of machine parts: Handbook* (Moscow, Engineering Publ.) p 640

[21] Kazantsev A G 2001 *Low-cycle fatigue under complex thermal and mechanical loading* (Moscow: Bauman Moscow state technical University) p 248