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PROVISION OF ADHESION STRENGTH OF GAS-THERMAL COATINGS ON PISTON RINGS OF QUARRY TRANSPORT ENGINES

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The main trend in the development of modern diesel engine manufacturign is the creation of high-powered, reliable and economical internal combustion engines (ICE), which are widely used in various industries, including mining machinery. The application of the methods of gas-thermal and gas-plasma coating for obtaining wear-resistant layers on piston rings for large internal combustion engines of quarry transport – diesel locomotives and dump trucks- is considered. It is shown that the abrasive-jet machining of base coat is widely used as a preparatory operation before coating process, and the roughness of the working surface of the rings after abrasive-jet machining has a significant impact on the adhesion strength of the coating with the base material. The selection of the surface roughness and the conditions of abrasive-jet machining for increasing the coating adhesion strength to the base coat significantly determines both the thickness of the coating and the reliability of the part itself.

The aim of the paper is to investigate the dependence of the adhesion strength of a gas-thermal wear-resistant coating of piston rings of large engines of quarry transport, including dump trucks and diesel locomotives, from the roughness of the working surface after abrasive-jet machining, which in turn depends on its modes (distance to the nozzle exit section, the number of passes, the working air pressure, the shot change rate).

The working surface adhesion strength of piston rings with diameter of 210 mm coated with molybdenum and steel wire composition was investigated by the twisting angle at which the coating peeled. It is shown that the roughness providing a twist angle greater than 35° should be more than 22 μm, which does not cause coating peeling off. Modes of abrasive-jet machining providing the specified values of roughness: working air pressure is 0.4 MPa, distance to the nozzle exit section is 110 mm, the number of passes is 2, and the shot changes after processing 40 mandrels.

***Key words*:** surface roughness, adhesion strength, abrasive-jet machining, wear resistant coatings, piston rings

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Introduction. Increasing the reliability of modern machinery, reducing the cost of maintenance, ensuring competitiveness, extending the service life, and renovating by applying modern technologies to restore the operability of the machine units to the level of new products are the most priority areas for the technological advance.

The main trend in the development of modern diesel engine manufacturing is the creation of high-powered, reliable and economical internal combustion engines (ICE), which are widely used in various industries, including mining and oil and gas engineering [3, 4]. One of the main directions of providing their operational life is aimed at increasing the wear resistance of the critical parts of the units and reducing the losses due to friction, which in many cases is solved with the help of wear-resistant coatings [1, 2].

The application of technologies for the application of protective and wear-resistant coatings, among which gas-thermal and gas-plasma processes are of paramount importance, is one of the principal ways of solving this problem. Existing equipment, materials and technologies for coating can significantly reduce or eliminate the influence of such wearing out factors as erosion, corrosion (including high temperature), cavitation, etc. [5, 9].

Gas-thermal and gas-plasma coatings are used in the repair of equipment and hardening of the working surfaces of new parts. Depending on the purpose of the coating and its operatinf conditions they change the requirements to the accuracy of following the main parameters of the coating – its composition, thickness, density and adhesion to base coat [8]. Gas-thermal coatings are used in the manufacture and repair of a number of critical parts of internal combustion engines and, in the first place, parts of the assembly (pistons, piston rings), crankshaft necks, connecting rod journals and some others.

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Abrasive-jey machining of base coat is the widely used technology, which is a preliminary operation before sputtering process. This type of operation cleans the surface and changes its state of thermodynamic equilibrium with the medium, releasing the interatomic bonds of surface atoms, i.e. chemically activates the base coat. However, the activity of the base coat is rapidly reduced due to chemical adsorption of gases from the atmosphere and oxidation. The treatment makes the surface rough, this leads to an increase in the contact temperature under the sputtered particles on the asperities and increases the total area of the adhesive zones. In comparison to smooth surface the rough one has a larger area, which increases the strength of the adhesion. The presence of an optimum roughness for the required strength of adhesion is also determined by the volume of the roughness cavities providing the necessary shrinkage value of the sprayed layer upon cooling. The choice of the surface roughness and modes of abrasive-jet machining to improve the adhesion strength of the coating with the base coat greatly determines both the thickness of the coating and the reliability of the part itself.

The purpose of this paper is to investigate the dependence of the adhesion strength of a gas-thermal wear-resistant coating of piston rings of large engines of quarry vehicles, including dump trucks and diesel locomotives, on the roughness of the working surface after abrasive-jet machining, which in turn depends on its modes (distance to the nozzle exit section, the number of passes, the pressure of the working air, and the shots change rate).

Features of surface preparation for the application of wear-resistant gas-thermal coating. The existing technological methods for ensuring the surface wear resistance of parts of friction units are divided into several groups: chemical-thermal, volumetric and surface hardening, electrochemical, chemical treatment, mechanical-thermal treatment, sputtering of wear-resistant layers, spraying of powder coatings, ion-plasma treatment, cladding, mechanical hardening, etc.

In countries with developed industry, during solving environmental issues of the technological advance processes, gas-thermal coating displaces galvanic «dirty» technologies. In many works of foreign and domestic authors, various methods of applying protective and wear-resistant coatings are proposed, including the development and improvement of methods for sputtering on various critical parts [10-14, 16-18].

The current situation in Russia makes it possible not to revive obsolete technologies, but to adapt to new conditions and to use the latest sputtering technology applying thermal spraying methods instead of galvanic methods. Domestic enterprises struggling for their place on the market are increasingly beginning to introduce modern methods of gas-thermal coating to improve the quality of their products.

The technological process of coating application includes the following operations: preliminary preparation of the product surface, which helps to ensure a good adhesion of the sprayed material; preparation of the material; coating application; mechanical treatment of the coating after spraying.

To increase the adhesion strength of coatings on the surface of the workpiece, roughening is required. In order to do this abrasive-jet machining, etch machining, and electric spark methods are used. Increasingly frequently in recent years, the application of a sublayer of materials with high adhesion to the base metal has been used.

Preliminary treatment of the base coat surface is an important factor for ensuring a firm adhesion of the sprayed coating to the workpiece, since in most cases the adhesion of the coating to the base coat occurs as a result of mechanical adhesion. Therefore, in order for the sputtered particles, which strike and deform the base coat, to firmly adhere to surface irregularities, the base coat must be sufficiently rough [8, 9]. The increase in the strength of mechanical linkage is associated with an increase in the base coat surface area and the creation of greater base coat activity, which is also important for other types of compounds. Therefore, the creation of a well-developed roughness on the surface of the base coat is an important requirement.

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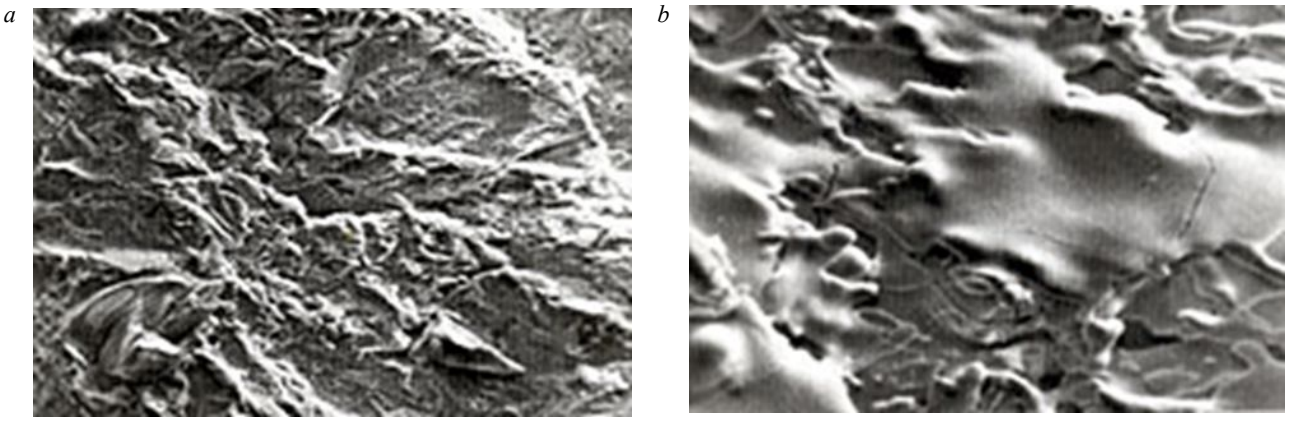


Fig.1. The surface after shot blasting treatment (*a*) and after sputtering (*b*)

One way to prepare the surface before spraying is shot blasting, which results in rough surface. Figure 1 shows the surfaces after shot blasting and after sputtering.

Preparation of the surface of piston rings for the application of wear-resistant coating. Increase in specific power and economy of internal combustion engines (ICE) is characterized by higher temperatures in the combustion chamber and parts of the sleeve assembly (SA). The operational experience of ICE shows that their reliability largely depends on the wear rate of the top piston rings, which is determined by the vibrational and stress-strain state, as well as the composition and technology of wear-resistant coatings, which allows controlling their structure. At the same time, in the foreground there is an increase in wear resistance, provision of appropriate lubrication and compaction in extreme operating conditions. The coating material must be combined with both the materials from which the piston ring and the cylinder wall are made, and with used lubricants. The use of a coating of the working surface on piston rings has been widely used. Often, the mass production engine rings have a coating made of chromium, molybdenum and ferroxide.

One of the main reliability factors is the assigned operation time, which depends on the wear resistance of friction pairs. It is known that the work of friction of piston rings constitutes up to 50 % of all work of engine lost in friction, and of all piston rings the highest friction work is at the top piston ring. This is caused by the operation of the ring under high-temperature conditions up to 200 °C and in the mode of semi-dry friction. However, up to now, the actual operation time of the top piston rings is significantly lower than the longevity of other parts of the ICE SA. Thus, the widely used galvanic method of covering the working surface of piston rings with chromium reduces the wear rate only by 30% compared to non-plated rings, which is clearly not efficient enough, especially at higher cylinder combustion pressures characteristic of high-powered internal combustion engines [6]. With the increase in the level of the engine power augmentation, the previous technologies of applying wear-resistant coatings to the piston rings with porous chromium less meet the increased requirements for coatings for operating at higher temperatures and pressures.

In many cases during production of top piston rings of large engines for quarry dump trucks, diesel locomotives and other machinery they use the coating based on the sprayed molybdenum and its compositions (Fig.2). Molybdenum provides high thermal stability due to the high melting point (2620 °C). Due to this coating method, a porous structure of the material can be obtained. In the created micro-cavities on the working surface of the rings (Fig.2, *b*) the engine oil can be retained, which prevents the formation of scoring under extreme operating conditions. In this case, the thickness of the coating layer reaches 0.5-1 mm or more.

The apparent condition for the normal operation of piston rings with wear-resistant coating is the strength of the coating contact with the base coat. In the working conditions of the piston ring in the engine, in the region of adhesive contact, the stresses are created, they are associated with external forces acting on the ring and a high temperature. To estimate the stresses arising in [3], the plane problem of the thermally stressed state of the cross-section of a piston ring with a coating deposited in a trapezoidal groove was examined under the influence of external loads and an increased temperature simulating the real operating conditions of the piston ring in the engine.

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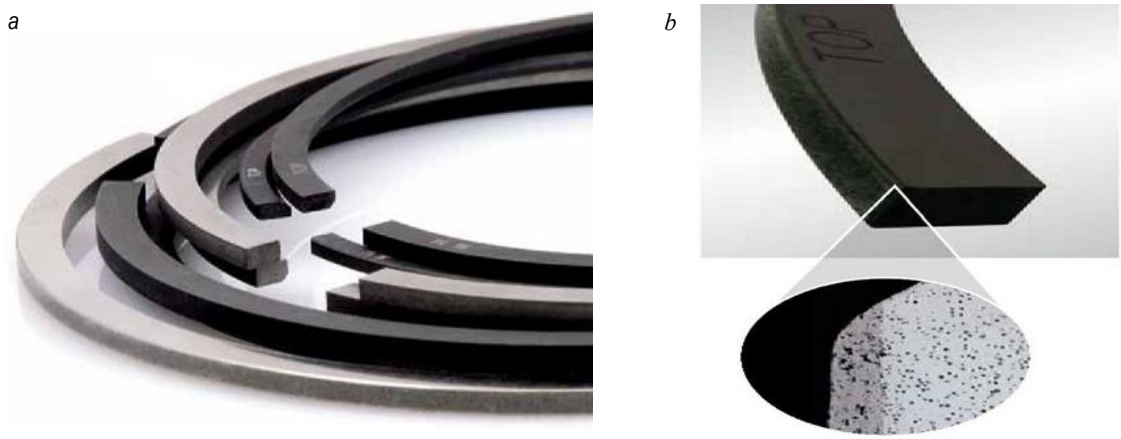


Fig.2. Types of structures of top piston ring (*a*) and ring with molybdenum coating (*b*)

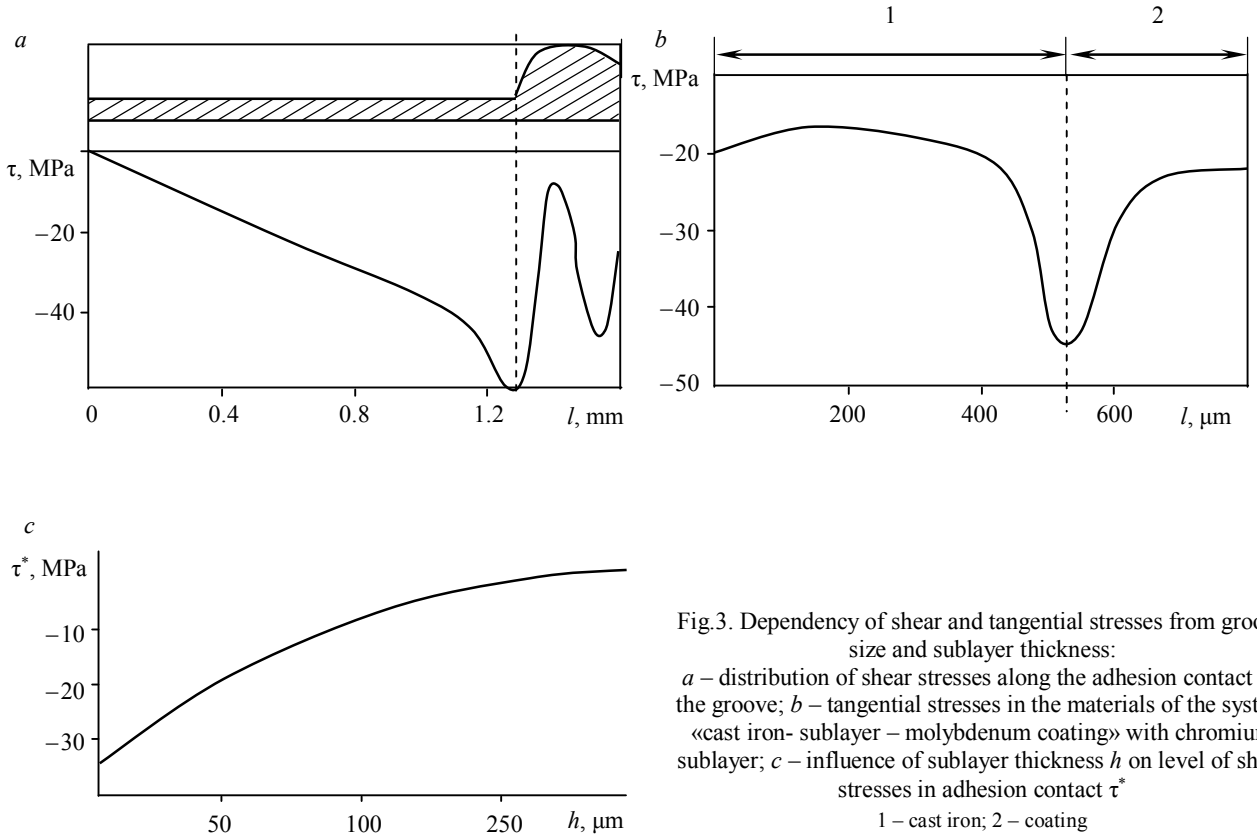


Fig.3. Dependency of shear and tangential stresses from groove size and sublayer thickness:
a – distribution of shear stresses along the adhesion contact on the groove; *b* – tangential stresses in the materials of the system «cast iron- sublayer – molybdenum coating» with chromium sublayer; *c* – influence of sublayer thickness *h* on level of shear stresses in adhesion contact τ^*
1 – cast iron; 2 – coating

Fig.3, *a* shows the results of studies performed for a cast-iron piston ring with a molybdenum coating having thickness h = 300 μm at T = 800 K. Analysis of the obtained dependences shows that when approaching the angles of the groove the shear adhesion stresses increase sharply, and in this case their values exceed the limit of the adhesion strength of the molybdenum coating contact with the cast iron base, which means the peeling of the coating under the given conditions (which is observed in practice).

In order to assess the effectiveness of introducing a sublayer with an intermediate value of the coefficient of thermal expansion before coating, we set a task of identifying the stress field in the cross section of a cast-iron ring with molybdenum coating sprayed on a chrome sublayer deposited in a trapezoidal groove. The problem was solved for different thicknesses of the sublayer. From the total stress field obtained at each value of the sublayer thickness h, the values of the most critical shear stresses at the boundary with the coating were chosen for the analysis.

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The change in tangential stresses along the direction from the base to the coating (Fig.3, *b*) explains the choice of the dangerous stresses value τ. The dependence of the critical stresses values on the thickness of the sublayer *h* is shown in Fig.3, *c*, from which it can be seen that in this case, to ensure the required adhesive strength, the thickness of the sublayer should be *h* = 50-100 μm.

However, in a number of cases, the application of the chrome sublayer is a complex and costly task, while provision of necessary strength of adhesion of the wear-resistant coating on the working surface of the piston rings can be obtained by a reasonable choice of abrasive-jet machining modes [15].

Thus, for the piston rings of internal combustion engines, the strength of the adhesion of the wear-resistant coating to the base coat is a very important performance factor, which largely depends on the method of surface preparation. For piston rings of large internal combustion engines, shot blasting is used before the application of gas-thermally sprayed coatings, in particular, coatings based on molybdenum [15]. The task of providing the necessary surface microrelief and shot blasting conditions before applying a wear-resistant gas-thermal coating is essential.

Discussion of the research results. The paper considered a composite steel-molybdenum coating obtained from molybdenum wire and steel wire 11H18M-ShD, applied by a gas-thermal method on the working surface of piston rings with a diameter of 210 mm.

Before coating, the rings were assembled on a mandrel of 20 pieces, a trapezoidal groove was traversed on the working surface of every ring, then the same rings mounted on a mandrel were subjected to shot blasting abrasive-jet machining with following gas-thermal sputtering.

The adhesion strength was determined by the twisting angle α at which the coating was peeled off on final finished rings. The dependence of the twist angle α on the roughness parameter *Rz* was determined indirectly. Initially, the dependence of *Rz* and α on the shot change rate *n* was established, and then their mutual influence was estimated.

The abrasive-jet machining was carried out in the following modes: the distance to the nozzle exit section is 130 mm; working air pressure – 0.4 MPa; number of passes – 2; the frequency of mandrel rotation is 17 min^{-1}; the angle of attack of the nozzle is 80°; shot - DSK-08 according to GOST 11964-81.

Replacement of the shot was carried out after processing 35, 40 and 43 mandrels of rings. The roughness of the ring samples was measured on a profilograph-profilometer, model 201.

In the first part of the research the roughness *Rz* of the ring samples was determined as a function of the shot change rate *n* (Fig.4, *a*). Obviously, the roughness provided by the newer shot rate is higher. The results of the tests for determining the twist angle α at which the peeling of the coating occurred as a function of shot change rate *n* are shown in Fig.4, *b*. In this case, the twist angle varied from 57° at *n* = 35 to 39° at *n* = 43.

Summarizing the results presented in Fig.4, *a, b*, we can obtain the dependence of the twisting angle α on the roughness *Rz* (Fig.4, *c*). It can be seen that in the considered range of roughness variation this dependence is approximated practically in a linear form, i.e. the adhesion strength increases with increasing surface roughness.

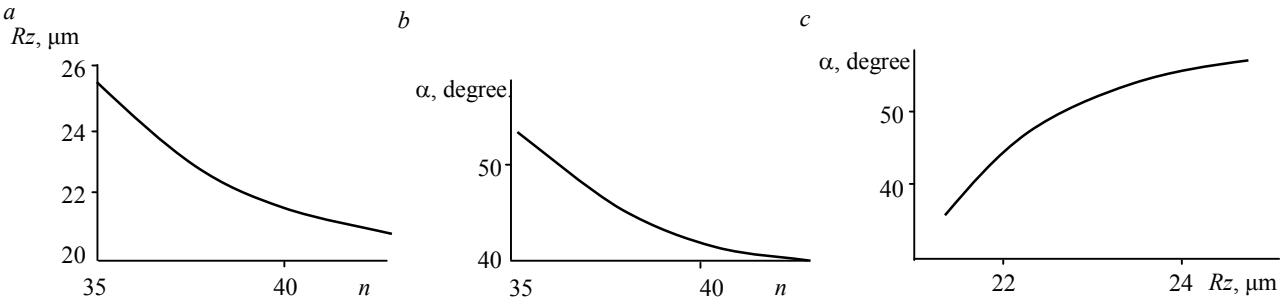


Fig.4. Dependency of roughness *Rz* (*a*) and twist angle α (*b*) from shot change rate *n* and twist angle α from surface roughness *Rz* (*c*) after abrasive-jet machining

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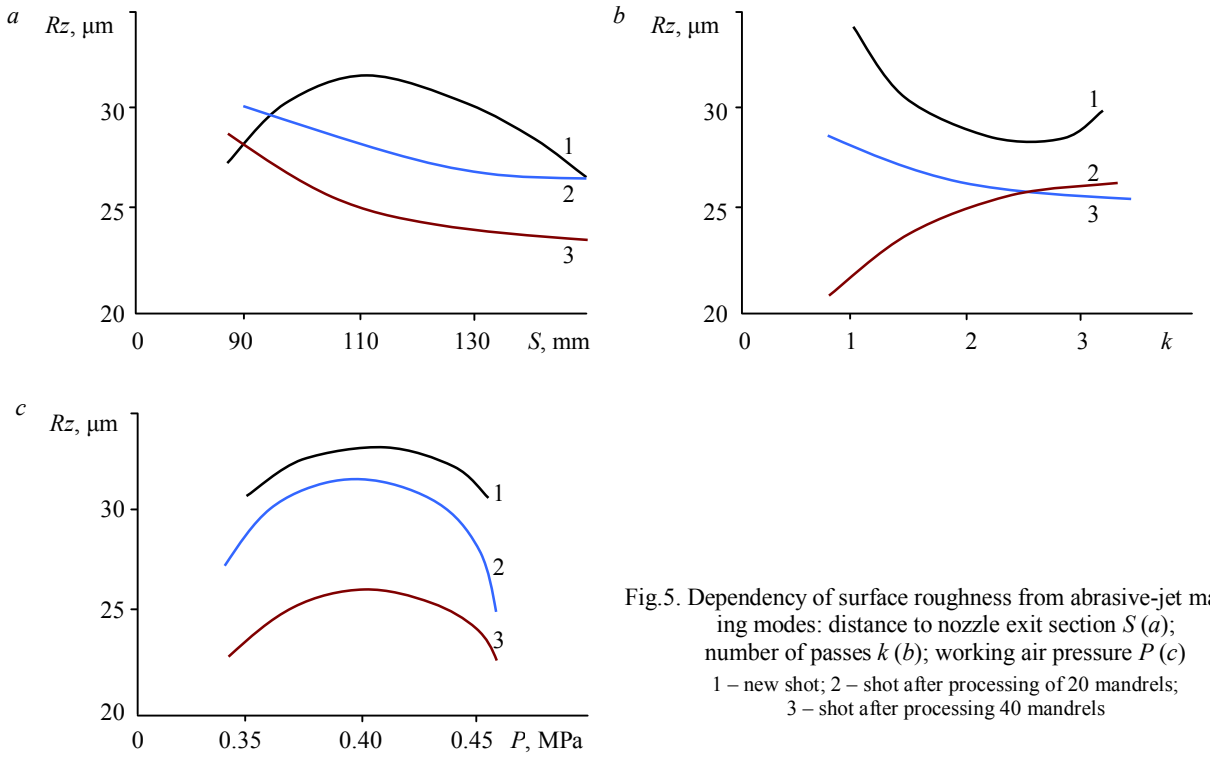


Fig.5. Dependency of surface roughness from abrasive-jet machining modes: distance to nozzle exit section S (*a*); number of passes k (*b*); working air pressure P (*c*)
1 – new shot; 2 – shot after processing of 20 mandrels; 3 – shot after processing 40 mandrels

Thus, considering that the normal operation of the piston rings, as operation experience has shown, is ensured when the coatings are peeled off at angles above 35°, it can be concluded that it is necessary to change the shot after processing no more than 40 mandrels. In this case, the roughness will be limited in the base and corresponds to $Rz \geq 22$ μm. According to the data of [8], the roughness peak limiting is usually taken up to $Rz \leq 160$ μm, since with higher roughness there appear points of applied coating separation from the base metal.

In the second part of the research in order to provide the required surface roughness after the abrasive-jet machining, various modes were investigated and their interrelation with the parameters of roughness was revealed. In each series of experiments, one of the processing modes varied: the nozzle exit section distance S, the number of passes k, the working air pressure P, while the other two characteristics remained constant (Fig.5).

In the first series of experiments, the distance to the nozzle exit section (S = 70, 90, 110, 130 and 150 mm) was varied, and the machining was performed in two passes at a working air pressure of 0.4 MPa. It is seen from Fig.5, *a* that for both the new shot and the shot after processing 40 mandrels, the total optimal distance to nozzle exit section is 110 mm.

In the second series of experiments, the number of passes (k = 1, 2, 3) was varied with a nozzle exit section distance of 110 mm and a working air pressure of 0.4 MPa. As shown in Fig.5, *b*, the optimal value is k = 2.

In the third series, the working air pressure (P = 0.35, 0.40 and 0.45 MPa) was varied during machining for two passes and 110 mm distance from the nozzle exit section. Optimum in terms of obtaining the required roughness should be considered P = 0.4 MPa (Fig.5, *c*).

Thus, as a result of the conducted research, the dependence of the adhesion strength of the gas-thermal wear-resistant coating of piston rings on the roughness of the working surface after abrasive-jet machining was found, and the modes providing the optimum roughness were established: working air pressure is 0.4 MPa, the number of passes is 2, and the nozzle exit section distance is 110 mm. In this case, it is necessary to change the shot after abrasive-jet machining of no more than 40 mandrels of the rings.

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Conclusions

1. Surface roughness resulting from abrasive-jet machining, has a significant effect on the adhesion strength of the coating obtained by the methods of gas-thermal and gas-plasma sputtering.

2. Sputtered coatings based on molybdenum and its compositions are widely used in the manufacture of piston rings of large internal combustion engines, including engines of mine dump trucks and diesel locomotives. At the same time, ensuring the adhesion strength of the coating to the base coat is closely related to providing the required roughness and modes of abrasive-jet machining.

3. As a criterion for the adhesion strength of the piston ring coating, the twist angle at which the coating peels off can be used. This approach allows indirectly establish the relationship between the coating adhesion strength and the surface roughness.

4. Modes of abrasive-jet machining are proposed (working air pressure is 0.4 MPa, distance to nozzle exit section is 110 mm, number of passes is 2, shot change after processing 40 mandrels), providing the required roughness of the working surface of the piston ring ($Rz \geq 22$ μm) before coating application.

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