Modeling wear process of oil scraper piston rings with pyrolytic chromium coating

V V Maksarov, V A Krasnyy, D A Klochkov

Saint-Petersburg Mining University, 2, 21 line V.O., 199106, St. Petersburg, Russia

E-mail: maks78.54@mail.ru

Abstract. The modern designs of oil scraper piston rings of internal combustion engines, including box-section rings with an expander are considered. Pyrolytic carbide of chrome coating of the working edges of oil scraper piston rings are proposed as a possible alternative to galvanic chromium coating. The results of model tribotechnical samples tests, which showed the effectiveness of pyrolytic chromium carbide plating in comparison with galvanic coating with chromium, are presented. Under the same conditions the wear of samples with pyrolytic chromium plating is 3.5 ... 4 times less. It is shown that pyrolytic carbide chromium coating is promising for piston oil scraper rings.

1. Introduction

Internal combustion engines (ICE) are widely used in mining equipment, including mining vehicles. The operating conditions of such machines are very severe. Thus, a haul truck, as a rule, moves up with a load, and down without it. When lifting, significant dynamic and vibrational loads on engine components arise, which often leads to increased wear of critical engine parts, primarily, a piston-cylinder group [1 ... 4].

Considerable attention is paid to improving the operational properties of machine parts and, in particular, ICE. As a rule, the main directions of increasing their wear resistance are the use of modern materials and coatings as well as the improvement of technological methods of manufacturing and the use of new types of equipment and tools [5 ... 15].

The operability of the cylinder-piston group components (piston rings, liners, pistons) largely determines the reliability and durability of internal combustion engines as a whole. It should be noted that it is the wear resistance of piston rings that is most often the limiting factor in the service lifetime which determines the engine overhaul necessity. At present, the requirements for high efficiency of internal combustion engines, in particular, fuel conservation, increased service lifetime and reduced oil consumption are becoming very significant.

Consequently, strict requirements are specified to piston rings both in terms of reducing breakdowns, burns, oil consumption and increasing its service lifetime, reducing friction and increasing gas-tightness.

According to a number of researchers [2 ... 4], up to 50% of ICE entire friction goes to the piston rings friction. Improving the operational properties of a piston rings working surface is achieved both by improving the materials used, machining activity and by applying modern wear-resistant coatings [16].

An O-ring consists of the following set of rings: compression, scraper and oil scraper (Figure 1).
The upper (compression) ring undergoes the most intensive wear due to being operated under the most severe conditions in the mode of semi-dry friction and high temperatures. At the same time, according to a number of researchers, the friction power of oil scraper rings is from 30 to 60% of the total piston ring set friction. Oil scraper piston rings are designed to remove excess oil from the walls of the cylinder liners and to dump it into an engine crankcase. In modern engine designs, oil scraper rings of box section with two narrow working edges and an internal expander are used to create the necessary ring elasticity (Figure 2).

![Figure 1. O-ring: compression ring, scraper ring, oil scraper ring of box with expander](image1)

The narrowness of working edges (up to 0.6 mm) in combination with a significant downward pressure against the cylinder walls posed by an expander (0.6 ... 1.2 MPa) create conditions leading to rapid wear during operation, which is manifested in relation to oil scraper rings in increased oil consumption through burning.

![Figure 2. Structure diagram of oil scraper piston ring with expander: 1 is ring, 2 is expander, 3 is chrome-coated working edges, 4 is drainage slot](image2)

An electrolytic coating with hard chrome is traditionally used to increase the wear resistance of the working edges of such rings. However, in addition to high energy intensity, the chrome coating of the working edges (scrapers) of an oil scraper ring presents serious technological difficulties. To obtain a high-quality coating, it is necessary to ensure particularly strict adherence to the conditions of the surface preparation and chrome coating modes. In addition, the tendency to hydrogen pickup and treeing during electrolytic chromium plating as well as the difficulty of subsequent grooves cutting for oil discharge should be taken into account. Some difficulties are presented by processing after chromium coating. Thus, when coating with chromium, there is a need to insulate a surface between
edges to ensure the subsequent drainage slot milling since such a treatment on the chrome surface is impractical due to the rapid wear of cutters. Cutting drainage slots before coating with chrome leads to the working surface uneven chroming.

The present work proposes coating oil scraper rings based on chromium carbide deposited by gas-phase pyrolysis, and presents the results of laboratory tribotechnical test of samples coated with electrolytic chromium and pyrolytic carbide chromium.

2. Materials and methods

Pyrolytic chrome coatings are applied in vacuum by decomposing the vapors of a mixture of chromium organic compounds (industrial liquid “Barchos”) at the temperature 400 ... 4500°C and the pressure 2x10⁻³ MPa. The resulting coating consists mainly of chromium carbide with the gross formula Cr₇C₃ and is characterized by high adhesion to the substrate material (30 MPA or more), microhardness of up to 20 ... 25 GPa.

In corrosive environments, pyrolytic chromium has a similar effect to a precious metal, and its wear resistance [17 ... 20] significantly exceeds the wear resistance of galvanic chromium. Heat resistance of coatings is an important property. As a result of heating, the hardness of pyrolytic carbide chromium coatings obtained by vapor deposition not decreases (like galvanic coatings do) but even increases. The decisive technological factor by which the wear resistance and microhardness of the coating can be controlled is the temperature of a substrate. A small amount of impurities (1 ... 3%) at the temperature of ~ 500°C result in coating films having a basic layered microstructure and containing separate inclusions, namely, globules (Cr₇C₃ single crystals), whose size varies depending on the temperature and deposition time in the range from 5 to 80 μm (Figure 3).

The application of pyrolytic chrome carbide coating is characterized by the greatest dispersion of the applied material, which results in high-quality coatings on products with a complex profile of a surface being processed. Moreover, the corrosion and erosion resistance of such coatings is higher than the structural elements (chromium and its carbides) included in their composition. Figure 4 presents some types of parts with the proposed coating.

We consider the possibility of applying such a coating to the working surface of oil scraper rings instead of traditional electrolytic chromium plating to be advantageous.

![Figure 3. Coating microsection of the (x500)](image)

![Figure 4. Chrome carbide coated components](image)

Tribo technical tests of the samples were carried out on the friction machine SMC-2 according to the “block-roller” (Figure 5a) and “roller-roller” (Figure 5b) schemes.

In the first test sequence (Scheme 5a), the comparative wear rate of the samples (with a coating on a rotating roller, block without coating, material of gray cast iron samples) in a lubricating oil MS-20 environment was evaluated. The roller and block were run-in before being coated. The coating
thickness for galvanic chromium was 60 ... 80 microns and for pyrolytic chromium it was 8 ... 10 microns. The contact temperature, estimated by the thermocouple, reached 96 ... 1000 °C, which corresponds to the operating conditions of piston rings. Testing each pair of samples lasted for 5 hours, while at the initial stage, stepwise loading (from 0.5 to 1.2 MPa) was carried out with a gradual increase in the frequency of the roller rotation (from 700 to 1200 min⁻¹). Wear of the samples was determined by being weighed on an electronic scales with a division value of 0.1 mg.

In the second series of tests (Scheme 5b), the wear rate of the combined surface “cast iron – carbidochrome” was compared with a pure cast iron surface. In the first group of friction pairs, only a fixed sample had the coating of pyrolytic chromium, in the second group castors made of cast iron without coating were used. The comparative wear was determined by using a microscope MPB-3 for measuring the width of a slot developed on the surface of a stationary roller.

The wear criterion, which was formed on the specimen after a predetermined test time (60 min), was taken as the wear criterion for testing samples with non-constant contact geometry. It is obvious that the best material in friction should have the smallest wear spot area under otherwise equal test conditions. The test time was chosen so that it was possible to obtain the area of the wear spot, which could be measured with sufficient accuracy using an optical instrumental microscope with a division value of 0.01 mm.

With this friction pattern, a wear slot is formed on the stationary sample during wearing. In order to simulate the wear process for measuring and comparing the area of the wear slot, the procedure described below was developed.

\[ A \] is the length of the slot in sliding direction, \( b \) is the width in perpendicular direction, and \( h \) is the height in the center of the slot. To calculate the volume and area of the wear spot of a rectangular shape under the condition of the misaligned contact of two cylinders, it is possible to carry out approximate calculations of the segment area using the following formula:

\[ S = \frac{a^2}{6D} = \frac{1}{3} ah, \]

and volumetric wear of a cylindrical sample along the width of the wear slot can be calculated using the following formula:

\[ V = \frac{a^2 b}{6D}, \]

where \( D \) is cylinder diameter.

For a comparative assessment, wear spots were assumed to be rectangular in terms of shape.

**Figure 5.** Test patterns: \( a \) is test pattern “block (1) – roller (2)”; \( b \) is test
pattern “stationary roller (1) – rotating roller (2)”;

3. Results and Discussion

The results of accelerated comparative tribological testing of chrome-coated rollers and cast-iron blocks on a friction machine are presented in Figure 6 in the form of comparative histograms.

The results analysis show that under the same conditions the wear of samples with pyrolytic chromium coating was 3.5 ... 4 times less than with galvanic one. At the same time, the wear of the mating counter-pattern was significantly reduced (5 ... 10 times), which made it possible to simulate the wear of a cylinder liner paired with the ring. A similar phenomenon can be explained by the absence of dendrites on the surface of pyrolytic chromium and a lesser tendency to abrasive wear.

At the same time, the possibility of applying an oil scraper ring of galvanic chromium of significantly greater thickness (60 ... 80 microns) than pyrolytic chromium coating (10 ... 12 microns) to working edges, at first glance undermines the practical significance of the results. However, it should be born in mind that in addition to the high energy intensity of the electrolytic chromium coating process, the coating is present only on the working surface of the edge, and after its operation, actually increased wear of the cast iron substrate begins. At the same time, the working edges of the used oil scraper rings are often completely worn out. Pyrolytic chrome coating is performed on the finished rings and creates a coating on the entire ring surface, including lateral chamfers. Therefore, after the coating is activated, an inhomogeneous surface consisting of gray cast iron of the substrate in the middle and pyrolytic chromium at the edges is created on the edge.

Figure 6. Outcomes of averaged laboratory test results of sample wear (in mg) according to scheme 5a: a are rollers coated with galvanic (1) and pyrolytic (2) chromium; b are cast iron counterbricks run together with the corresponding rollers

In order to simulate the wear process of such a combined surface, specifically, cast iron – carbidechrome surface in comparison with a cast iron one, tests were carried out according to the scheme shown in Figure 5b, and based on measuring the area of the wear spot S of a fixed sample. Figure 7 presents the results demonstrating that the wear of the combined pair with the coating is much lower. This indicates that even after the wear of chromium on the working edges of the rings, pyrolytic chrome stored on the sides of the edges continues to have a significant effect on reducing wear on working edges. Thus, simulating a two-stage process wear process (before the chromium wear on the working surfaces and after wear while maintaining chromium on the sides) it can be stated that, in general, the wear resistance of oil scraper rings with pyrolytic chromium plating will be higher than
even with galvanic chrome coating of greater thickness. In addition, the simplification of the manufacturing process of oil scraper rings and the reduction of energy consumption during pyrolytic chromium coating should be considered.

![Graph](image)

**Figure 7.** Dependence of the dynamics of the increase in the wear spot $S$ on a stationary roller with test scheme 5b: (1 is sample with a coating, 2 is sample without a coating) on the test time $t$ for the same initial wear spot

4. Conclusion

Thus, testing the samples of oil scraper rings with a pyrolytic carbide chrome coating showed that they outperformed the samples that are electrolytically chrome coated in tribological performance.

The proposed technology is promising for piston oil scraper rings. It simplifies the manufacturing process and significantly reduces its energy consumption.

5. Acknowledgments

This article was prepared with the support of the project of the state task № 0792-2018-0008.

References

[1] Xu X, Sun S, Wang P A and Lei Peng G 2015 *Tribol. Online* **10** 172-176
[2] Söderfjäll M 2017 Friction in Piston Ring—Cylinder Liner Contacts, Luleå University of Technology, Graphic Production: Luleå, Sweden
[3] Pachaiyappan I, Thamildorai N and Mani K 2019 *IOP Conf. Series: Journal of Physics: Conf. Series* **1240** 012003
[4] Rozario A, Baumann C and Shah R 2019 *Lubricants* **7** 8
[5] Bolobov V I and Thanh B Le 2018 *Journal of Mining Institute* **233** 508-512 DOI: 10.31897/pmi.2018.5.525
[6] Chupin S A and Bolobov V I 2018 *Materials Science Forum* **945** 695-699 DOI: 10.4028/www.scientific.net/MSF.945.695
[7] Zverev E A, Skeeba V Yu, Martyushev N V and Skeeba P Yu 2017 *Key Engineering Materials* **736** 132-137
[8] Samoylenko V V, Lenivtseva O G, Polyakov I A et al 2016 *IOP Conf. Ser.: Mater. Sci. and
[9] Sivenkov A V, Konchus D A, Nikitina V O, Serdiuk N A and Priyhin E I 2019 IOP Conf. Ser.: Mater. Sci. and Engineer 560 012188 DOI: 10.1088/1757-899X/560/1/012188
[10] Martynov S A and Bazhin V Y 2019 Journal of Physics: Conference Series 1399 1 - 5
[11] Gabov V V and Zadkov D A 2017 IOP Conf. Series: Earth and Environmental Science 87 22007 DOI: 10.1088/1755-1315/87/2/022007
[12] Maksarov V V and Keksin A I 2018 IOP Conference Series: Materials Science and Engineering 327 (4) 42068.
[13] Olt J, Efimov A E and Maksarov V V 2019 Agronomy Research 17 (1) 1146 - 1154
[14] Ershov D Y, Timofeev D Y and Zlotnikov E G 2019 IOP Conference Series: Materials Science and Engineering 560 (1) 12015
[15] Khalimonenko A D, Timofeev D Y and Golikov T S 2019 Journal of Physics: Conference Series 1399 (4) 44082 DOI: 10.1088/1742-6596/1399/4/044082
[16] Krasnyy V A, Vazhenin A Y 2018 AER - Advances in Engineering Research 177 213 - 217
[17] Vodnik D R, Petersen R J, Bennett B L, Hubbard K M, Patterson B M and all 2020 Nuclear Technology 206 (1) 23-31
[18] Vasin V A, Krit B L, Nevrovskii V A and Somov O V 2016 Surface Engineering and Applied Electrochemistry 52(5) 475-479
[19] Michau A, Maury F, Schuster F, Boichot R, Michel Pons et al 2017 Surface and Coatings Technology, Elsevier 332 96 - 104
[20] Vasin V A, Prozhega M V and Somov O V 2014 Poroshkovaya metallurgiya i funktsional’nye pokrytiya 2 50-54