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Wear Resistance Research and Its 2-factor Modeling of Nanoscaled Silicon Carbide Detonation Coatings

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Abstract

This research is related to the spheres of wearproof coating testing. The SiC coating has been deposited on the medium carbon steel using detonation deposition using the magnet coil flux of back direction. It has been established that only nanoscaled particles are deposited on the surface which had been accumulated in aggregates of different shape. The structure of the obtained coating has been thoroughly researched on the electronic microscope in previous publication. The obtained coating has been developed for testing on the friction bench modeling the friction process that is taking place in the couple of main and rod journals of internal combustion engines. The coating has also the corrosion protection properties. The nanoscaled coating on mild carbon steel had been tested under specified conditions and their friction surfaces had been researched on electronic microscope with the view of determination of wear mechanism. The two-factor modeling of the wear rate and friction factor has been done and three-dimensional diagrams have been plotted and analyzed.

Key words: wear, wear rate, friction factor, nanoscaled coating, detonation coating deposition, magnet modified deposition

Introduction

The lifetime of the internal combustion engine elements can be improved by wearproof coatings deposited by different methods. The main component of coating suggested is the silicon carbide SiC and as the bond for it the alumina has been selected. Having the good hardness all these elements are of well abrasive properties, but not in small gain sizes. If the granularity of these abrasives is no bigger than 5 micrometers they did not wear the steel surfaces owing two features. The first one is too small size of particles makes the smallest scratches on surface resulting in so-called surface polishing to mirror roughness grade. The second one this dimension of particles “fills” the generic steel roughness cavities thus increasing the friction contact area and reducing the contact pressure. So, the abrasive particles sized less than 5 micrometers is not “wear abrasive” that increases the wear, but it is “run-in abrasive” that decreases the wear of steel surface. It has been proven several times using the compact fine grain material made of silicon carbide and alumina when mixed and milled up to less than 5 micrometer granularity and avoiding recrystallization processes during the material synthesis as well as the same fine grained coating on the steel surface. Recently, the nanoscaled coating (100 micrometers thick) had been acquired [3] and its structure has been investigated. This study is devoted to tribotechnical investigation of these coatings, establishing the wear mechanisms and results modeling.

Review of the latest research

Formerly [1], the specific way acquired batch mixture of $SiC\text{-}Al_2O_3$ (which was milled in steel vessels by steel milling bodies in 32 hours up to 2,1 micrometers average particle granularity) content, which had the iron millings in the batch mixture charge, was used for acquisition of wearproof coating deposition by detonation method modified by magnetic field. So it had been established on direct polarity of coil magnet the microparticles of silicon carbide and alumina had been deposited on the substrate. The coating had demonstrated not only high wear resistance 40-55 micrometers/km and friction factor 0,42-0.45 [1], but also high wear resistance at elevated temperatures up to 500°C it makes 40-55 micrometers/km and friction factor 0,32-0.34 [2] due to formation of the glass-like superficial structures reducing the wear rate and friction factor comparing with the 250°C.

Using the gas detonation deposition from the batch mixture which contains the silicon carbide and aluminum oxide particles, with the steel millings which have a size from 250-400 nanometers, on the direct polarity the fine grained microstructure is acquired and on the reverse polarity of the magnet coil the nanostructure the particles of 70,9, 115,2, 76,5, 54,0, 50,5, 65,6, 82,9 and 73,0 nanometers had been acquired [3] and its structure had been thoroughly researched. The present paper is devoted to research the tribotechnical descriptions of these coatings.

Scientific interest to silicon carbide coatings is growing throughout the world.

So, in article [4] researchers had investigated the laser-prepared SiC nanocoating: preparation, properties and high-temperature oxidation performance. The SiC nanocoatings were prepared on graphite substrates via a laser treatment process. A high-temperature oxidation test was also conducted to determine their antioxidation performance. The results show that laser irradiation triggers the transformation from micro SiC particles into SiC nanocoating consisting of numerous polycrystalline SiC nanoparticles. At the laser energy density of 10.42 kJ/cm^2, the prepared SiC nanocoating reveals the best oxidation resistance at a high-temperature environment in tested samples [4].

Scientists publishing paper [5] have been studying silicon carbide coatings produced at different deposition conditions with use of high temperature nanoindentation. So, The elastic modulus and hardness of different silicon carbide (SiC) coatings in tristructural-isotropic fuel particles were measured by in situ high temperature nanoindentation up to 500 °C. Three samples fabricated by different research institutions were compared. Due to varied fabrication parameters the samples exhibited different grain sizes and one contained some visible porosity. However, irrespective of the microstructural features in each case the hardness was found to be very similar in the three coatings around 35 GPa at room temperature. The elastic modulus differed for the three tristructural-isotropic coatings with room temperature values ranging from 340 to 400 GPa [5].

The research [6] signifies an attempt to apply composite coating by co-deposition coating and assessing, enhancement the Nickel coatings features, by adding the particles of silicon-carbide to solution of electrodeposited. Stainless steel specimens have been subject to electroplating coating utilizing Nickel and Nano silicon carbide particles (70-100 nm) with various amounts (16, 24, 32 and 40) g/L. After coating, the specimens were tested by SEM, AFM, impeded in a solution with 3.5 percent NaCl to investigate the corrosion performance. Then testing the microhardness, and wear resistance. Results obtained from this work showed a great reduction in corrosion currents caused by adding of inert nanoparticles. These enhancements had been detected on all conducted tests for corrosion and wear.

So, in article [7] researchers had investigated the strengthening and thermal stabilization of polyurethane nanocomposites with silicon carbide nanoparticles by a surface-initiated-polymerization approach. Silicon carbide reinforced polyurethane nanocomposites were fabricated by a facile surface-initiated-polymerization (SIP) method. The particle loading was tuned to up to 35 wt% without any obvious shrinkage and breakage as compared with the conventional direct mixing method. An increased thermal stability of the composites was observed with the addition of the silicon carbide nanoparticles under thermo-gravimetric analysis (TGA). Tensile strength was observed to increase dramatically with the increase of the particle loading. Both the uniform particle dispersion and the strong chemical bonding between the nanoparticles and the polymer–matrix contributed to the enhanced thermal stability and improved mechanical properties.

Scientists publishing paper [8] have been studying the compacting of silicon carbide nanopowder in high-pressure device. The nanopowders of silicon carbide were sintered under the pressure from 3,5 GPa and under the temperatures 1600-1800 °C. So the obtained materials had the following properties: density - 3,07-3,20 g/cm^3; microhardness – 15-30 GPa; porosity – 1,2-4,4 and weight wear rate – 0,0061-0,0462 g/cm^2. On the SEM images the big grain growth had been noticed.

The research [9] is about the synthesis of silicon carbide nanoparticles exhibiting monolayer to few-layer graphene coatings and characterizes their optical response to confirm their plasmonic behavior. A multistep, low temperature plasma process is used to nucleate silicon particles, carbonize them in-flight to give small silicon carbide nanocrystals, and coat them in-flight with a graphene shell. These particles show surface plasmon resonance in the infrared region. Tuning of the plasma parameters allows control over the nanoparticle size and consequently over the absorption peak position. A simplified equivalent dielectric permittivity model shows excellent agreement with the experimental data. In addition, optical characterization at high temperatures confirms the stability of their optical properties, making this material attractive for a broad range of applications.

In the paper [10] researchers have discovered the development and characterization of silicon carbide coating on graphite substrate. The development of materials with unique and improved properties using low cost processes is essential to increase performance and reduce cost of the solid rocket motors. Specifically, advancements are needed for boost phase nozzle. As these motors operate at very high pressure and temperatures, the nozzle must survive high thermal stresses with minimal erosion to maintain performance. Currently three material choices are being exploited; which are refractory metals, graphite and carbon-carbon composites. Of these three materials graphite is the most attractive choice because of its low cost, light weight, and easy forming. However, graphite is prone to erosion, both chemical and mechanical, which may affect the ballistic conditions and mechanical properties of the nozzle. To minimize this erosion Pyrolytic Graphite (PG) coating inside the nozzle is used. However, PG coating is prone to cracking and spallation along with very cumbersome deposition process. Another possible methodology to avoid this erosion is to convert the inside surface of the rocket nozzle to Silicon Carbide (SiC), which is very erosion resistant and have much better thermal stability compared to graphite and even PG. Due to its functionally gradient nature such a layer will be very adherent and resistant to spallation. Despite its very good adhesion due to its functionally gradient nature, this layer due to its porous nature exhibit poor oxidation performance compared to a dense SiC layer. The research [10] is focused on synthesizing, characterizing and oxidation testing of a bi-layer; a functionally gradient inner layer and dense outer layer, SiC coating on graphite.

In the article [11] researchers had investigated the fabrication of silicon carbide (SiC) coatings from pyrolysis of polycarbosilane/aluminum. So, the SiC coatings were fabricated by the pyrolysis of polycarbosilane (PCS)/aluminum, in which PCS acts as preceramic precursor of SiC and aluminum (Al) powder acts as an active filler to both compensate the volume shrinkage of SiC coatings during pyrolysis and enhance the adhesion of SiC coatings with Ferroalloy substrate. SiC coatings as thick as ~35 lm without cracking can be fabricated through our approach. Microstructural analysis revealed that the SiC coatings were composed of α-Al2O3 and β-SiC. Hardness and modulus of the SiC coatings as measured by nano-indentation were 12.2 ± 4.0 and 153.7 ± 47.0 GPa, respectively

Scientists publishing paper [12] have been studying high-performance Ni-SiC coatings fabricated by flash heating. In this research, a novel flash heating coating application technique was utilized to create Ni-SiC coatings on carbon steel substrates with SiC contents much higher than is achievable using certain conventional coating techniques. Hardness profiles showed that the coatings improved the substrate by as much as 121%, without affecting the substrate. Tribotests showed that the wear performance was improved by as much as 4.7 times in terms of the wear rate ($mm^3/N*m$) for the same coating when using an Al_2O_3 counterpart. Pure SiC coatings as a reference were also fabricated. However, the SiC coatings experienced elemental diffusion of Fe from the carbon steel substrate into the coating during fabrication. This occurred due to the increased heat input required for pure SiC to fuse to the substrate compared to the Ni-SiC coatings and resulted in decreased tribological performance. Diffusion of Fe into the coating weakened the coating’s hardness and reduced the resistance to wear. It was concluded that ceramic–metallic composite coatings can successfully be fabricated utilizing this novel flash heating technique to improve the wear resistance of ceramic counterparts.

The research [13] is about the wear characterization and microstructure evaluation of silicon carbide based nano composite coating using plasma spraying. So there thin films of various thickness of SiC – Al_20_3 composite is deposited on aluminum alloy 6061 using Plasma spraying process. Wear tests on pin-on-disc tester is conducted to compare the wear characteristics of uncoated and coated samples. The micro hardness tests of coated samples and uncoated samples are compared. The microstructure characterization of the Nano-coated films using Scanning Electron Microscope (SEM) of the samples is studied. The results and studies clearly depicts that the major variations in coating performance can be obtained by exploiting proper plasma spray conditions and optimum percentage of SiC – Al_20_3 in composite coatings.

In the paper [14] researchers have discovered the tribological behavior of thermally sprayed silicon carbide coatings. SiC coatings have been successfully deposited using thermal spray detonation technique with a newly patented feedstock. Their tribological performance was compared to bulk SiC for dry and lubricated conditions (polyalphaolefin and 3.5 wt% NaCl solution).The lowest coefficient of friction (CoF=0.10) and wear-rate were detected with polyalphaolefin lubricant regardless of the test pair due to mixed fluid film lubrication. Contradicting results were recorded under other test conditions. The coatings show low CoF of 0.20 in comparison to four times higher CoF of bulk SiC under dry sliding. Oppositely, SiC coatings in NaCl solution record five times higher CoF compared to bulk SiC CoF of 0.20. Such behavior is associated with tribochemical reaction and tribo-corrosion mechanisms occurring in dry and NaCl sliding, respectively.

Scientists publishing paper [15] have been studying the properties features of nanostructured silicon carbide films and coatings, acquired by new method. There the new method of nanostructured silicon carbide films and coatings acquisition, which structure can be changed depending on the application industry, had been developed. Acquired films and coatings are suitable for use in metallurgy, nuclear power industry, microelectronics and in high-temperature stoves. The nanostructures coatings were acquired from the silicon vapors and gaseous carbon under high temperatures, and changing the supply speed, pressure and temperature the grains sizes of silicon carbide in coating can also be changed. Some improved properties of acquired coatings had been revealed.

So, as it can be already seen, the great worldwide interest to silicon carbide coatings in different application areas is continuously growing and any research is worthy to promote the scientific progress.

Research aim

Scientific development of nanoscaled composition coatings for crank shaft journal of internal combustion engines.

Originating from the aim of article paper the following tasks of research were preset:

1. Simulating the friction conditions similar to crank shaft journals of internal combustion engine without lubricant.
2. Nanoscaled coatings wear testing and their friction surfaces research.
3. Modeling the wear rate and friction factor of the nanoscaled silicon carbide coatings in the preset ranges of factors.

Research methodology

For study of interactions between properties of coatings with their phase composition and structure, and also an external factors influence the choice of research methods has the great importance. The receiving of reliable results of research in this work is provided by modern equipment and devices, approved methodologies, necessary productivity of experiments, by careful treatment of specimens before and after the experiment, strict adherence of order of experiment.

For receiving a charge of silicon carbide ceramics with aluminum oxide admixtures, the starting powders were used: silicon carbide grade 64C (ГОСТ 26 327-84) with an average size of 45-55 µm, aluminum oxide (ТУ 6-09-03-350-73) with particles of average size 45 -50 microns.

The chemical content of the initial powders and possible admixtures is given in Table 1.

Table 1

Results of analysis of initial powders in masses. %

Powder name	Al	Si	Mg	Fe	Ni	Cr	Ti	Ca	Zr	Ag	Cu
SiC	10^{-3}	maj.	10^{-4}	10^{-3}	-	-	-	10^{-4}	-	-	-
Al_2O_3	maj.	-	10^{-3}	>0,1	>1	0,01	-	-	-	10^{-4}	10^{-3}

The common procedure for the formation of composite materials from the initial powders is their mutual mixing and grinding.

For acquisition of SiC-based coating the batch mixture charge with 50% Al_2O_3 additive, and the powders components in the appropriate proportions were mixed with simultaneously grinded for 32 hours in the laboratory planetary mill Sand-1 in an alcohol (ethanol) medium in order to avoid particles agglutination.

In this case, the table rotational speed was 648 rpm, the drum vessels rotation speed was 1620 rpm throughout 32 hours. To prepare the charge, the steel vessels of 340 cm^3 volume and steel grinding bodies (balls) made of steel of ШХ15 with a diameter of 10-15 mm were used.

The ratio of the batch mixture charge mass to the grinding bodies (balls) mass is 1: 3. After grinding, the batch mixture charge was dried and sifted to avoid lumps and clods. The granulometric composition of the resulting mixtures after milling was determined in aqueous media on a laser microanalyzer "SK Lazer Micron Sizer PRO 7000" and average particle size makes about 2,1 micrometers. Content and size of nanoscaled particles have not been determined in any technique.

Coatings in the work were deposited by the detonation method on the installation “Dnepr-3M” detonation-gas installation is intended for coating made of metal powders, hard alloys, ceramics and composite materials on the surfaces of machine parts, devices, apparatuses and tools during their manufacture, as well as reconditioning. On the barrel of detonation installation the magnet coil of the reverse polarity current was fed in it. Thus the iron millings had retardated the microsized particles, but not nanosized. The coating thickness varied about 60 micrometers after about 120 shots of detonation installation barrel (so approximately 0,5 micrometer per shot) [3] comparing with the microstructural coating 200 micrometers per 30 shots (so approximately 5 micrometer per shot) [1-2]. So the about 90% of batch mixture charge was wasted, what allows making the conclusion the amount of nanosized particles was about ~10% (overwhelming majority of nanoscaled particles is SiC) The content of the nanoparticles is about 85% of SiC, 10% of Al_2O_3 and 5% of Fe_2C. No metallic particles were detected in the coating content. Coating thickness was about 50-60 micrometers. Within the 40 000 electronic zoom [3] the particles of 70,9, 115,2, 76,5, 54,0, 50,5, 65,6, 82,9 and 73,0 nanometers are acquired

For research of structure and phase composition of the structure and phase content of coating on the basis ($SiC-Al_2O_3$), and also their friction surfaces was conducted by SEM microscopy and micro X-ray spectral analyses, X-ray-phase (ДРОН-2.0 in $Cu_{k\alpha}$ -radiation).

Composite coatings (charge of $SiC-Al_2O_3$ after 32 hours milling deposited by detonation through the reverse magnet) were testes on the friction test machine MT-89 of Institute for Problems of Materials Science under the loads from 0.2 to 15 MPa and under the friction speeds from 0.2 to 20 m/sec. Friction layout is “pin-on-shaft” without lubricants. The coating has been deposited on the pin surface.

Research results and discussion

Modeling of the wear resistance process of the composition coatings for crankshaft journal of internal combustion engines has demonstrated the following results. The range of factors was divided on the three levels of change (table.2.)

Table 2

Conditions of research of wear resistance of nanocomposite coatings in conditions of high load wear

Factors	Load X_1, P, [MPa]	Speed X_2, V, [m/s]
Top level (+1)	15	20
Lower level (-1)	0,2	0,2
Basic level (0)	7,5	10
Variable interval (J)	7,5	10

The experimental results of wear rate (micrometers/kilometer) and friction factor (unitless) were recorded to relevant factors in the model matrix (table 3.)

Table 3

Central noncomposite rotatable matrix of the 2nd order for number of factors K = 2

№ of experiment	Factors						Experimental data on proper factor level		Model-estimated data on proper factor level	
	X_0	X_1	X_2	X_1X_2	X_1^2	X_2^2	Y_1	Y_2	Y_1	Y_2
1	1	1	1	1	1	1	14,1	0,25	48,29	0,40
2	1	1	-1	-1	1	1	0,9	0,19	2,73	0,20
3	1	-1	1	-1	1	1	19,3	0,31	57,73	0,57
4	1	-1	-1	1	1	1	1,3	0,24	9,29	0,37
5	1	1	0	0	1	0	10,1	0,22	24,20	0,23
6	1	0	1	0	0	1	16,8	0,28	50,11	0,42
7	1	-1	0	0	1	0	12,5	0,28	32,20	0,40
8	1	0	-1	0	0	1	1	0,21	3,11	0,22
9	1	0	0	0	0	0	10,3	0,25	10,30	0,25

Response function of experimental data for modeling: Y_1 is linear wear rate (I, μm/km). Y_2 is a friction factor.

The function of response in the factor space has the mathematic expression: $Y = B_0 + B_1X_1 + B_2X_2 + B_{12}X_1X_2 + B_{11}X_1^2 + B_{22}X_2^2$

Finally, when the coefficients B were calculated and after their statistical significance check. the models, obtained after rotatable planning of the second power order, have the mathematic expression:

For wear rate Y_1 (fig 1.): $Y_1=10,3-4X1+23,5X_2-0,72X_1X_2+2,896X_1^2+1,312X_2^2$.

For friction factor Y_2 (fig 2.): $Y_2=0,25-0,085X1+0,1X_2-0,0015X_1X_2+0,0697X_1^2+0,0664X_2^2$.

According to the data, two-dimensional graphic dependencies were plotted (fig. 1. and 2.). Thus, an analysis of the effect of all two factors both the load and friction speed to wear rate and friction factor are held.

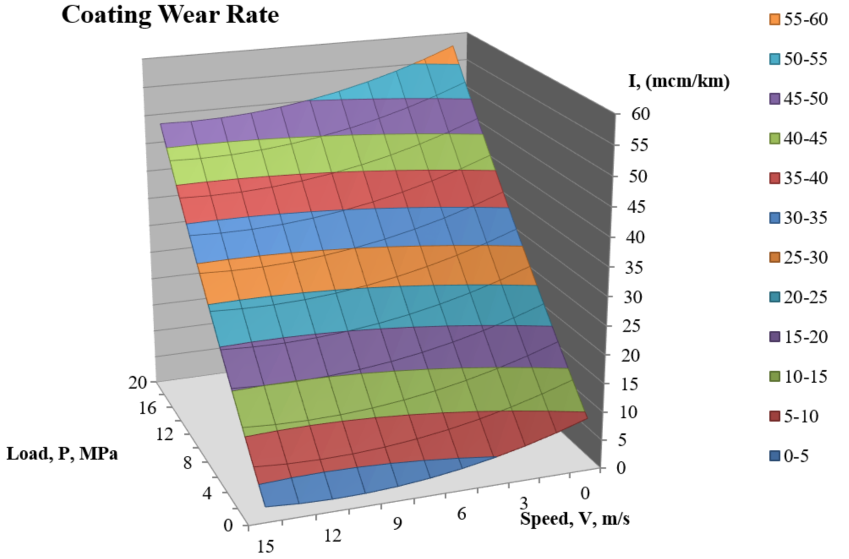


Fig. 1. Diagram of wear rate modeling of nanoscaled coating from friction speed and contact load

The developed model allows to comprehensively and visually estimating the influence of factors on the desired function of the response, to carry out optimization measures and mathematical processing of regression dependence, like a derivation and the precise optimum detection.

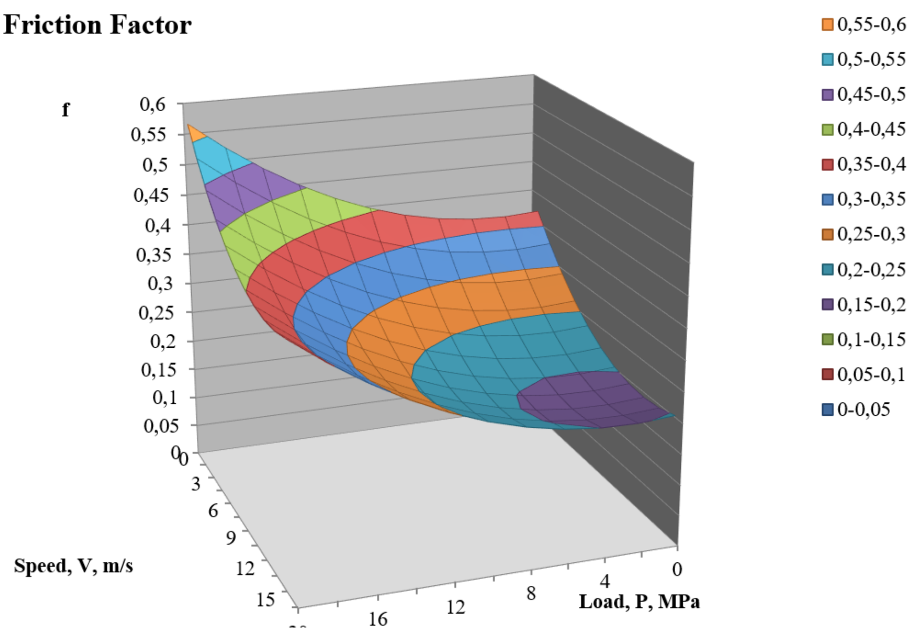
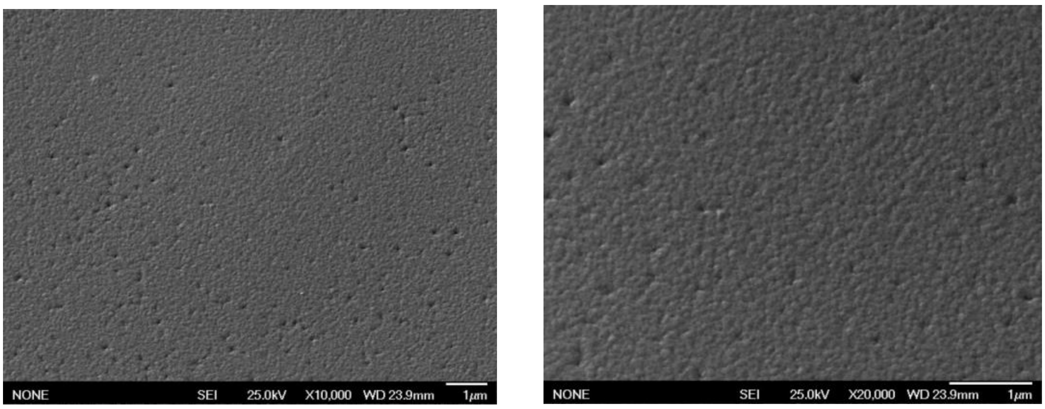


Fig. 2. Diagram of friction factor modeling of nanoscaled coating from friction speed and contact load.

The optimum friction modes of the nanoscaled particles coating is the following. The minimal wear of the coating is 2,18 micrometers per kilometer path under the modes: speed 12,5 m/s and load 0,2 MPa, and the minimal friction factor is 0,188536 for the load 12,5 m/s and load 17,5 MPa. It is about sparing run-in process, but the working modes of the coating 20 MPs and 15 m/s the wear rate of the coating will be 48,288 micrometers per kilometer and the friction factor will be 0.3996. Totally the nanoscaled coating will work in the antifriction mode so as the friction factor will be less than 0,4.

Wear mechanisms of the nanoscaled coatings for crankshaft journal of internal combustion engine were researched using the scanning electronic microscopy (SEM) images.

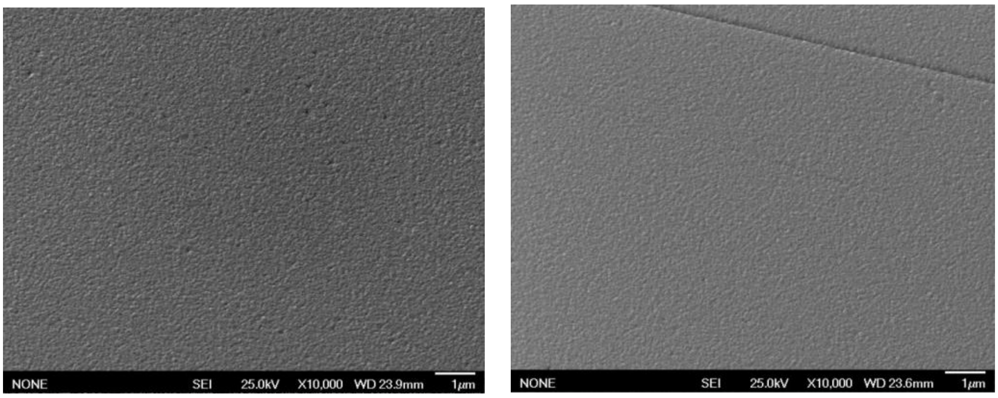
The tests were carried out at sliding speeds of 0,2-15 m/s and loads of 0,2-25 MPa, which simulates the work of the contact area of the “crank shaft journal-insert” elements of medium load intensity. As a counterbody: steel X16H4 (HRC 60-64) was used, since it is the material of the ICE crank shaft journal inserts. For the explanation of the results of the friction and detection of wear mechanism let’s consider the friction surfaces of the coating investigated on the microscope. For the convenience of comparison let’s consider the initial surfaces (fig. 3.). So the initial view of the friction surfaces are about the presence of even, uniform and similar grain structure under the 10000 and 20000 electron zoom (excepting some pits between the elements of the structure).



a) b)

Fig. 3. SEM-images of the Initial Surfaces of the Nanoscaled Detonation Coatings: a) 10 000 zoom; b) 20 000 zoom.

After application of small loads the compacting of the friction surface is observed unlike a rough surface of initial surfaces [3]. And even creation of the some friction lines are detected on the friction surfaces those are not detected under the light optical observation under the magnifying lens (fig. 4.).

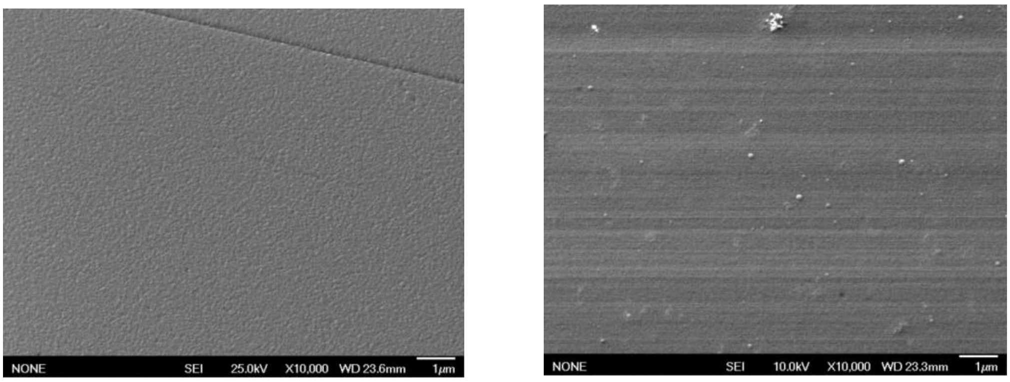


a) b)

Fig. 4. SEM-images of the Friction Surfaces of the Nanoscaled Detonation Coatings under the 0,2 MPa load (15 m/s) 10 000 zoom: a) 1 stripe area; b) 2 stripe area.

So the analysis of the fig. 4. is about the formation of the compact friction surface and even some friction lines are seen on the surface. So as the surface roughness was satisfactorily, the single wear stripes were created due to formation of the big wear products and those are scaring the surface deeply. Son under the smallest friction load the compaction of the friction surface was noticed and surfaces do not have the pores and cavities the initial surfaces have.

When increasing the load to 20 MPa on the friction bench MT-89 on the scanning microscope images (fig. 5.) the even uniform wear was detected of value 19,3 micrometer per kilometer. So well friction stripes were observed on the friction surfaces. The wear process was liked a burn out from the MT-89 test specimens.



a) b)

Fig. 5. SEM-images of Sliding Friction Surfaces of the Coatings Developed (10 000 zoom): a) under 0,2 MPa load; b) under 20 MPa load

The chemical content made by microscope X-ray analyzer of the top surface layer was of the following oxides: SiO_2, Al_2O_3, FeO and Fe_2O_3 and pure iron was detected as well, what was proven by X-ray phase analysis. So the wear mechanism is close to oxidative one.

Conclusions

Using the gas detonation deposition from the batch mixture which contains the silicon carbide and aluminum oxide particles, which have particle of iron sized from 250-400 nm, on the direct polarity the fine grained microstructure is acquired and on the reverse polarity the nanostructure the particles of 70,9, 115,2, 76,5, 54,0, 50,5, 65,6, 82,9 and 73,0 nanometers [3] had been acquired.

Under the friction modes the nanoscaled particles coating compacting and formation of an integral protection layer had been detected using the scanning electron microscopy and low wear rate and friction factors were detected and acquired.

As a result of the mathematical modeling of the experimental data obtained by the polynomial regression dependence of the 2nd order for 2 factors, taking into account all experimental data, it was established the optimum for these coatings use. The optimum friction modes of the nanoscaled particles coating is the following. The minimal wear of the coating is 2,18 micrometers per kilometer path under the modes: speed 12,5 m/s and load 0,2 MPa, and the minimal friction factor is 0,188536 for the load 12,5 m/s and load 17,5 MPa. It is about sparing run-in process, but the working modes of the coating 20 MPs and 15 m/s the wear rate of the coating will be 48,288 micrometers per kilometer and the friction factor will be 0.3996. Totally the nanoscaled coating will work in the antifriction mode so as the friction factor will be less than 0,4.

References

1. A. Dovgal, L. Pryimak, I. Trofimov A Modified Method of Applying Detonation-Sprayed Composite Coatings by a Magnetic Field.// Eastern-European Journal of Enterprise Technologies.– Volume 6/5 (84). – 2016. – P. 33-38.

2. L. Pryimak, A. Dovgal, Ye. Puhachevska Analysis of Structure and Tribotechnic Properties of Plasma Carbide-Silicon Coatings Under Conditions of Elevated Temperatures // Eastern-European Journal of Enterprise Technologies. – Volume 1/5 (85). – 2017. – P. 46-53.

3. A.H. Dovhal*, L.B. Pryimak Structure research of nanoscaled silicon carbide detonation coatings of tribotechnical application, Problems of Tribology, V. 27, No 1/103-2022, P. 26-33.

4. XiaodongHu, Rongjie Jiang, Fang Luo, Yuanhang Lu, Yuxin Wang and Zhen He The laser-prepared SiC nanocoating: preparation, properties and high-temperature oxidation performance. // Mater. Res. Express 8 (2021) 085003 pp. 1-12.

5. Nadia Rohbeck, Dimitrios Tsivoulas, Ian P. Shapiro, Ping Xiao, Steven Knol, Jean-Michel Escleine, Marc Perez, and Bing Liu Comparison study of silicon carbide coatings produced at different deposition conditions with use of high temperature nanoindentation // J Mater Sci (2017) 52: pp. 1868–1882.

6. Nawal Mohammed Dawood, Nabaa S. Radhi, Zainab S. Al-Khafaji Investigation Corosion and Wear Behaviour of Nickel Nano-Silicon Carbide on Stainless Steel 316L // Material Science Forum, Vol. 1002, 2020, pp. 33-43.

7. Zhanhu Guo, Ta Y. Kim, Kenny Lei, Tony Pereira, Jonathan G. Sugar, H. Thomas Hahn Strengthening and thermal stabilization of polyurethane nanocomposites with silicon carbide nanoparticles by a surface-initiated-polymerization approach // Composites Science and Technology N 68 (2008) pp. 164–170.

8. А. П. Гаршин, С. П. Богданов, В. А. Пономаренко Компактирование нанопорошка карбида кремния в аппарате высокого давления // Порошковая металлургия: Инженерия поверхности, новые порошковые композиционные материалы, сварка. Сборник докладов 9-го международного симпозиумаМинск, 8-10 апреля 2015 года. с. 288-297.

9. Devin Coleman and Lorenzo Mangolini Plasmonic Core−Shell Silicon Carbide−Graphene Nanoparticles // Material Science & Engineering Program and Mechanical Engineering Department, University of California, Riverside, Riverside, California 92521, United States, ACS Omega Press 2019, N 4, pp. 10089−10093.

10. F Z Mohammad, M Akhtar Sharif, M Anas Ahmed, Muhammad Suhail. Development and Characterization of Silicon Carbide Coating on Graphite Substrate. // J Chem Edu Res Prac, 2022, N 6 (2), pp. 258-266.

11. Daxiang Yang, Yuxi Yu, Xiaofeng Zhao, Yongcai Song, Eddie Lopez-Honorato, Ping Xiao, Delin Lai Fabrication of Silicon Carbide (SiC) Coatings from Pyrolysis of Polycarbosilane/Aluminum // J Inorg Organomet Polym (2011) N 21 pp:534–540.

12. Peter Renner, Ajinkya Raut and Hong Liang High-Performance Ni-SiC Coatings Fabricated by Flash Heating // Lubricants 2022, 10, 42 pp.1-20. https://doi.org/10.3390/lubricants10030042

13. S.M.Muneera, M.Nadeerab Wear characterization and microstructure evaluation of silicon carbide based nano composite coating using plasma spraying // Materials Today Proceedings Volume 5, Issue 11, Part 3, 2018, Pages 23834-23843.

14. F. Mubarok, N. Espallargas Tribological behaviour of thermally sprayed silicon carbide coatings // Tribology International, N 85 (2015) pp. 56–65.

15. К. Н. Филонов, В. Н. Курлов, Н. В. Классен, Е. А. Кудренко, Э. А. Штейнман Особенности свойств наноструктурированных карбидокремниевых пленок и покрытий, полученных новым способом. // Известия РАН. Серия физическая, 2009, том 73, № 10, с. 1457–1459.

А. Г. Довгаль, Л. Б. Приймак, В. В. Варюхно. Дослідження та двофакторне моделювання зносостійкості нанорозмірних карбідокремнієвих детонаційних покриттів

Це дослідження пов'язане з галузями, випробування зносостійких покриттів. SiC покриття наносилося детонаційним методом на середньовуглецеву сталь, використовуючи зворотній магнітний потік котушки. Встановлено, що тільки нанорозмірні частинки осаджуються на поверхні та накопичуються в агрегатах різної форми. Структура одержаного покриття цілком досліджена на електронному мікроскопі в попередній публікації. Одержане покриття розроблене для випробування на машині тертя, що моделює процес тертя, який має місце у корінних і шатунних шийках двигунів внутрішнього згоряння. Покриття має також властивості захисту від корозії. Нанорозмірне покриття на м'якій вуглецевій сталі, було випробувано згідно з конкретизованими умовами та їх поверхні тертя були досліджені на електронному мікроскопі з метою визначення механізму зношування. Було проведено двофакторне моделювання інтенсивності зношування і коефіцієнта тертя та були побудовані і проаналізований двовимірні графіки.

Ключові слова: знос, зносостійкість, коефіцієнт тертя, нанорозмірне покриття, детонаційне нанесення, магнітномодифіковане нанесення.ня, максимальні дотичні напруження, мікрогеометрія, тертя спокою.