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Analysis of changes in the microstructure of compression rings of an auxiliary marine engine

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ABSTRACT

Introduction. The cylinder-piston group (*CPG*) of a marine-type internal combustion engine is subjected to high operational loads. The reliability, durability and efficiency of the engine depend on the proper operation of the *CPG*. The change in the direction of piston movement and the lack of lubrication caused by the spraying of lubricant during operation, lead to increased wear of the moving package of piston rings. Having determined the factors influencing the changes in the structure of the metal during operation, it can be taken into account in the manufacturing technology and hardening of these parts. **The subject of the study:** the object of research is the used-out upper and lower compression rings of the cylinder-piston group of the *HIMSEN 4H21/32* auxiliary marine engine. **Purpose of the work** is to consider the change in the structure and microstructure of the material of the compression piston rings of the *HIMSEN 4H21/32* auxiliary marine engine arising as a result of operation; to compare the results of evaluating microstresses and deformations of the surface layer of parts by metallographic methods and X-ray diffraction analysis for various operating conditions of the upper and lower compression rings. **Methods.** Metallographic and X-ray methods were used in the study. The conditions of X-ray photography are described; X-ray diffraction analysis was carried out on a *Dron-3M* diffractometer. Residual microdeformations were determined, as well as the sizes of coherent scattering regions (*D*) and the density of dislocations on the surfaces of the samples. **Results of the work.** The results of metallographic and X-ray diffraction analysis (*XRD*) are presented. The residual macro- and microstresses and the sizes of the coherent scattering regions (*D*) of the surface layer of compression rings are determined. The results of X-ray diffraction analysis are comparable with the results of metallographic studies, and the convergence of the results is observed. **Scope of the results application:** the results of the study can be used in the selection of manufacturing technology for compression rings of marine internal combustion engines (*MICE*). **Conclusions.** It is advisable to evaluate changes in the manifestations of the stress state of cast iron under the influence of various factors. This will allow selecting the optimal technology for manufacturing compression rings to ensure the reliability of its operation. Ring quality control by various methods of structure assessment also makes it possible to predict the conditions of destruction of compression rings during operation. An increase in the degree of defectiveness of the upper ring occurs due to various kinds of deformations of the crystallites. As a result of inelastic deformations during ring operation, the resulting dislocations cause strong mechanical stresses.

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Introduction

The cylinder-piston group (*CPG*) of a marine-type internal combustion engine is subjected to high operational loads. The reliability, durability and economic efficiency of the engine depend on the proper operation of the *CPG*. The change in the direction of piston movement and the lack of lubrication caused

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by the splashing of lubricant during operation, lead to increased wear of the moving package of piston rings located in the upper part of the cylinder [1].

Compression rings and oil rings are part of the *CPG*. Oil rings are used in four-stroke engines with a lubricant spray system to remove excess oil from the bottom of the cylinder and regulate its flow to the top of the cylinder. Compression rings have two functions: sealing and heat dissipation, as well as helping to distribute oil over the cylinder walls during operation. During operation, the compression rings make several types of movement. *Forward-backward (radial) movement* of the rings within the piston groove (ring grooves on the cylindrical surface of the piston) creates deformations perpendicular to the formations and contribute to wear of both the rings and the bottom surface of the piston groove. This leads to deterioration of the sealing effect of compression rings, and afterwards to radial vibration and ring breakage, most often in the middle part, opposite the lock. *Axial movement* is due to the difference in gas pressure above and below the ring, the gravity of the ring itself and the friction force between the ring and the piston groove surface. *Rotational movement* of the rings is caused by the engine shaft revolutions.

The operating conditions of the upper and lower compression rings are different. The pressure behind the upper compression ring is 0.75***Pr***, behind the lower compression ring is 0.20***Pr*** (***Pr*** is the operating pressure) and is one of the components of the force pressing the rings to the cylinder, and also creates radial deformations of the ring material. This causes increased wear of the upper compression ring and the lower surface of the piston groove on which it is seated.

The service life of the *CPG* depends is highly dependent on the wear rate of the compression rings. In order to increase the service life of piston rings, various methods of hardening of mating surfaces have been developed: plastic deformation, hardening by high frequency currents, creation of adhesive surfaces, placement of wear-resistant inserts in the friction zone of the ring at the top dead center, porous chromium plating, grinding of grooves for filling with tin, application of hardening coatings of molybdenum and other materials that increase tribotechnical properties [2, 3].

High strength and elasticity, wear resistance, low coefficient of friction are the main design requirements for rings. The uniform distribution of radial pressure around the circumference of the ring is of great importance [4].

Piston rings are made of grey alloyed cast iron with lamellar graphite or high-strength cast iron with spheroidal graphite. Along with high casting properties grey cast iron has good damping ability, high antifriction properties, lower tendency to thermal deformations compared to steel. Differences of phase states of grey cast irons, diffusion of elements, inhomogeneity of linear and volume expansion coefficients of ferrite, cementite and graphite lead to anisotropy of stress state. This is a source of nucleation and development of defects called *dislocations*.

It seems expedient to evaluate the change of cast iron stress state manifestations under the influence of various factors in order to predict the conditions of compression rings fracture in the process of operation. The technology of compression rings manufacturing is determined by reliability requirements and is described in the relevant standards for each type of rings. Quality control of rings is carried out by various methods of assessing the structure of castings, taking into account the technology of hardening, normalisation, heat treatment and machining [1–5].

The use of grey cast iron for the manufacture of compression rings is due to its good fluidity and low shrinkage. Mechanical properties of cast iron are determined by the quantitative ratio of structural components, mainly ferrite, pearlite and graphite. Cast iron with perlite base is the strongest and most wear-resistant. Ferrite reduces mechanical properties of cast iron. Large graphite inclusions reduce strength, but provide high cyclic toughness and low sensitivity to external notches. The material structures of the upper and lower rings undergo significant changes during operation. Rings made of grey alloyed cast iron with lamellar graphite should have a certain microstructure: the metallic base consists of medium and fine lamellar or sorbitic pearlite. Perlite corresponds to high hardness, wear resistance and good machinability by cutting. The presence of ferrite in the form of individual small inclusions should not exceed 5 % of the section area. Ferrite indicates a decrease in mechanical properties and wear resistance of cast iron.

Non-structural cementite is not allowed. Phosphide eutectic may be present in the form of small uniform inclusions or broken meshes, and triple phosphide eutectic with plates is not allowed [6].

The appearance of cementite in the structure leads to brittleness [7, 8]. According to *GOST 7133-80*, rings made of cast iron with spheroidal graphite as a metallic base should contain fine, sorbitic and medium plate pearlite. The percentage of cementite in the form of small inclusions should not exceed 10 % of the section area, and the percentage of ferrite should not exceed 10 % of the section area.

There are techniques of the optical-mathematical method of describing metallographic images that allow estimating the percentage of inclusions of various phases of high chromium cast iron [9].

The problem of improving the reliability of *CPG* can be solved by comprehensive studies of possible operational changes in materials, using modern testing, research techniques and analytical programs. With any dynamic and thermal impact on the rings during operation the internal structure of the material changes, the plastic deformation zone acquires characteristic features. This is confirmed by layer-by-layer texture analysis of metal in the brittle fracture region for an undeformed new specimen and a specimen with defects after operation [10].

An increase in dislocation density, changes in the microstructure, and possible appearance of textural inhomogeneities can be studied using metallographic methods and diffraction of X-ray and electron diffraction [11–14].

The analysis of literature sources on this subject allows us to draw conclusions about the relationship between changes in the structure and operational properties of the material.

In the work [15] the researchers found out that when the material of the working parts of submersible pumps made of cast iron is changed, when the lamellar form of graphite inclusions is changed to spherical, such operational characteristics of cast iron as strength and ductility are significantly improved, but there is an increased volumetric shrinkage and worse flowability in liquid state. These factors should be taken into account when selecting the technology of compression rings manufacturing.

A similar nature of the influence of microstructure changes on the material properties is observed for cast irons and steels. Analysis of changes in the microstructure and crystallographic texture of ferritic steel during stress corrosion failure (*SCF*) using scanning electron microscopy made it possible to determine the size and type of nonmetallic inclusions, the elemental composition of corrosion products, and the nature of fracture in the zone of *SCF* [16]. Within the framework of X-ray diffraction analysis (*XRD*), which took into account the shape and size of grains-crystallites, crystallographic texture, atomic occupancy of the crystal lattice, atomic displacements, *Debye-Waller* factor and instrumental line broadening, the parameters of the fine structure of ferritic steel in the fracture zone and in the zone free from the CRN were estimated. It is shown that the fracture region is characterised by a high density of introduced edge-type dislocations, strong elastic distortions of the crystal lattice and a relatively small size of coherent scattering regions (*CSR*).

Many studies on various steels show that increasing the strain rate at high temperatures increases the threshold strain, which occurs before the onset of dynamic recrystallization of austenite. When boron microalloying is used, the opposite effect is observed, i.e. the threshold strain decreases. The presence of boron in the solution promotes the formation of grains at the boundaries, which prevents the rearrangement of atoms and facilitates the migration of these grains. Rapid dynamic recrystallization improves the ductility of steel and also promotes grain refinement, which reduces its brittleness [17–18].

It is also interesting to study the effect of the stress-strain state on the propagation of cracks in quasi-cleavages of steel subject to embrittlement due to the presence of hydrogen. The role of hydrogen in the crack propagation mechanism was investigated, and it was found that the crack path in quasi-scales in hydrogen embrittled ferritic and ferritic-perlitic low-carbon steels is determined more by the nature of the stress-strain state than by the microstructure or the crystallographic orientation of individual grains [19].

There are new technologies for the production of steel piston rings, which provide for surface grinding [20], surfacing wear-resistant coatings, including the development of a method of three-layer hardening of its surface. This method includes carbonitriding, ion implantation of titanium nitride and then sulfiding, which leads to improved processing and increased wear resistance of piston rings [21]. Electroacoustic sputtering method can be very effective in hardening of piston rings [22]. The resulting nanocrystalline coating on the metal surface is less susceptible to relaxation, which allows increasing the service life of the part by 6–8 times.

Objectives of the study**:** to examine the changes in the structure and microstructure of the material of the upper and lower compression piston rings of the *HIMSEN 4H21/32* auxiliary marine engine, arising as a result of the operation of these rings under different conditions and different loads; to compare the microstresses arising due to deformations of the surface layer of the upper and lower compression rings, using metallographic methods and the method of X-ray structural analysis.

Materials and methods

The subject of the study is the end-of-life piston compression rings (upper and lower) of the *HIMSEN 4H21/32* auxiliary marine engine.

Existing methods of metallographic research and X-ray diffractometry [14–24] allow studying the stress state and atomic structure, microstrain and particle size variation of the material.

In this study, metallographic and X-ray methods were used to investigate the microstructure of compression rings.

Changes in the structure of the material of the upper ring during wear caused by the different operating conditions of the upper and lower compression rings results in a loss of mobility of the lower ring. This means that the entire thermal and mechanical load is borne by the hot reserve of the upper ring. The analysis of changes in the material structure of the upper and lower rings will allow confirming the differences in dynamic and thermal effects on the material during operation, which will allow determining the technological parameters for the manufacture of rings and its special hardening.

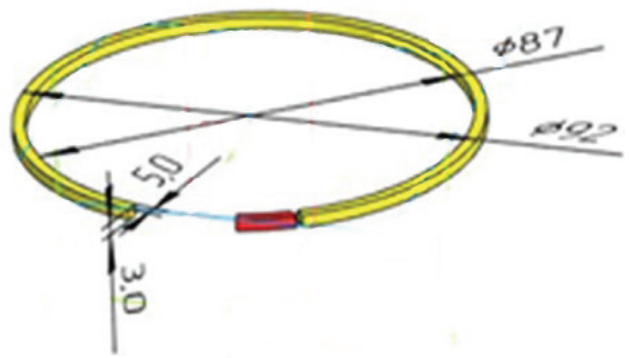


Fig. 1. Ring cutting pattern

Specimens for preparing sections to determine the microstructure and phase composition of the material were made by cutting perpendicular to the ring generatrix (Fig. 1). Since dynamic and thermal loads are equally probable in all radial directions in the ring plane, the location of the cut is of no particular importance. If a possible fracture or crack is present, the location of the cut should be adjacent to the defect.

In order to reveal the entire microstructure, etching was carried out with nital solution (4 % alcoholic solution of HNO_3) for 1 minute. The quality of etching was controlled using a metallographic microscope *MMN-2*. The same microscope was used to obtain photographs of the microstructure of the cross-sections of the rings (Figs. 2, 3).

X-ray diffraction studies at room temperature were carried out on a *Dron-3M* diffractometer. The diffraction profiles were imaged using *Bragg-Brentano* geometry on *CuK*α-radiation with a wavelength of 1.5406 Å (the average value of the $K\text{-}\alpha_{1,2}$ *Cu* wavelength, usually used for processing X-ray radiographs) in the interval of angles $20° < \mathbf{2\theta} < 90°$, with a scanning step of 0.02° and pulse set time at each point $\boldsymbol{t} = 2$ s. The diffraction profiles of the compression rings were processed using *PowderCell* the computer program, version 2.3, and the *ICSD* database was used to analyze and clarify the structural characteristics. Note that a significant background in the X-ray images is associated with the fluorescence of iron when its atoms are excited by *K*-α copper radiation.

The lattice parameters, the sizes of coherent scattering regions on the surfaces of the specimens, as well as lattice microdistortions (microstrains) and dislocation density were determined.

The *Selyakov-Sherrer* formula [23] was used to estimate the effective sizes $\boldsymbol{D}$ of the coherent scattering regions (mosaic blocks).

$$D = \frac{k\lambda}{\beta \cos\theta}, \tag{1}$$

where ***k*** is a coefficient depending on the particle shape and is close to 1; $\boldsymbol{\lambda}$ is the radiation wavelength; $\boldsymbol{\beta}$ is the half-width of diffraction reflection; $\boldsymbol{\theta}$ is the diffraction angle.

Dislocation density $\boldsymbol{\rho_D}$ [24] was calculated from effective crystallite sizes according to the formula

$$\rho_D = 3D^{-2}. \tag{2}$$

The size of the coherent scattering regions ***D*** was estimated from the most intense diffraction reflection 110 lying in the region of small angles 2θ. The broadening of reflections caused by the $K\alpha_1 - K\alpha_2$ doublet, which is significant at large diffraction angles, can be neglected for it.

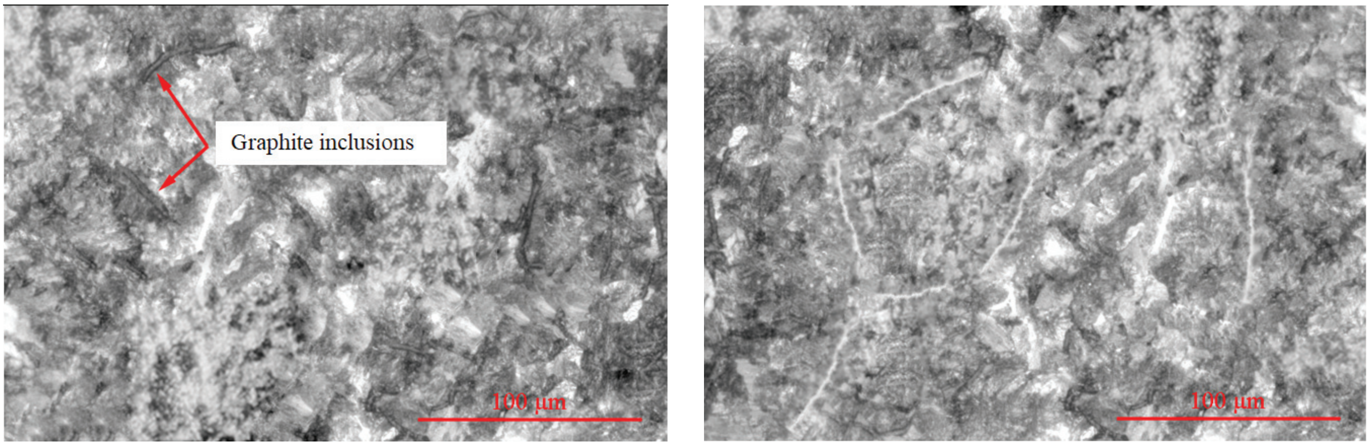
The contribution to the broadening of diffraction lines due to microstrain is also present; the relative lattice strain $\frac{\Delta d}{d}$ [25] was determined by the formula

$$\frac{\Delta d}{d} = \frac{\beta}{4\text{tg}\theta}. \tag{3}$$

The separation of the contributions of microstresses and crystallite refinement to the broadening of diffraction reflections showed that microstrains have the main influence on the broadening of reflections.

Results and discussion

The microstructure of undeformed rings (Fig. 2 *a*) consists of graphite inclusions and pearlitic matrix. In addition, the microstructure shows a small amount of ferrite grains, but its amount is not high, about 5 %. Photographs of the microstructure (Figs. 2 *b*, 3) of the cross-sections of the compression rings, which have served its service life, indicate that the cast iron has a fine plate-like pearlitic base with insignificant (not more than 5 %) inclusion of ferrite grains [6, 9, 11]. This corresponds to international standards for compression rings. Schemes of structures permissible for the material of compression rings were selected according to *GOST 3443-87* "*Castings from cast iron with different graphite shape. Methods of structure determination*" [6].



a *b*

Fig. 2. Photo of the microstructure of the upper compression ring:
a – before deformation during operation; *b* – after deformation during operation

The first photo represents the microstructure of the upper compression ring and shows the presence of lamellar cementite: the base is fine-plate pearlite with insignificant inclusion of ferrite grains; the presence of some cementite elements indicates increased brittleness of this material. The measured *Brinell* hardness of the ring material is HB135 (regulated hardness for compression rings of marine engines of this size is 92–102). The increase of hardness is accompanied by higher brittleness of the material. The second photo shows the microstructure of the lower compression ring: the primary base is pearlite with inclusions of

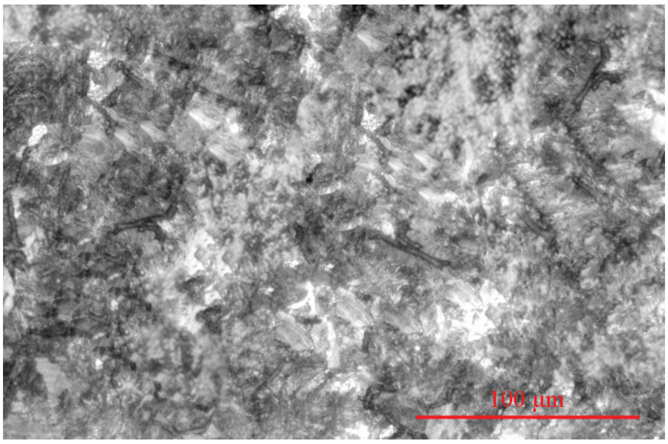


Fig. 3. Photo of the microstructure of the lower compression ring

fine-grained ferrite. The material hardness of the lower compression ring is less than HB85. The lower ring is subjected to lower temperatures, so the structural changes here are significantly lower. However, cyclic loads and deformation effects lead to the formation of fatigue cracks and a decrease in mechanical properties.

The cementite inclusions in the upper compression ring occupy a larger area than the cementite inclusions in the lower compression ring. This indicates more significant mechanical and thermal stresses on the upper ring. Also, according to the microphotographic images, microcrystallites are observed to be crushed in the most stressed material, which correlates with the X-ray diffraction data (Table 1).

Table 1

Results of X-ray diffraction data processing

Phase	***a***, Å	*V*, $Å^3$	***hkl***	**2θ**	**β**, grad	**D**, Å	Dislocation density $\boldsymbol{\rho_D}$, $см^{-2}$	Lattice micro-distortions **Δ*d*/*d***
Fe, lower ring	2.8785	23.9	110	44.20	0.5	180	$9.3 \cdot 10^{11}$	0.00758
Fe, upper ring	2.8870	24.1	110	44.07	0.63	142	$14.8 \cdot 10^{11}$	0.00998

Fig. 4, *a* and *b* show fragments of X-ray diffraction patterns of the surfaces of the lower (*a*) and upper (*b*) compression rings. The results of X-ray diffraction data processing are summarized in Table 1. As shown by the X-ray diffraction studies (Table 1), the upper compression ring shows an increase in dislocation density (approximately 60 %) as well as larger values of lattice microstrains (approximately 30 %) compared to the lower ring. In addition, in the upper compression ring there is a greater refinement of the coherent scattering

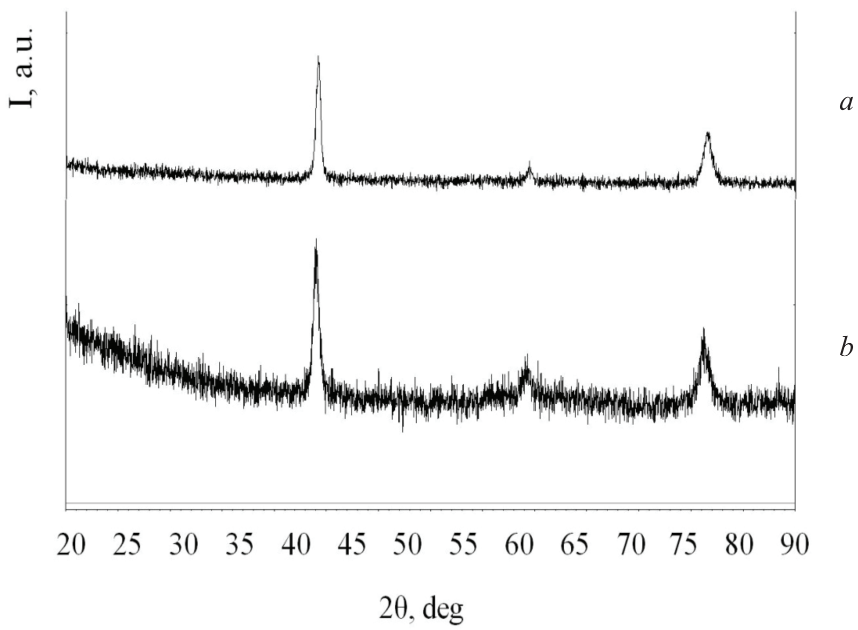


Fig. 4. X-ray patterns of the surfaces of the lower (*a*) and upper (*b*) compression rings

regions (average size of the perfection regions ***D***), approximately by 20 %, which in the experiment corresponds to larger values of the half-widths of the X-ray reflections (Fig. 4) and slight increase in the cell parameters

Conclusion

The changes in the structure, microstructure and hardness of the material of the compression piston rings of the *HIMSEN 4H21/32* auxiliary marine engine, which occur as a result of operation, are experimentally established in this work, using X-ray diffraction and metallographic analysis methods.

A difference of half-widths of X-ray diffraction reflections of iron in the material of the upper compression ring in comparison with the lower one is established, which testifies to the reduction of the average size of coherent scattering regions due to different conditions of operation of the rings. At the same time, a difference in the dislocation density of 1.6 times is observed, it is $9.3\ 10^{11}$ cm^{-2} for the lower compression ring and $14.8\ 10^{11}$ cm^{-2} for the upper compression ring. A difference in the values of microstrains for the two rings is also established (for the lower compression ring, microdeformations are approximately 1.3 times higher). It should also be noted that the crystal lattice parameters of iron for the upper ring are increased compared to the lower ring.

Thus, the results of metallographic and X-ray analyses indicate a higher degree of defectiveness of the upper compression ring as compared to the lower ring due to a greater refinement of microcrystallites and the appearance of stronger stresses due to dislocations and inelastic deformations during ring operation.

The results obtained show that to increase the durability and stability of the rings, it is necessary to harden the rings material itself, as well as the surfaces of these rings. It is expedient to evaluate changes in the manifestations of the stress state of cast iron under the influence of various factors. This will allow selecting the optimal technology of compression rings manufacturing to ensure the reliability of its operation. Quality control of rings using various methods also makes it possible to predict the conditions under which compression rings may be damaged during operation.

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Conflicts of Interest

The authors declare no conflict of interest.