This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0), which permits use, distribution, and reproduction in any medium, provided the original publication is properly cited. No use, distribution or reproduction is permitted which does not comply with these terms.

TECHNOLOGICAL PROPERTIES OF CYLINDER LINERS OF AUTOMOTIVE INTERNAL COMBUSTION ENGINES RESTORED BY CENTRIFUGAL INDUCTION SINTERING

Khasan Ilyamov[1], Zhandos Zhumagulov[1], Erbol Sarkynov[1], Shamil Abdreshov[2], Gabit Bakyt[2,*], Yerzhigit Saparbayev[1]

[1]Kazakh National Agrarian Research University, Almaty, Kazakhstan
[2]Mukhametzhan Tynyshpayev ALT University, Almaty, Kazakhstan

*E-mail of corresponding author: gaba_b@bk.ru

Zhandos Zhumagulov 0000-0003-1813-902X,
Shamil Abdreshov 0000-0003-3385-2181,
Erbol Sarkynov 0000-0002-4933-762X,
Gabit Bakyt 0009-0009-8454-6791

Resume

Cylinder liners of an automotive internal combustion engine are subject to significant losses during operation. Severe operating conditions of cylinder liners lead to the appearance of various defects that must be eliminated to ensure the performance of the internal combustion engine. Currently, several methods have been developed for restoring and strengthening the inner surface of cylinder liners of automobile and tractor engines. Analyzing the considered methods for strengthening and restoring cylinder liners, their advantages and disadvantages from the point of view of increasing their durability, it can be assumed that the high-quality restoration of cylinder liners will be provided by a method of applying a coating by centrifugal induction sintering of powder material. Self-fluxing powders were used as baked powder material.

Article info

Received 3 April 2024
Accepted 18 July 2024
Online 26 August 2024

Keywords:

sleeve cylinder
NI-resist inserts
tinned and chrome rings
micro-contact setting
metal contacting
centrifugal induction sintering
cylinder -piston group

Available online: https://doi.org/10.26552/com.C.2024.051

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Engine life, first of all, depends on the wear resistance of the cylinder parts - piston group, which during the engine overhaul are replaced with new ones or restored. Cylinder liners of automotive internal combustion engines are subjected to significant loads during operation. Severe operating conditions of cylinder liners lead to the appearance of various defects that must be eliminated to ensure the performance of the internal combustion engine. For each type of liner defects, there are various methods and devices for their eliminating, in particular for restoring the geometry and dimensions of the worn working surface. All these methods and devices for their use have their advantages and disadvantages, which must be taken into account when choosing a rational method for restoring the working surface of cylinder liners.

Currently, several methods have been developed for recovery and strengthening the inner surface of automotive cylinder liners engines, which, according to their technology, are divided into boring for repair size and restoration to nominal size. For restoration of cylinder liners to nominal size, the following methods are used: metallization, galvanic methods, pressing wear-resistant plates, surfacing of wear-resistant powders on the inner surface, restoration by heating, etc.

The most common material used for the manufacture of cylinder liners for automobile and tractor engines is gray cast iron - a cheap and technologically advanced material that, under normal operating conditions, has sufficient durability and reliability. At present, when production is faced with the task of increasing standards for engine reliability indicators, gray cast iron requires further improvement through the introduction of wear-resistant alloying elements or hardening of its surface. For the manufacture of monometallic sleeves, a chromium-silicon alloy of the following composition has been developed : C - 2%, Cr - 12 to 15%, Si - 1.0%, Mn - 0.8%, Ni < 0.3% [1]. Performance tests of chromium-silicon cylinder liners indicate that their wear is approximately 4 times less than the wear of gray

cast iron liners. The advantages of the alloy include its increased rigidity, which is 1.5 to 2 times greater than that of combined sleeves. However, the given alloy has poor machinability and low workability.

Scientific Automotive Institute (SAI) has developed two more types of wear-resistant chromium cast irons with carbides in the structure and compact graphite - ICHK-33K, with carbides in the structure and lamellar graphite - ICHK-33, which exceed the wear resistance of gray cast iron by 1.9 and 2.2 times, respectively. However, all of the above wear-resistant alloys have a common drawback - excessive consumption of expensive scarce material, poor machinability, and therefore have not found wide application in production.

To increase the wear resistance of cylinder liners made of gray cast iron, volumetric, isothermal or surface hardening of the inner surface of the liner is carried out. At the same time, due to the finely dispersed structure of martensite or troostite in austenite and the high hardness of the hardened surface (HRC 42 to 46), the wear resistance of the surface during bulk, isothermal, and high-frequency hardening increases by 1.4, 1.6 and 1.7 times, respectively, [2]. However, despite the widespread use of hardening of sleeves in production, this method has such disadvantages as significant warping of the part, instability of the process, and poor machinability of sleeves after hardening. In addition, hardening no longer meets the increased requirements for liner wear resistance due to the creation of forced engines. Due to the listed shortcomings in production, hardening of sleeves has not found widespread use.

Another way to increase the wear resistance of the working surface of the liner is nitriding [3], in which a layer of nitrides with high microhardness (Hμ = 12500 to 13000 MPa) is formed on the working surface. Nitriding is carried out in gas or liquid media at temperatures of 793 to 8I3 K (520 to 540 °C). According to data [4], the wear of nitrided cast iron is 3 times smaller than that of non-nitrided alloyed cast iron. The disadvantages of this process include the duration of the process, warping of parts and heterogeneous properties across the thickness of the nitride layer, especially on cast iron.

Works [2-3] consider increasing the durability of liners using thermal diffusion sulfidation. In this case, relatively thick and easily wearing films are formed, which facilitate processing and protect against jamming in the initial period of operation, but do not allow long-term protection of the friction surface from intense wear.

Increased wear resistance of cylinder liners is achieved by chrome plating [5-6]. This type of hardening allows to increase the service life of liners by 2 to 3 times. High hardness and good adhesion of the coating to the base metal up to 600 MPa are ensured by smooth chrome plating, but it has poor run-in and insufficient oil-holding ability. The best results are obtained by porous chrome plating, which eliminates the above disadvantages. Its antifriction properties depend on the porosity and hardness of this coating. Minimal wear of a rubbing pair with a chrome-plated sleeve is observed at microhardness Hμ = 10000 to 10500 MPa and porosity 20 to 30%. Electrolytic chrome plating of liners, while providing working surfaces with high resistance to chemical, electrochemical, temperature and mechanical influences, however, as a method of strengthening worn liners does not satisfy all the requirements of modern production. The main reasons are low productivity and high cost of the coating deposition process. In addition, chromium has low resistance to adhesion to aluminum, its alloys and other materials. An important disadvantage of chrome plating, as well as other galvanic processes, is the need to have expensive treatment facilities at the plant to protect the environment.

Increasing the wear resistance of cylinder liners should include surface plastic deformation [7], which involves rolling out the inner surface of the liners with balls of a diameter of 8.23 and 9.53 mm under the following modes: speed - 100 to 150 m/min; feed - 0.01 to 0.03 mm/rev, tension - 0.03 to 0.05 mm. GAZ-53 and ZIL-130 cylinder liners processed using this technology showed an increase in wear resistance by 1.2 times compared to serial ones. However, this is no longer enough for modern high-performance engines; in addition, the disadvantages of this method include the fact that the process does not provide the required accuracy, usually obtained by honing.

To increase the efficiency of processing by surface plastic deformation, the author proposed to carry it out in combination with heating the surface layers with electric current, which leads to an increase in wear resistance up to 2 times. The disadvantages of this method include low tool life, small thickness of the hardened layer since a significant part of the hardened layer is removed by subsequent honing, as well as the presence of deformations of the cylinder liners.

For ZMZ-53 engines, a method of manufacturing combined liners was used by pressing a special insert made of an alloy - Ni-resist - into the upper part. At the same time, an increase in the durability of liners by an average of 2.5 times was achieved [8]. However, the use of inserts has a number of significant disadvantages. Pressing inserts with an interference fit along the diameter of 0.14 to 0.30 mm causes warping of the sleeve, and the slightest deviations in size and failure to maintain the cylindricality of the seating surfaces lead to the insert being squeezed out of the sleeve after it is pressed. During the engine operation, the insert moves in the liner, resulting in formation of an annular gap between the lower end of the insert and the flow line in the liner, which leads to the penetration of oil, which carbonises and makes it difficult to remove the heat from the working surface of the insert to the coolant. It has been established that in sleeves with inserts the ovality in the upper belt is approximately two times greater than in the lower, while in sleeves without inserts the change in ovality is the same.

Increasing the durability of cylinder liners is possible

by creating an oil-retaining surface. For this purpose, phosphating of cylinders is used [9], artificial creation of porosity and oil-retaining relief [10]. When phosphating an oil-retaining surface is formed when cast iron liners are treated in Majef salts. In this case, pearlite is etched, and the phosphide eutectic, which does not interact with Majef salts, forms protrusions. After phosphating, the surface of the sleeve has a height of microroughness of 3.0 to 6.0 microns. Phosphated cylinder liners are approximately 3 times more wear-resistant than the serial ones. However, the more phosphide eutectic in cast iron, the higher the efficiency of phosphating. However, phosphorus is an undesirable impurity in cast iron sleeves. A disadvantage of phosphating is the increased wear of the rings, despite their good running-in properties.

The oil-retaining relief on the working surface of automotive engine liners was created using vibratory rolling [3, 11-12]. At the same time, an increase in the wear resistance of the liners by 1.5 to 2 times was noted. The disadvantages of this method include increased oil waste and deformation of the liners during running-in.

Analysis of methods for restoring cylinder liners, from the standpoint of increasing their durability, shows that not all the methods satisfy this requirement. Thus, methods for restoring the cylinder liners using repair dimensions, thermal shaping, installing an easily removable bushing, pressing in easily removable inserts, and welding steel strips do not allow increasing the durability of the liners and have a number of significant disadvantages, such as weakening the rigidity of the liner, increasing its deformation and thermal stress in operation. In addition, the inclusion of additional parts in the dimensional chain of the cylinder - piston group tightens the tolerances, which, in conditions of mass production, significantly increases the cost of the finished product.

In contrast to methods for the restoring cylinder liners using additional parts (compensators), methods for creating a monolithic liner through metallization and surfacing, in principle, make it possible to restore the functionality lost by the interfaces and increase its wear resistance.

In [13], a method was proposed for restoring the internal surfaces of cylinder liners by surfacing austenitic cast iron (Ni-resist). The metal in the molten state was poured into a previously prepared internal bore of a sleeve rapidly rotating around the vertical axis, heated to a temperature of 1173 K (900 ˚C) and it was welded to its base. At the same time, the rigidity of the sleeve and its operational characteristics increased; the disadvantages include separate heating of the deposited material and the use of fluxes, which significantly complicates the surfacing process. Restoration of the internal cylindrical surfaces of a number of parts by centrifugal induction surfacing with a sormite-type hard alloy ensures fast and uniform heating of the part and sormite over the entire restored surface. The wear resistance of the deposited surface increases by 2.0 to 2.5 times.

In [14], a method was proposed for increasing the wear resistance of cast iron tractor liners through centrifugal induction surfacing with self-fluxing powder material PG-KhN80SR4, which ensured an increase in the wear resistance of cylinder liners by more than 5 times.

However, surfacing methods have significant disadvantages; the high temperature at which surfacing is carried out causes a change in the structure of the substrate and the deposited material, which negatively affects the wear resistance of coatings. In addition, due to the high deposition temperature, noticeable deformations occur during rotation of the part, which entail the introduction of additional treatments to eliminate them. The disadvantage is the use of special fluxes and the difficulty of subsequent mechanical processing.

These disadvantages are eliminated in works [1-2], in which, with the centrifugal induction method of applying powder coatings, thermal diffusion sintering of powders is proposed instead of surfacing. When choosing a powder material for sintering, it is necessary that it contains at least 85% ferromagnetic elements. The melting temperature of the powder must be close to the melting temperature of the base metal so that they simultaneously reach a sintering temperature that lies within 0.7 to 0.85 of the melting temperature. The powder must contain activating elements (such as boron, silicon, etc.) that can act as a flux and form a liquid phase at lower heating temperatures than the powder base.

In work [15], the issues of applying the PG-SR2 powder coating to the inner surface of cylinder liners were studied, equipment for centrifugal induction sintering was developed, and the issues of mechanical processing of the powder coating and baked liner by boring followed by honing were studied.

Analyzing the considered methods for strengthening and restoring cylinder liners, their advantages and disadvantages from the point of view of increasing their durability, one can assume that the high-quality restoration of cylinder liners would be provided by a method that satisfies the following basic requirements:

- the least temperature influence on the metal base of the liner, excluding changes in its microstructure and the appearance of significant residual deformations;
- high-quality adhesion of the applied layers to the base;
- increasing the wear resistance of restored liners by 3 times or more;
- availability of materials used in equipment restoration;
- the ability to perform subsequent mechanical processing using standard equipment available at repair plants;
- high productivity of applying layers;

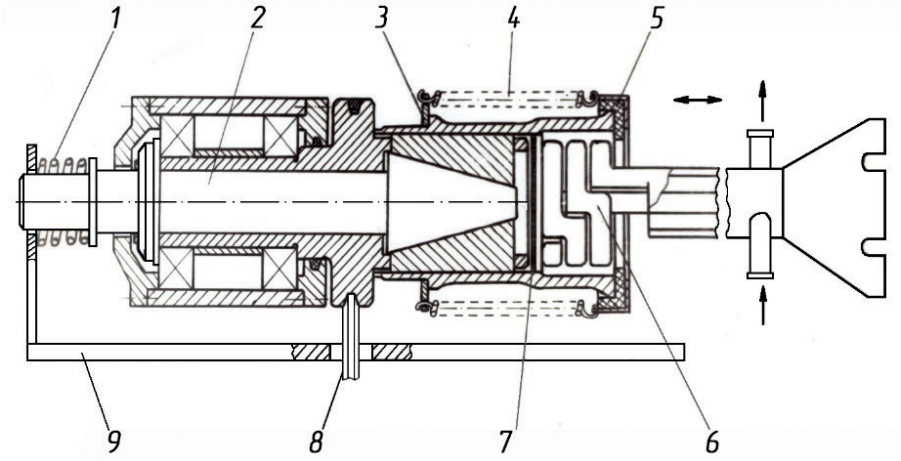


Figure 1 *Installation diagram for restoring cylinder liners: 1, 4 - spring; 2 - rod with a conical head; 3 - ring; 5 - cover; 6 - inductor; 7 - gasket; 8 - V-belt drive; 9 - bed*

- technology and equipment must meet safety requirements;
- application of the method must be economically feasible.

An analysis of the methods for strengthening and restoring the cylinder liners, discussed in the article, shows that the most promising method for strengthening and restoring the cylinder liners is centrifugal induction sintering with metal powders. This method is carried out at temperatures that do not significantly affect the structure of the metal base of the sleeve and the applied material, with small deformations of the sleeve. Sintering makes it possible to obtain a wear-resistant layer on the surface of the liner by preserving the physical and mechanical properties of the powder material and creating an oil-resistant surface due to the optimal porosity of the coating. When baked, a monolithic sleeve is obtained, which increases its rigidity and reduces deformation when installing it in a block and during operation. The process of subsequent machining requires standard metal-cutting machines in the form of boring and honing machines. The process of sintering a powder coating onto the inner surface of the cylinder liner and subsequent machining can be automated [16].

The main method of restoring the worn cylinder liners is boring for repair size, which entails a reduction hardness of the inner surface and the need for organization production of oversize pistons and piston rings. Methods of restoration of cylinder liners to nominal size is not widely available applications due to the fact that they do not meet the requirements of the standard for quality and have a high cost. In this regard, the development of a method for restoring the cylinder liners to the nominal size meeting the requirements of the standards is urgent task of repair production. When deciding on the choice of a method for restoring parts, the most important factor is the issue of processing the coating of the restored liners. Currently, many methods of applying materials have been developed.

The industry supplies a fairly wide range of wear-resistant and hard materials for creating coatings. However, many of them have not found widespread use due to the difficulty of processing coatings.

If scientific work on the mechanical processing of hard-alloy coatings applied to parts of the shaft type is to some extent carried out, then the work on the processing of internal holes restored by the same coatings is very limited. Therefore, the issue of processing the inner surface of cylinder liners seems quite complicated.

2 Materials and research methods

2.1 Technological process for restoring cylinder liners

The proposed technology for restoring cylinder liners of the ZMZ-53 engine, includes: washing, defect detection, removal of the insert from the liners, preparation of their surface, coating by induction sintering and mechanical processing (boring, rough and fine honing).

The cylinder liners of ZMZ-53 engines that had worked for two overhaul periods were used in this study. Before coating, wear-resistant Ni-resist inserts were removed from the liners. In laboratory wear tests and comparative performance tests, liners with inserts were also examined in addition to remanufactured ones. The powder material to be baked was self-fluxing powders.

Research on applying a coating of metal powders to the restored part of the inner surface of the cylinder liner was carried out on a device specially manufactured for this purpose. Figure 1 shows a diagram of the installation for restoring cylinder liners. The cylinder liner is mounted on an expanding four-jaw mandrel. The mandrel ensures reliable fastening of the sleeve, its rotation in a horizontal axis and the ability to quickly change the sleeve. The ETO 2-20 electric drive and V-belt drive allow for stepless regulation of the liner rotation speed in the range from 100 to 1200 min^{-1}.

The sleeve was heated by an internal multi-turn inductor (Figure 1), made of a rectangular copper pipe. To increase the electrical efficiency of the inductor, ferrites were installed in it. The inductor is mounted on the rod of the pneumatic cylinder, which ensures the input and output of the inductor from the cylinder cavity. The inductor was powered by a VChG 1-100/0.066 high-frequency unit with a power of 100 kW and a generated current frequency of 66 kHz.

The coating application mode is carried out at the following indicators: grid current - I_s = 1 A; anode current I_a = 5 A; anode voltage U_a = 5 kV; load voltage on the circuit - U_n = 0.45…0.5 V; heating time, t = 150…180 s ; cylinder liner rotation speed - n = 950 to 1000 min^{-1}.

The coating used in this work, although it has a low hardness HRC 32 to 42, has poor workability. This is due to the presence of porosity in the coating up to 10 to 15 %, solid inclusions with a hardness of up to $H_{100} = 29 \cdot 10^3$ MN/m^2 (2.9 kN/m^2) and viscous nickel base. All this together creates unfavorable conditions for mechanical processing of the coating. The coating was applied with a thickness of 2 mm per side.

There were no cracks, holes or large pores in the coating. However, this coating had a microporosity of 12 to 15 %. The mechanically processed surface of the coating met the requirements.

The individual sintering time for one sleeve was 10 minutes or 0.166 hours with a basic time of 3 minutes. In the future, by improving the sintering installation and reducing the auxiliary time, the piece time can be reduced. The boring and honing time for the restored cylinder liners was 0.25 hours. The longer processing time for restored liners was due to the difficulty of machinability of the coating compared to the machinability of gray cast iron.

Based on the above and physical and mechanical studies, one can conclude that this process of centrifugal induction sintering with metal powder can be recommended for use when restoring cylinder liners that are subject to rejection after using their second post-repair resource. This process can be used not only when restoring the liners that have wear-resistant inserts, but when restoring monometallic liners, as well. In this case, it is necessary to bore the space under the coating to a depth of 0.5 mm. Here, one obtains savings in the applied material due to the fact that the thickness of the applied layer is reduced from 2.0 to 0.5 mm.

Processing of the restored cylinder liners was carried out using standard equipment.

Boring of the sleeves was carried out on a high-precision finishing and boring machine, type 2E78PN. A boring cutter with a replaceable multi-edge plate made of VK8 material was used as a cutting tool. The use of such cutters significantly reduces the time required to prepare them when they become dull. Boring was carried out in two passes (at a cutting depth of t = 0.5 mm). The first pass treated only the coating. During the second pass, the sleeve was processed along its entire length. The cutting speed and feed were assumed to be equal: V = 35.0 m/min (n = 120 min^{-1}), s = 0.2 mm/rev. The durability of the cutter with the VK8 plate made it possible to process up to 10 cylinder liners.

Honing was carried out on a 3G833 machine. To obtain the higher accuracy of the machined hole, an extended honing head was used. Honing modes: rotational speed V = 45.6 m/min; reciprocating speed V_p = 8 m/min; pressure in the system P = 0.1 to 0.2 MPa.

For preliminary honing we used diamond stones ACP 100/80 M1 100 %, for final honing we used diamond stones ACP 80/63 P11/P9 50 %.

This technology for mechanical processing of restored cartridges made it possible to obtain processed surfaces with a roughness corresponding to class 9a, ovality and taper of the hole not exceeding 0.02 mm.

The individual time spent on boring the liner and honing was 0.25 hours.

2.2 Selection of material for rebuilding the cylinder liners

When choosing a material for restoring the cylinder liners, it is necessary to take into account their operating conditions and its physical and mechanical properties when working in tandem with piston rings. In this case, it was necessary to apply a coating that would be superior in wear resistance to serial liners, have good wearability and low tendency to scuff, have sufficient adhesion strength to the metal base of the liner and the ability to subject it to machining. Finally, the material should be relatively inexpensive. All these factors should have determined the choice of material for restoring cylinder liners.

The three pre-selected materials met the requirements for the coating according to individual parameters. To make the final selection of one material, studies were carried out on its sinterability and sinterability to the base, and the workability of the material. A number of physical and mechanical properties were compared according to literature data.

The three most common types are: PG-SR, SPGN, and NPC. One material was selected from each type. When choosing a material, its costs, hardness, workability and other physical and mechanical properties obtained from literary sources, were taken into account.

The chemical composition of self-fluxing metal powders selected for preliminary studies is given in Table. 1.

Sintering and sintering modes for each material were selected individually. When selecting modes, we varied the heating rate, temperature, heating duration and centrifugal force of pressure of the powders to the base (sleeve rotation speed). At the same time, we achieved a baked coating without cracks and with good adhesion to the base, especially in places where there

Table 1 *Chemical composition of self-fluxing metal powders*

Brand material	Element content in %										Hardness, HRC
	C	Cr	Si	Mn	B	Fe	Ni	Cu	P	S	
PG-SR2	0.2-0.5	12-15	2.0-3.0	-	1.5-2.1	5.0	ost	-	0.04	0.04	38-42
SNGN-55	0.7-1.0	14-17	3.5-4.5	up to 1.0	3.2-4.0	up to 4.0	ost	-	-	-	53-58
NPC-1	0.1-0.3	-	1.3-1.5	-	1.2-1.5	0.1-0.7	ost	4-5	-	-	HB 190-230

was a stepwise transition of the inner surface of the liner, where there was an insert.

The assessment of the sinterability of the powders and their adherence to the base was determined visually by chipping the sleeve. As a first approximation, the adhesion of the coating to the base was considered satisfactory if their fracture was monolithic.

When selecting a material, the machinability of the baked material was linked to its hardness. Coatings with high hardness (SNGN-55) are difficult to process and thereby increase the costs of restoring parts.

The choice of material was also carried out taking into account the costs of the powder material. For example, the NPCh-1 alloy is slightly different in its properties from the PG-SR2 alloy, but the costs are twice as much. Even more expensive is the SNGN-55 alloy.

Therefore, based on preliminary experiments to determine adhesion and obtain a high-quality coating, as well as taking into account the hardness of the material and its costs, powdered hard alloy PG-SR2 was chosen as a material for restoring cylinder liners. This material met the requirements for the product being repaired. Restoring the cartridges with the specified material was supposed to ensure their normal performance and increased their service life.

3 Results

3.1 Determination of run-in and adhesion of coating

Research has shown that samples worked in tandem with tinned rings ran in faster (by 15 to 25 %) than in pairs with chrome-plated rings. This can be explained by the fact that tin, compared to chrome plating, is a softer and more ductile material and increases the wearability of rubbing pairs.

The coated samples, which were paired with tinned rings, took significantly longer to break in than the samples with an insert and gray cast iron samples. The running-in time was about 25 hours. After finishing the running-in process, the coating had a shiny surface.

Samples with an insert ran in slightly better than the samples with a coating. Their break-in time was 15 to 17 hours when working with tinned rings.

For samples made of gray cast iron without coating and inserts, the running-in process was the least. Their break-in time was 10 to 12 hours when working with tinned rings. They had a uniform running-in surface, which was explained by the homogeneity of the material.

Testing the samples for adhesion showed that the lowest values were for the coated samples. The operating time with a load on the sample of 1.1562 kN, under boundary lubrication conditions, was about three minutes. For samples with an insert, under the same conditions, setting occurred within the same time as for the samples with a coating. However, the load on the sample was slightly less than 1.187 kN. The adhesion of gray cast iron samples appeared a little faster than that of samples with an insert (2 to 3 min). The load was the same.

Tests have shown that the presence of solid inclusions in the coating somewhat increases the process of their breaking-in. However, this structure of the samples significantly reduces their setting when working with tinned rings.

3.2 Study of the coating wear resistance

When testing samples of sleeves in conjunction with chrome-plated rings (Figure 2), the wear resistance of sleeves with an insert (red curve) and experimental sleeves (green curve) was almost the same.

Over 100 hours of testing, linear wear was 0.085 and 0.082 mm, respectively. The wear of gray cast iron samples (blue curve) was 1.866 times greater than the previous ones and amounted to 0.153 mm during the same testing time.

When working with tinned rings (Figure 3), the wear of the sleeve samples with an insert (red curve) remained the same as when working with chrome-plated rings, and amounted to 0.084 mm over 100 hours of testing. However, the wear of coated liners (green curve), wear value 0.04 mm, decreased by half compared to samples of liners with an insert and four times compared to samples of gray cast iron liners (blue curve), wear value of which was 0.162 mm.

At the reversal points or at the so-called dead points MT1 and MT2, the wear value is greater than at other friction areas between MT1 and MT2. This can be explained by the fact that at these points the speed of movement of the counter samples (piston rings) drops to zero, while the specific pressure increases. This nature of the work of the rubbing pair causes rupture of the oil film and thereby creates the condition

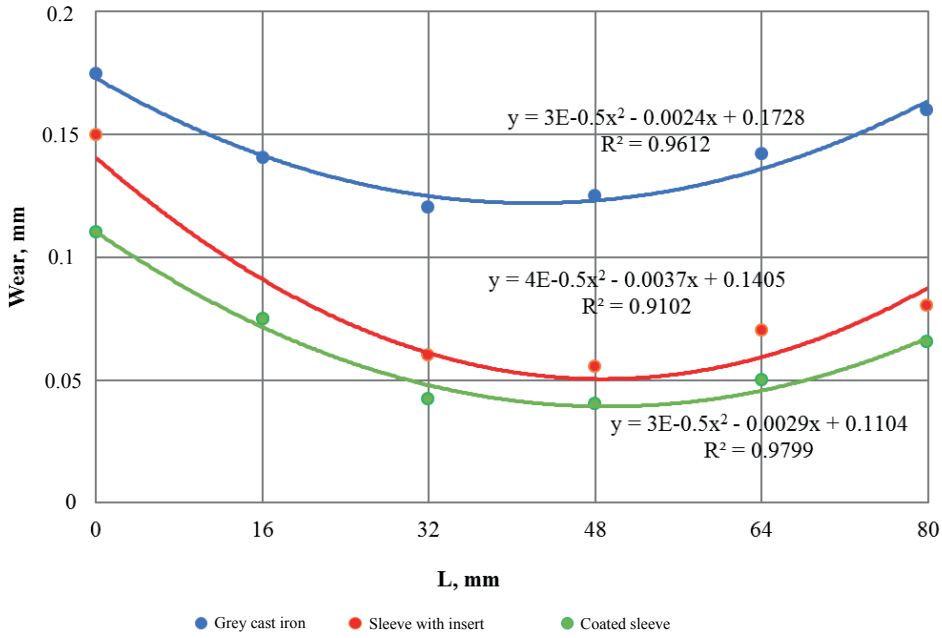


Figure 2 *Wear distribution between dead points MT1 and MT2 along the length of samples with chrome rings*

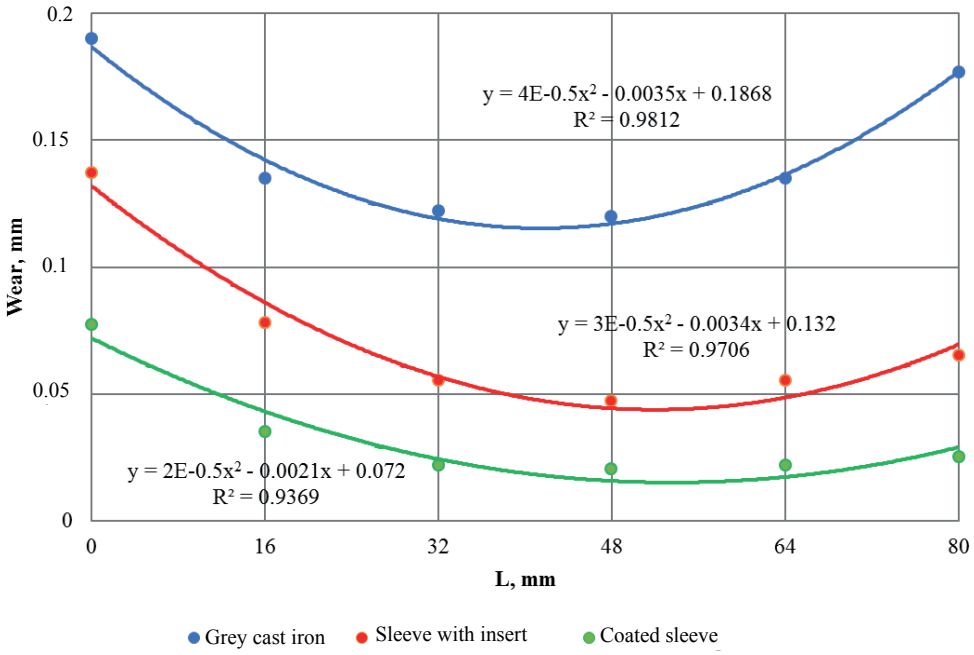


Figure 3 *Wear distribution between dead points MT1 and MT2 along the length of samples with chrome rings*

of boundary lubrication. In this case, at the indicated points, interaction occurs between the metal surfaces of the sample and the counter-sample. These conditions cause increased wear of the samples at the reversal points.

The reduction in wear of coated liner samples when working with tinned rings can be explained by the fact that tin, having a low melting point, significant ductility, and the ability to be deformed many times without destruction, acts during friction as a liquid lubricant, localizing the process of metallic interaction in the tin coating layer, and thus eliminates the intense destruction of surfaces during the initial period of operation of mating samples, and facilitates the running-in. The favorable running-in process has a noticeable effect on the period of established wear.

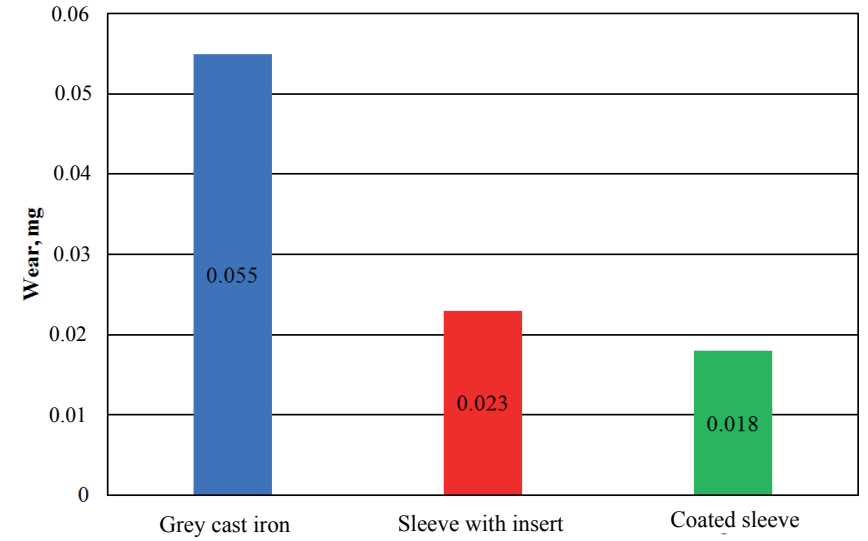
The high wear resistance of coated liner samples can also be explained by the high hardness of the coating itself and its porosity, which creates an oil-intensive friction surface. With an optimal coating porosity, a reliably separating film of lubricant is retained on the friction surface of the liner samples, making it difficult

to form large adhesion units, their growth and long-term existence between the contacting surfaces.

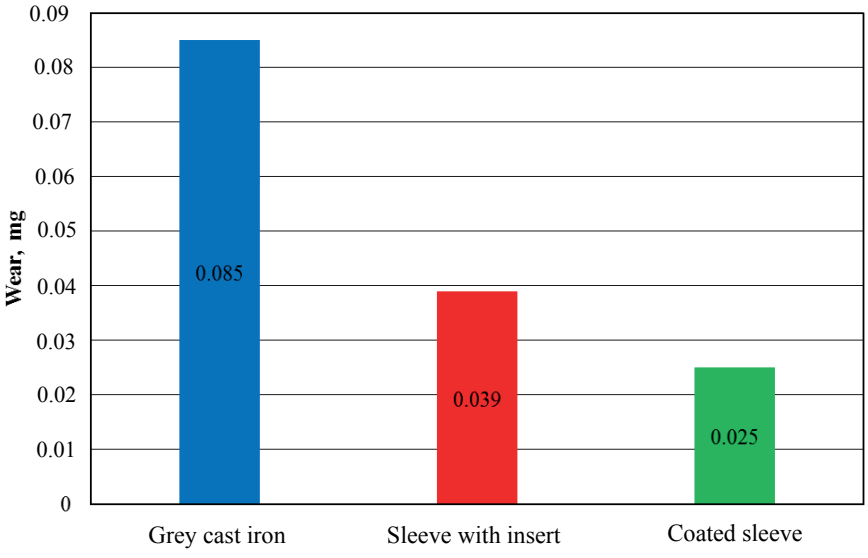
The high hardness of the coating ensures minimal sizes of damage spots on its surface in comparison to the sizes of damage to the surfaces of cast iron unstrengthen liner samples.

Analysis of the wear distribution curves on the formation surface of the liners considered above also showed that in the reversal zones of the piston ring sample, i.e., at dead points MT1 and MT2, the amount of wear is greater than in other areas, where the sliding speed is higher and the lubrication film is more reliable. This wear topography is generally characteristic of cylinder liners of internal combustion engines and indicates the influence of sliding speed on the thickness of the lubricant film and the intensity of damage to the friction surface itself. In places where the direction of movement MT1 and MT2 changes, a thin film of lubricant does not provide reliable separation of the surfaces. In this zone, characteristic damage due to microcontact setting is observed and maximum wear is obtained. An increase in sliding speed leads to the manifestation of a hydrodynamic effect, an increase in the thickness of the lubricant film, a decrease in the likelihood of metal contact, and less damage is obtained.

The wear of the chrome-plated and tin-plated rings themselves (compression rings) is shown in Figure 4. It shows that the wear of unhardened tin-plated rings is approximately 1.50 to 1.65 times higher than the wear of chrome-plated rings. However, rings of both types have approximately three times less wear when paired with samples of experimental liners with a coating than when paired with samples of liners made of gray cast iron, and somewhat less (1.3 to 1.4 times) compared to pairing samples with sleeves with a Ni-resist insert.



a)



b)

Figure 4 *Wear of tin-plated (a) and chrome-plated (b) rings during friction with liner samples: 1 - for gray cast iron; 2 - with insert; 3 - coated*

4 Discussion

1. Research has shown that the coating of cylinder liners obtained by centrifugal induction sintering (viscous nickel base with solid inclusions) has lower machinability than the gray cast irons used for cylinder liners.
2. It has been established that boring such a coating is possible when using cutters with VK8 carbide inserts at a cutting speed of 35 m/min and a feed of 0.2 mm/rev. It is recommended to do boring in two passes with a cutting depth of 0.5 mm.
   Honing after boring can be done with diamond stones type ABH 100x8x4x2x ACP 100/80 M 1 100 % at the mode: V_0 = 45 m/min, V_p = 8 m/min, pressure (1.5 to 2.0) x 10 ·5 Pa). Final honing using ACP 80/63 P11/P9 stones 50 %.
3. Sleeves with a carbide coating have worse running-in properties than the serial cast iron sleeves (with an insert). The running-in time for coated sleeves was about 25 hours, and for sleeves with an insert - 15 to 17 hours.
   The adhesion of coated sleeves when working with tinned rings occurred after 3 minutes at a load on the sample of 1.562 kN, and for serial sleeves under the same conditions (the same time) at a slightly lower load of 1.187 kN.
4. The presence of hard inclusions in the coating structure of the liners provides the mirror of the cylinder liners with high wear resistance. Laboratory wear tests of these sleeves showed that sleeves with a wear-resistant coating, when mated with chrome-plated rings, had approximately the same wear resistance as sleeves with Ni-resist inserts and 3.5 times greater than those of gray cast iron sleeves.

When working with tinned rings, coated sleeves had half the wear of sleeves with an insert and four times less wear than the gray cast iron sleeves.

The wear of chrome-plated and tinned piston rings, when working with restored liners, is 1.3 to 1.4 times less than when working with liners with Ni-resist inserts, and three times less than when working with gray cylinders cast iron. In this case, the tinned rings wear out slightly more (1.5 to 1.65 times).

5 Conclusions

Analyzing the test results of samples of liners unstrengthen and subjected to local hardening due to a hard coating, one can see that the intensity of destruction of the reversal zones has a significant impact on the wear of zones located in more favorable friction conditions.

From the data obtained, it is clear that strengthening the liners in the zones of change in the direction \of the piston rings movement by applying a coating with high oil-retaining ability and hardness, reduces the likelihood of the formation of micro-setting units, their sizes, and the intensity of damage by fixed wear products to the unstrengthen surface of the liner samples. At the same time, a decrease in piston ring wear is observed, which indicates a strong influence of the nature of mutual damage to the surfaces of the friction pair under consideration.

Research shows that local hardening of cylinder liners is an effective means of reducing wear of the friction unit.

Acknowledgements

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] FU, X., WANG, B., TANG, X., JI, H., ZHU, X. Study on induction heating of workpiece before gear rolling process with different coil structures. *Applied Thermal Engineering* [online]. 2017, **114**, p. 1-9. ISSN 1359-4311, eISSN 1873-5606. Available from: https://doi.org/10.1016/j.applthermaleng.2016.11.192

[2] BASHIROV, R. J., AMIROV, F. G. Method for determining the thermal state of the cylinder sleeve during centrifugal induction sintering. *BMSTU Journal of Mechanical Engineering* [online]. 2022, **8**(749), p. 33-41. ISSN 0536-1044, eISSN 2411-7196. Available from: https://doi.org/10.18698/0536-1044-2022-8-33-41

[3] WOS, P., MICHALSKI, J. Effect of initial cylinder liner honing surface roughness on aircraft piston engine performances. *Tribology Letters* [online]. 2011, **41**, p. 555-567. ISSN 1023-8883, eISSN 1573-2711. Available from: https://doi.org/10.1007/S11249-010-9733-Y

[4] MUSSABEKOV, M. O., BAKYT, G. B., OMIRBEK, A. M., BRUMERCIKOVA, E., BUKOVA, B. Shunting locomotives fuel and power resources decrease. *MATEC Web of Conferences* [online]. 2017, **134**, 00041. eISSN 2261-236X. Available from: https://doi.org/10.1051/matecconf/201713400041

[5] SETYAWATI, R. B., STULASTI, K. N. R., AZINUDDIN, Y. R., SUCI, W. G., ALIWARGA, H. K. (KIWI), DYARTANTI, E. R., PURWANTO, A. High power and thermal-stable of graphene modified LiNi0.8Mn0.1Co0.1O2 cathode by simple method for fast charging-enable lithium ion battery. *Results in Engineering* [online]. 2024, **21**, 101651. eISSN 2590-1230. Available from: https://doi.org/10.1016/j.rineng.2023.101651

[6] PRIEST, M., TAYLOR, C. M. Automobile engine tribology - approaching the surface. *Wear* [online]. 2000, **241**(2), p. 193-203. ISSN 0043-1648, eISSN 1873-2577. Available from: https://doi.org/10.1016/S0043-1648(00)00375-6

[7] MYAGKOV, L. L., SIVACHEV, V. M. Methods for determining the thermal state of medium-speed diesel engines taking into account boiling of the coolant. *BMSTU Journal of Mechanical Engineering* [online]. 2020, **7**(724), p. 22-28. ISSN 0536-1044, eISSN 2411-7196. Available from: http://doi.org/10.18698/0536-1044-2020-7-22-28

[8] TULENOV, A., BAUBEKOV, Y., BAKYT, G., BEKBOLATOV, G., TANSHANLO, M. Methodology for assessing the level of development and efficiency of the functioning of the traffic management system, taking into account the environmental factor. *Vibroengineering Procedia* [online]. 2024, **54**, p. 300-307. ISSN 2345-0533, eISSN 2538-8479. Available from: https://doi.org/10.21595/vp.2024.24066

[9] LIU, S., SHI, H., FENG, L. Transformer harmonic loss model considering skin effect and proximity effect. *Dianli Zidonghua Shebei / Electric Power Automation Equipment* [online]. 2015, **35**(3), p. 133-139. ISSN 1006-6047. Available from: http://doi.org/10.16081/j.issn.1006-6047.2015.03.021

[10] GRABON, W., PAWLUS, P., WOS, S., KOSZELA, W., WIECZOROWSKI, M. Evolutions of cylinder liner surface texture and tribological performance of piston ring-liner assembly. *Tribology International* [online]. 2018, **127**, p. 545-556. ISSN 0301-679X, eISSN 1879-2464. Available from: https://doi.org/10.1016/j.triboint.2018.07.011

[11] BAKYT, G., JAILAUBEKOV, Y., ABDULLAYEV, S., ASHIRBAYEV, G., ASHIRBAYEVA, I. Assessment of carbon dioxide emissions in road transport, using exhaust gas cleaning technology, in the Republic of Kazakhstan, *Vibroengineering Procedia* [online]. 2023, **48**, p. 87-92. ISSN 2345-0533, eISSN 2538-8479. Available from: https://doi.org/10.21595/vp.2023.23163

[12] CODREAN, M., CODREAN, M., NOVAC, M. C., NOVAC, O.-C., GORDAN, C., FARCAS, V. I. Analyzing the process of tempering a semifinished product using the FLUX2D and FEMM software. In: 2019 15th International Conference on Engineering of Modern Electric Systems EMES: proceedings [online]. IEEE. 2019. eISBN 978-1-7281-0773-8. Available from: https://doi.org/10.1109/EMES.2019.8795169

[13] DOYON, G., RUDNEV, V., RUSSELL, C., MAHER, J. Revolution not evolution-necessary to advance induction heat treating. *Advance Materials and Processes* [online]. 2017, **175**(6), p. 72-80. ISSN 0882-7958. Available from: https://doi.org/10.31399/asm.amp.2017-06.p072

[14] ABDULLAYEVA, A., KALABAYEVA, A., IVANOV, A., ABDULLAYEV, S., BAKYT, G. Methods for identification of complex industrial control objects on their accelerating characteristics. *Communications - Scientific Letters of the University of Zilina* [online]. 2022, **24**(3), p. B239-B246. ISSN 1335-4205, eISSN 2585-7878. Available from: https://doi.org/10.26552/com.C.2022.3.B239-B246

[15] PARK, H.-S. DANG, X.-P. Multiobjective optimization of the heating process for forging automotive crankshaft. *Journal of Manufacturing Science and Engineering* [online]. 2015, **137**(3), 031011. ISSN 1087-1357, eISSN 1528-8935. Available from: https://doi.org/10.1115/1.4029805

[16] XUN, W., JIE, Z., QIANG, L. Multi-objective optimization of medium frequency induction heating process for large diameter pipe bending. *Procedia Engineering* [online]. 2014, **81**, p. 2255-2260. ISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2014.10.317