Service life predicting of the piston ring with laser-hardened cylinder liner

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Abstract. The article considers the issues associated with the evaluation of hardening treatments influence on the service life of the piston ring in the cylinder of a heavy-duty diesel engine. The statement about the high efficiency of laser hardening of cylinder liners made of cast iron is substantiated. Model experiments on a laboratory friction machine investigate the wear resistance of the friction surfaces of the coupling piston ring-cylinder liner. The effect of piston ring wear on the loss of elasticity and the service life of the coupling is analyzed. The calculation method determines the service life of the coupling and analyzes the efficiency factor of the laser hardening treatment. On the basis of the study, it was found that laser hardening of the friction surfaces of cast-iron cylinder liners has a positive effect on the coupling wear resistance, but increases the wear of the piston rings. To eliminate the increase in wear resistance of piston rings, it is proposed to make them from steel and apply laser treatment of a wear-resistant coating from a high-entropy alloy of the Fe-Cr-W-Mo-Co-Ni system, which can significantly increase the service life of the piston ring-cylinder liner coupling in heavy diesel engines.

1 Introduction

The cylinder-piston group of heavy-duty diesel engines is one of the largest consumers of energy and a source of air pollution. One of the ways to improve the efficiency of diesel engines is to optimize the operation of the cylinder-piston ring coupling, the improvement of which has been the subject of many scientific papers. The whole range of measures to improve the efficiency of diesel engines is experimental research, theoretical modeling of processes, the use of hardening technologies and the improvement of lubrication. Special test benches are created to study the friction of piston rings under the operating conditions of diesel engines. The work [1] is devoted to the study of friction losses between the piston ring and the cylinder liner. A new reciprocating long-stroke tribometer has been developed. The simulation allows detailed investigation of the local nominal gap height and pressure distribution. To study the efficiency factor of the piston-cylinder liner assembly, a test setup [2] was developed that allows simultaneous measurement of forces by three piezoelectric sensors, which greatly expands the measurement capabilities. Much attention is paid to the effect of lubrication on tribological properties using numerical experiments. Modeling the...
wear process of engine parts is considered as an alternative to expensive tests. The results of calculation and experiment were compared. In the process of simulation laboratory tests, the type of oil characteristics, surface roughness, and mechanical properties of coatings were controlled. Comparison of experimental and calculated results gave an error of less than 5%. In [3], the results of numerical simulation of power characteristics are compared with experimental measurements of ring deformation in a single-cylinder engine using a strain gauge. It has been established that in order to predict the calculated friction of the ring, it is necessary to take into account the surface roughness. The problem of the effect of wear on the elasticity of a ring embedded in a cylinder was considered in [4], where it was found that the ring wears unevenly. In [5], the uneven wear of the piston ring is studied. The mechanism of the influence of the deformation of the annular groove on the properties of the ring and the complex tribodynamic behavior of the system is considered. It is noted that tribodynamic models that take into account its complex movements are very limited. In [6], a new wear analysis model for the piston ring-cylinder coupling is proposed, based on the theory of energy dissipation. The wear characteristic formula establishes the relationship between the amount of wear and the band energy of an acoustic emission signal. A close correspondence between the calculation and simulation results is shown. A number of works are devoted to the analysis of the effect of temperature on tribological properties. The wear characteristic formula establishes the relationship between the wear rate and the band energy of an acoustic emission signal. A close correspondence between the calculation and simulation results is shown. A number of works are devoted to the analysis of the effect of temperature on tribological properties. It has been shown [7] that a large temperature gradient can lead to a local lack of lubrication, sudden lubricating film destruction and engine failure. The work [8] is devoted to the study of the role of cylinder liner temperature, which affects the thermal characteristics of the engine and the frictional properties of the piston-cylinder system. It is noted that the reduction of heat losses and friction losses becomes a priority. The main attention is paid to the sealing function of the upper piston ring, which is an important component of the protection of the emission of harmful gases.

To increase the wear resistance of the piston ring-cylinder liner coupling, coatings of the friction surfaces of the piston rings are used in engines. In [9], the tribological properties of the Ni-P-TiN coating were studied on a laboratory tribometer. Coated piston rings were found not to increase cylinder liner wear. In [10], the characteristics of diamond-like carbon coatings are compared with standard nitrided piston rings. It has been established that carbon coatings reduce friction losses by up to 31%, and also reduce the wear of the piston ring-cylinder liner coupling. A number of works note the positive role of surface texturing, in particular, by photochemical etching [11, 12]. The experiments were carried out on a test bench for testing friction and wear according to the disk-on-finger scheme. The influence of the load, sliding speed and geometric parameters of the texture is determined. The analysis of the performed studies indicates that the wear process of the piston ring-cylinder coupling proceeds under conditions of a change in the force load on the piston ring, due to surface wear and research in the field of changing the force load of the piston ring during diesel operation is not enough.

The aim of the work is to develop a method for estimating the service life of the piston ring-cylinder liner of a heavy-duty diesel engine, taking into account the wear of friction surfaces.

1.1 Materials

To analyze the efficiency factor of the use of hardening treatments for the cylinder liner-piston ring, the following options were selected: a liner made of gray pearlite cast iron AXHMM and a piston ring made of unhardened as delivered; laser
and non-hardened cast iron piston ring; a laser-hardened cylinder liner and a piston ring made of AISI1045 steel with laser treatment of a wear-resistant coating based on a high-entropy Fe-Cr-W-Mo-Co-Ni alloy [13].

1.2 Equipment and technologies

Tribological tests were performed on a test bench with reciprocating motion of samples, simulating the operation of the cylinder-piston ring coupling [14]. Test samples were cut from the cylinder liner of a heavy-duty diesel locomotive engine, the friction surface was phosphated. The coupled element was a piston compression ring segment. Hardened paths were applied with a 2 kW CW CO2 laser. Laser treatment refers to processing technologies with concentrated energy flows, i.e., local action, therefore, attention was paid to the geometry of laser impact traces.

2 Results

The technology for applying hardened paths included laser-treated paths with high hardness (Fig. 1): in the melting zone $H_{50} = 708 \text{ kgf/mm}^2$, martensite $H_{50} = 727 \text{ kgf/mm}^2$, base $H_{50} = 290-300 \text{ kgf/mm}^2$.

Fig.1. Microstructure of AHNMM gray pearlitic cast iron after laser hardening on the verge of melting before wear testing.

It has been experimentally established that, depending on the speed of laser processing, the microhardness of the reinforcing paths has an extremum (Fig. 2.).
The selected optimal mode of laser hardening provided a hardened layer thickness of 0.15 mm when treated with a spot of 2.2 mm at a speed of 4.2 m/min. The path configuration forms a grid with a 5 mm pitch and a 45 degree inclination.

The performance of the cylinder liner-piston coupling is limited by the reaching of such values of the rubbing surfaces wear at which the effect of gas leakage from the diesel cylinders on its working process and fuel efficiency becomes unacceptable.

Surface wear can be characterized by the wear rate

\[ \frac{dh}{dt} = k(p), \]

where \( h \) – the thickness of the worn layer; \( t \) – time; \( k \) – the coefficient of proportionality; \( p \) – pressure; or linear wear rate

\[ I = \frac{dh}{L}, \]

where \( L \) – the path of friction.

It is more convenient to use the criterion \( F = \frac{I}{p} \text{ (mm}^2\text{/kgf)} \), commonly known as the Archard criterion.

The wear resistance of the coupling of the cylinder liner and the piston ring can be characterized by the total wear rate of the rubbing surfaces \( (dh/dt) \). For run-in surfaces, the wear intensity in a generalized form is directly proportional to the normal pressure:

\[ \frac{dh}{dt} \theta = k\frac{p}{p_k}v b, \]

where \( \theta \) – temperature.

The pressure of the ring on the cylinder liner is made up of the pressure due to the elastic forces of the ring and, mainly, the pressure drop across it, therefore, the first sealing ring wears out most intensively. The maximum pressure drop reaches \( 5,8 \text{ mPa} \). To take into account the pressure drop, we introduce the reduced wear coefficient, which is determined in the first approximation from the relation

\[ \Delta p = F_B + F_K p_k + \Delta p_r v b, \]

where \( \Delta p_r = \frac{p_k + \Delta p_r}{p_k} \).

For a complete turn (360°) the average initial pressure from the elasticity of the piston ring at \( N = 50 \text{ H} \) for a 260 mm ring is

\[ \frac{dh}{dt} \theta = k\frac{p}{p_k}v b. \]
\[ N = \pi \int p_k br \varphi d\varphi \]

The coefficient of proportionality \( k \) is determined from the results of laboratory tests for wear at boundary friction with heated lubricant (Table 1).

<table>
<thead>
<tr>
<th>№</th>
<th>Type of treatment</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_3 )</th>
<th>( k_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cylinder liner</td>
<td>cast iron</td>
<td>6.26*10^{-7}</td>
<td>8.32*10^{-7}</td>
<td>6.26*10^{-7}</td>
</tr>
<tr>
<td>2</td>
<td>Cylinder liner</td>
<td>cast iron</td>
<td>7.08*10^{-8}</td>
<td>2.89*10^{-7}</td>
<td>2.18*10^{-7}</td>
</tr>
<tr>
<td>3</td>
<td>Cylinder liner</td>
<td>laser hardened</td>
<td>7.08*10^{-8}</td>
<td>2.03*10^{-7}</td>
<td>2.32*10^{-7}</td>
</tr>
<tr>
<td>4</td>
<td>Piston ring</td>
<td>cast iron</td>
<td>2.06*10^{-7}</td>
<td>1.32*10^{-7}</td>
<td>1.05*10^{-7}</td>
</tr>
<tr>
<td>5</td>
<td>Piston ring</td>
<td>steel 45 with laser welding</td>
<td>1.32*10^{-7}</td>
<td>1.05*10^{-7}</td>
<td>1.05*10^{-7}</td>
</tr>
</tbody>
</table>

\[ \frac{d}{dt} \frac{h \theta t}{r} + \frac{h \theta t}{r} = -\frac{M \theta t}{EJ} \]

\[ p_{\theta t} = \sum_{n=1}^{\infty} \lambda_n A_n U_n \theta + \lambda_n t \]
also face the task of finding the conditional life of the ring. It is convenient to calculate the wear of surfaces in a dimensionless form.

For dimensionless time \( t \) values from 0 to 1 were taken with a step of 0.1. At the moment of time \( t = t_k \) sec., where \( J \) - the moment of inertia. Figure 3 shows the calculated dependence of wear on time in a dimensionless form.

For a cylinder liner of a heavy diesel engine with a diameter of 260 mm, the moment of inertia of the piston ring section is equal to \( J = \frac{bc^3}{12} \) mm\(^4\), \( b, c \) - the height and width of the ring.

At the current moment of time the wear of the coupling is calculated using the formula \( h = h.a \), here \( a = \frac{p_r r}{EJ} \).

\[ p_c = \frac{p_r}{b} \]

Table 2 shows the results of calculating the time to reach the wear value of the coupling at a given time interval.

<table>
<thead>
<tr>
<th>№</th>
<th>Friction pair</th>
<th>Material</th>
<th>Dimensionless time, 0.1</th>
<th>0.3</th>
<th>0.5</th>
<th>0.7</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cylind.</td>
<td>Cast iron</td>
<td>1.46 \times 10^7</td>
<td>4.38 \times 10^7</td>
<td>7.30 \times 10^7</td>
<td>1.02 \times 10^8</td>
<td>1.31 \times 10^8</td>
<td>1.46 \times 10^8</td>
</tr>
<tr>
<td>2</td>
<td>Cylind.</td>
<td>Laser hardened cast iron</td>
<td>5.28 \times 10^7</td>
<td>1.58 \times 10^8</td>
<td>2.64 \times 10^8</td>
<td>3.69 \times 10^8</td>
<td>4.75 \times 10^8</td>
<td>5.82 \times 10^8</td>
</tr>
<tr>
<td>3</td>
<td>Cylind.</td>
<td>Laser hardened cast iron</td>
<td>5.96 \times 10^7</td>
<td>1.79 \times 10^8</td>
<td>2.98 \times 10^8</td>
<td>4.17 \times 10^8</td>
<td>5.36 \times 10^8</td>
<td>6.96 \times 10^8</td>
</tr>
</tbody>
</table>

Fig. 3.
The piston ring–cylinder liner coupling comparison of the resource characteristics for various hardening technologies is given on Fig. 4.

Fig. 4. The actual operating time of the hardened coupling of the piston ring–cylinder liner for hardening treatments: 1 – without hardening; 2 – laser hardened cylinder; 3 – laser hardening of the cylinder and laser facing of piston rings.

The calculation results given in the table give reason to expect that an increase in the wear resistance of cylinder liners by about 1.5–2 times by laser hardening will lead to a decrease in the service life of serial piston rings by about 15%. Therefore, laser hardening of cylinder liners should be carried out in combination with measures to improve the wear resistance of rings.

3 Conclusion

1. A method for estimating the service life of a heavy-duty diesel engine piston ring–cylinder liner, taking into account the wear of friction surfaces, has been developed. The calculation is based on an analysis of the change in piston ring elasticity due to wear. The elemental wear law of the piston ring–cylinder liner coupling is determined experimentally on laboratory friction machines.

2. Tests for wear of the model piston ring–cylinder liner coupling were carried out under conditions of alternating motion of samples with lubrication using МГ-14А oil. The samples were cut from a full-scale cylinder liner and piston ring of a heavy diesel engine. As a result of tests, indicators of wear resistance of surfaces were obtained.

3. The effect of laser hardening of a cylinder liner on the wear resistance of friction surfaces has been studied. The service life of the piston ring–cylinder liner coupling with various hardening technologies has been established by the calculation method.
of work on the current maintenance of a diesel engine, it is advisable to introduce a hardening treatment for piston rings. To increase the wear resistance of piston rings, it is proposed to use steel with laser facing of a coating based on cast iron.

Durability of piston rings decreases, which requires a larger amount of current repairs to replace piston rings. On the basis of the calculated data obtained, it was found that laser treatment of electroless piston ring coatings and nanostructured coatings of piston rings can increase the service life of a heavy-duty diesel engine by 1.8 times in comparison with piston rings made of a piston ring/cylinder liner pair..meta and lubrication model for the study of the piston compression ring friction force under fully flooded and starved lubrication, (2023). Applied mathematics and mechanics, 12(3), 422–423.

References


A combined experimental and numerical study, Wear, 367-368, 200–208.


A combined experimental and numerical study, Wear, 367-368, 200–208.

