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Diamond derivating coating impact on wearing in combustion engine

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Abstract. Piston – ring – cylinder is the typical and simple example of the friction pair that we can find in combustion engine where wearing is one of the main problem. Research on stability of friction pairs are focused on the surface and the top layer of surface in the parts. The main goal is find new solutions in design and materials in order to reduce wearing, which is consistent with the observed trend of technology development. This article presents one of the stages in the re-search of the newly developed piston ring designed for an internal combustion engine, in which the novelty is an innovative diamond-derivative coating with very good anti-wear properties. Objective of this work was to realize an endurance test in railway engine EMD645 based on rings with diamond coatings and a test of roll-block type on tribotester to set wearing and friction forces of specimen. The super-hard, anti-wear amorphous coatings based on carbon-like diamond show a promising direction in automotive industry, mainly in terms of decreasing friction coefficient in parts of internal combustion engine. The work aims to show the possibilities and benefits of the application of new protective coatings on structural elements.

1. Introduction

Friction pairs are designed with elements in which it is very difficult to determine in an unequivocal way all parameters or features which can be accepted as a optimum. Research on the durability of friction pairs focuses on the surface and layers of the top elements which mainly consists of anti-wearing coatings. The purpose is to find a new design and material solutions in order to enable the mileage to be completed to the main repair in the example of internal combustion engines. The biggest structural difficulties occur in friction pairs, where is a reciprocating motion, at the same time connected to the sealing function. A typical and true sample of such pair is ‘the piston ring - the cylinder barrel’ in the piston - piston rings – cylinder assembly mounted in the internal combustion engines. [1,2,5,6]

Thanks to diamond derivating coatings, the main feature of the coated elements is decreased resistance of movement in meaningly way, comparing it to parts that do not possess such coating. Diamond as a partial ingredient of the coating reduces the friction coefficient, as well as mild wear in the linear function. The diamond coating during dry friction is even able to transfer the anti-wear function of the lubricant working medium. One of the more popular and successful techniques of diamond coating placing is PVD (physical vapour deposition) with reduced pressure is the physical deposition of diamond particles on the superficie of the component. [3,7,8,10,11]

Characteristic features of diamond coatings used in the automotive sector are undoubtedly resistance to pitting and chipping as well as low coefficient of friction, and thus resistance to wear.



The purpose of the coating is not only to protect the item against wear, but also to improve its integrity. Diamond-coated coating is recognized as hard coatings. Diamond copolymer coatings are amorphous raw materials with very thin layers and their properties depend on the conditions and the type of technology used in the production, but in general, the characteristic attributes of diamond-shaped coatings are listed below [10,11,12]:

- higher hardness than traditional materials, within 10-60 GPa,
- high adhesion to the substrate,
- high mechanical, physical and chemical stability,
- coefficient of friction below 0.1,
- high electrical resistance up to $10^{16} \Omega$,
- high abrasion resistance up to $10^{-7} \text{ mm}^3 / \text{Nm}^{-1}$,
- as well as optical transparency.

2. Researches

The spectrum of researches was composed of two types of researches. One of them was realized on the real object in real conditions and the second was accomplished like a model test. The first was an endurance test of diesel locomotive engine EMD645 what was made in San Antonio (USA) and the second was the study of the surface condition on the basis on wearing of rings in the wearing pair during the model tests on tribotester of the pair formed from the ring - cylinder on rule of sample – counter sample) made with cooperation with AGH University of Science and Technology in Cracow.

2.1. Endurance test of diesel locomotive engine EMD645

The subject of the research was to check the durability of a complex spark-ignition internal combustion engine equipped with steel piston rings made in technology behind the diamond coating of the first groove. The purpose of the work was to check the quantitative wear values of the tested piston rings with the applied diamond coating on the external surface. The scope of work included performing geometric measurements of piston rings (width and height) and a description of cylinder liner surfaces with which they cooperated. Piston rings were subjected to geometric measurements of radial width and axial height at ten points on the circumference, according to the measurement scheme.

After the geometric measurements was made an installation of engine components in the engine EMD 645-E, which was mounted on a test bench in the engine laboratory in the Southwest Research Institute in San Antonio, USA. The next step was the operation of the locomotive engine Pacific3450 Union in the ongoing 85 hours endurance test at maximum, the value of 550 rev / min and a rated power of 650 kW. After completion of the test the rings were measured geometrically again to determine the value of the wear. What needs to be mentioned is that the guiding idea of this endurance test unit is intensifying extremely variable loads. The transition from the traffic with a maximum torque of traffic without load at maximum speed has intensified engine load, contributing to a measurable value of wearing, despite the relatively short duration of the test. This type of test is called the test a "cold-hot".

Diamond coating. This coating is a multilayer porous chromium coating applied galvanically where in the pores after the reversed polarity of the process is deposited synthetic diamond dust. Coating constituted in that process is characterized by good tribological properties, while ensuring a high hardness. Elaborated coating is without any defects. At the same time in the case of boundary friction caused by the contact of surface roughness between the ring and the cylinder is accompanying increase of the temperature what causes the transition of diamond into a graphite. This occurs even at 873 K (700 ° C) and higher. Thanks to this transformation phenomenon this hardest known mineral becomes a kind of grease [3,7,12]. The presented coating consists of twenty-two layers.

The outcoming shape of the coating is dictated by optimization of the final composition of the coating and it is shown in the following table:

Table 1. PCD coating composition applied to the piston ring of EMD645 engine

Elem %	C	Al	Cr
Min:	0,640	0,000	98,020
Max:	0,900	0,090	98,570
Mean:	0,770	0,047	98,306
StdDev:	0,096	0,030	0,195
% MAS	0,75	0,09	99,20
% V	1,49	0,14	98,36

2.1.1. Measurements in the test. Measurements in the endurance test were performed before and after the test to gain results which research will be able to compare. The project of the research was composed on that way to gain the biggest intensification of two types of loads: mechanical and thermal. This is the reason why endurance test was consisted of 85 hours. It intensifies the wearing what takes a place in the most strenuous parts in friction pair which are piston ring and cylinder during their cooperation. The tests were designed for two-stroke diesel locomotive diesel engine type EMD 645 with a cylinder diameter of 9.065 inch (230.2 mm). Each of the cylinders of the engine is equal to the stroke volume of 10.35 liters. The tests were powered by turbocharged engine EMD 645E3 (V12) with a capacity of 1200 kW and a torque of 12 000 Nm. Because of motor with such diamond powder coated rings was find in USA and was just installed on the chassis dynamometer the place where the test was executed was Southwest Research Institute in San Antonio. The EMD645 diesel engine is the most popular power unit used in american locomotive market. The effect of the implementation of the diamond derivative sample was measurable wear on the radial thickness and axial height of rings, as well as cylinder and pistons wear with very positive and promising results. Measurements of the radial thickness and axial height were made at ten equally spaced points around the circumference of the ring. Due to direction of wearing in both is very similar, next part of work will focus on exemplary axial height to show and mark the main way of wearing. There was twelve piston ring specimens. Measurements were done in ten points in ring, as shown on figure below (Figure 1).

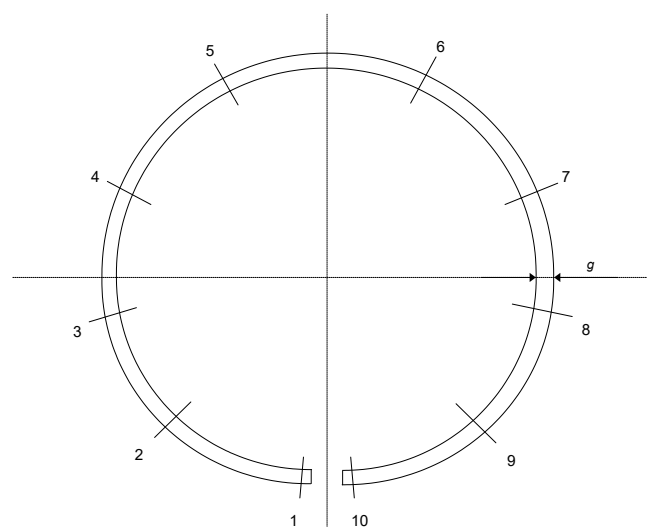


Figure 1. Measurement points on piston ring specimen

The average axial height of the piston ring with diamond derivating coating is 4,8mm. The measurements of the piston ring axial height were done before and after the wearing test. The results of these measurements are the difference in the piston ring axial height as it is shown in the following table (Table 2).

Table 2. Difference in the axial height of the rings after the wearing test

PISTON RING SPECIMEN	MEASUREMENT POINTS									
	1	2	3	4	5	6	7	8	9	10
1	-0.005	0.009	0.004	0.005	0.004	0.007	0.007	0.004	0.007	0.009
2	0.014	0.003	0.01	0	0.009	0.011	0.013	0.017	0.009	0.01
3	-0.012	0.001	0.001	0.004	0.01	0.008	0.008	0.006	0.001	0.008
4	0	0	-0.005	0.001	0.002	0.007	0.002	0.004	0.003	0.008
5	0.003	0.003	0	0.004	0.006	0.002	0.007	0	0.003	0
6	0	0.004	0.007	0.001	-0.002	0.014	0.004	0.002	0.003	0.005
7	-0.002	-0.003	-0.01	0.001	0.011	0.017	0.01	-0.007	-0.005	- 0.003
8	-0.002	0.002	0.003	0.004	0.006	0.003	0.015	0.02	0.011	0.007
9	0.001	0.001	0	-0.006	-0.006	-0.001	0.005	0	-0.001	- 0.005
10	0.002	0.016	-0.002	0.008	0.009	-0.003	0.018	0	0	0.003
11	-0.007	0.003	-0.002	-0.008	0.001	0.001	-0.001	0.005	0.005	0.008
12	0	0.004	0	0	0.006	0.014	0.002	-0.001	0.005	0.005

2.1.2. Results of the endurance test. The average wearing value is very promising, especially knowing that with a measurement accuracy equal to 0,001 mm differences between the wearing of new rings and standard rings are very important. Each 0,001 mm has a meaning in gaining of longer life in friction pairs. The piston rings are the parts that consume the most and the fastest which needs to be changed very often.

Very interesting is also the phenomenon where it can be seen the negative consumption in the above tables. It can be concluded in the way that the rings with diamond coating do not wear out, on the contrary - it is possible that there is material from the cylinder which is made from another material and consequently the honing features appear on the cylinder - after all, the diamond is a super-hard anti-wear coating. It would be good to take it into account in the future considerations.

Diamond – derivative coatings are mainly characterized by a lower friction coefficient and a much greater resistance to wear in comparison to rings that are covered by the common super-hard coatings. Without a doubt, the application of such coatings will have an impact not only to extend the life of system piston - ring - cylinder, but also will reduce fuel consumption even under the most strenuous conditions of work of the unit.

2.2. Model test in the tribotester (sample – counter sample)

Comparative research on tribotester test at model stations is considered as exploratory because many simplifications are used. The purpose of these studies is to compare the results of the tribological processes (wearing) that occur in the material connections in friction pairs. The research was done on a roll-block type tribotester. The tested elements are a rotating counter-sample in the form of a roll and a fixed sample in the form of a block.

Key loads in this type of friction pair test are unit pressure [MPa] and linear speed [m/s]. High pressure and low speed produce extremely difficult conditions in the engine.

A roller-block tribotester is used for testing elements working in linearly conformal contact conditions, allowing the input parameters to be assigned to determine the temperature value in the friction junction or friction force. This type of test is mainly used for research in friction and wearing of coated parts of machines and the device describes the characteristics of the tested parameters depending on time. The pressure of the friction pair illustrates the following figure:

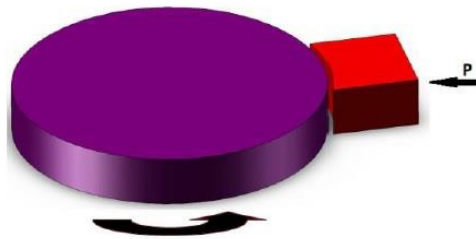


Figure 2. Scheme of pressing of the wearing pair in the roll-block tester.

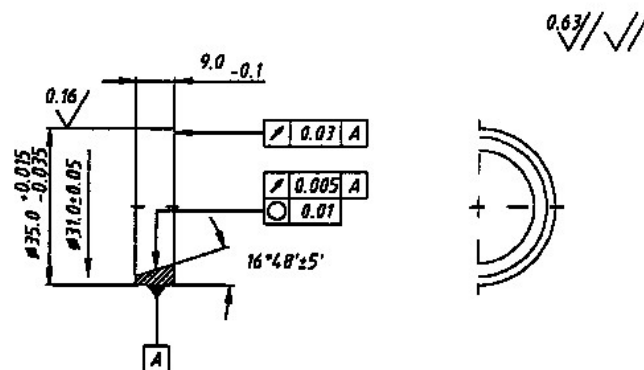


Figure 3. Sample intended to tribotester test.

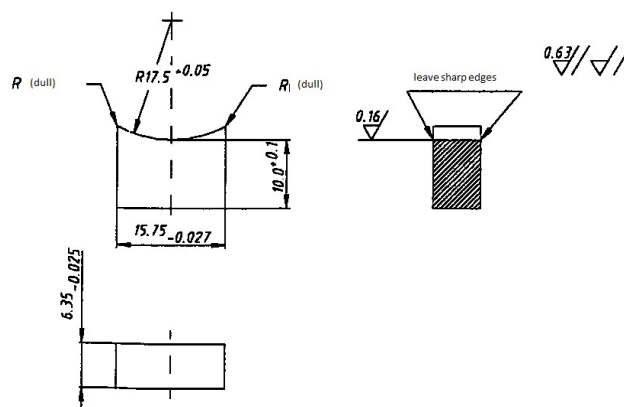


Figure 4. Countersample intended to tribotester test

2.2.1. Tribotester test description. The research was carried out in on a computerized tribotester T-05 type which is normally used in case of low-friction coatings tests. The counter-samples were pads with a spread contact made in accordance with the recommendations of the tester manufacturer and the working surfaces formed a contact of 100 mm² and the block was covered by diamond derivating

coating deposited by physical gas phase in various ratio with chromium. Everything was created to ensure the most similar conditions which normally appear in internal combustion engine. The subject of the research were ring samples provided with the markings. Mark PP means the specimen without diamond addition in the chromium coating. The specimens with marks from T-1 to T-5 has addition of diamond in the coating in various percentage ranges. Each type of specimen was prepared in three pieces. The *Table 3* shows the chemical composition for tested specimens.

Table 3. Chemical composition of coating with diamond powder.

	C [%]	Al ₂ O ₃ [%]	Cr [%]
T-1	0,84	0,62	98,84
T-2	0,89	0,09	99,07
T-3	0,54	0,09	99,42
T-4	0,80	0,09	99,15
T-5	0,49	0,07	99,48

The aim of the research was to determine the friction force, the intensity of total ring and block wear. In addition, measurements of microhardness of the rings before the friction test and after the tests to determine possible changes in surface layer. The whole series of tests was carried out at constant parameters like a unit pressure between the ring and the block was 5 MPa, friction speed (linear velocity) of $V = 1.25$ m/s and friction took place in the environment of synthetic oil GOLD SYNTHESIS VENOL 5W-40. In the test we performed 6 types of samples.

Measurements of the friction force in the tested node were recorded every certain period of time. On this basis, source diagrams of three runs of 50,000 meters were made from each group of rings.

The total consumption of rings and blocks was carried out directly on the T-05 during breaks in operation and after reaching a constant temperature which was set at 25 ° C. The measurement was carried out without disassembly of the friction junction and at a load of 5 MPa. For measurements, a clock sensor is used in the value of the parcel $We = 0.002$ mm, in the same angular position to eliminate the ring error. It should be noted here that the aggregate wear of the friction node is also burdened by the wear of bearings in the spindle and the angular position of the spheres. The friction force measurements at the testing node were recorded at a certain time interval, and on this basis was compiled a source graph for 50,000 meters long of run in 3 trials.

2.2.2. Results of the tribotester test. These studies do not fully reflect the working conditions of the steamed piston ring cylinder - there is no burning process. But the basis specimen material is steel with chrome coating (typical material of the piston rings) and the block was made of gray cast iron (typical material of the cylinder). Thus, the cooperation of the materials in the model of the same steamed pair, which are used in the tested for combustion engines, has been ensured. The defined motion parameters during the tribotester test result are difficult operating conditions, i.e. a pressure load is close to the maximum working cycle of the tested scraper piston ring and rotational speed lower about 70% of idle speed for motors. The trial was conducted in the gears (according to test procedure on tribotester type T05), each had a friction path of 1250 meters. Each test trial counted 40 gears, which means a friction path of 50 000 meters. In the oil exchanged after each series of tests, was observed a black precipitate. Experience shows that friction coefficient stabilizes after this friction path. As a result of the research work we have obtained the variation of the frictional forces as a function of the friction path, from which it is possible to calculate friction coefficient values and friction coefficient sum values. Results from Figure 5 is proper to compare with chart on the Figure 6. What can be observed there in the variation course of friction force from the road for samples marked T-4 is not consistent.

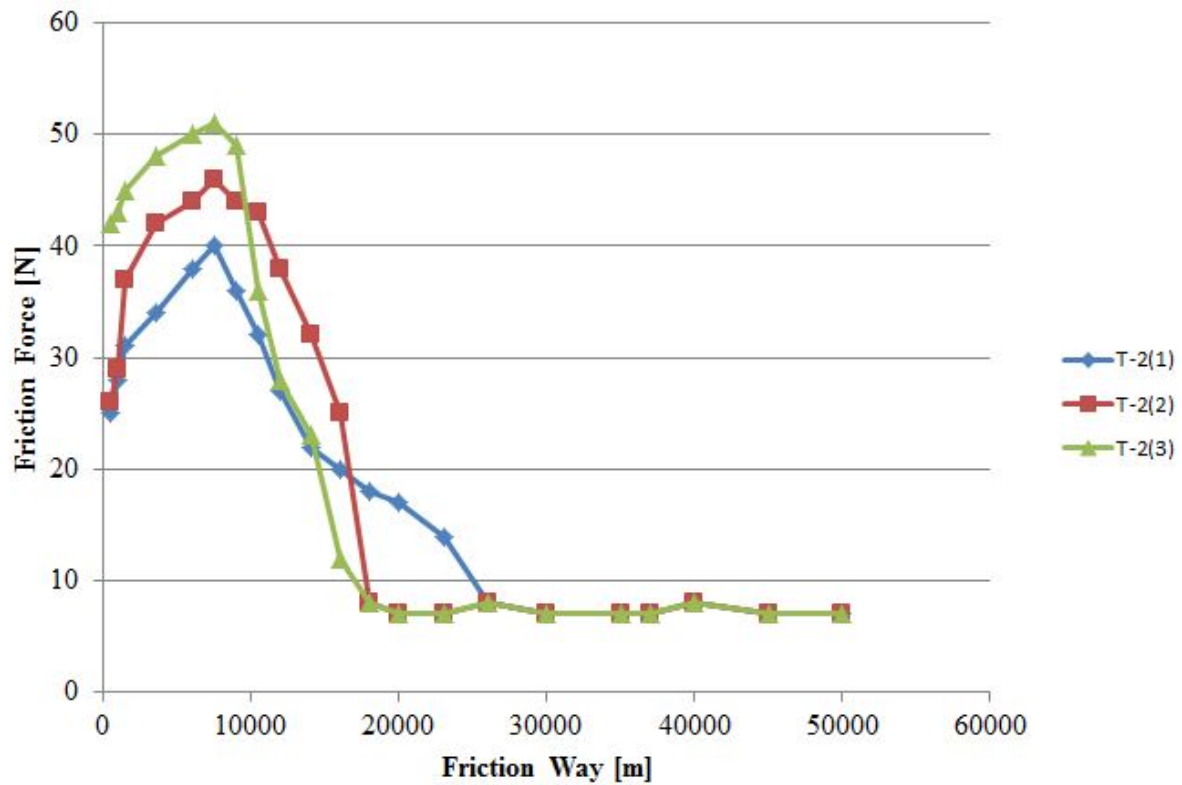


Figure 5. The variation course of the friction force from the road for samples marked T–2

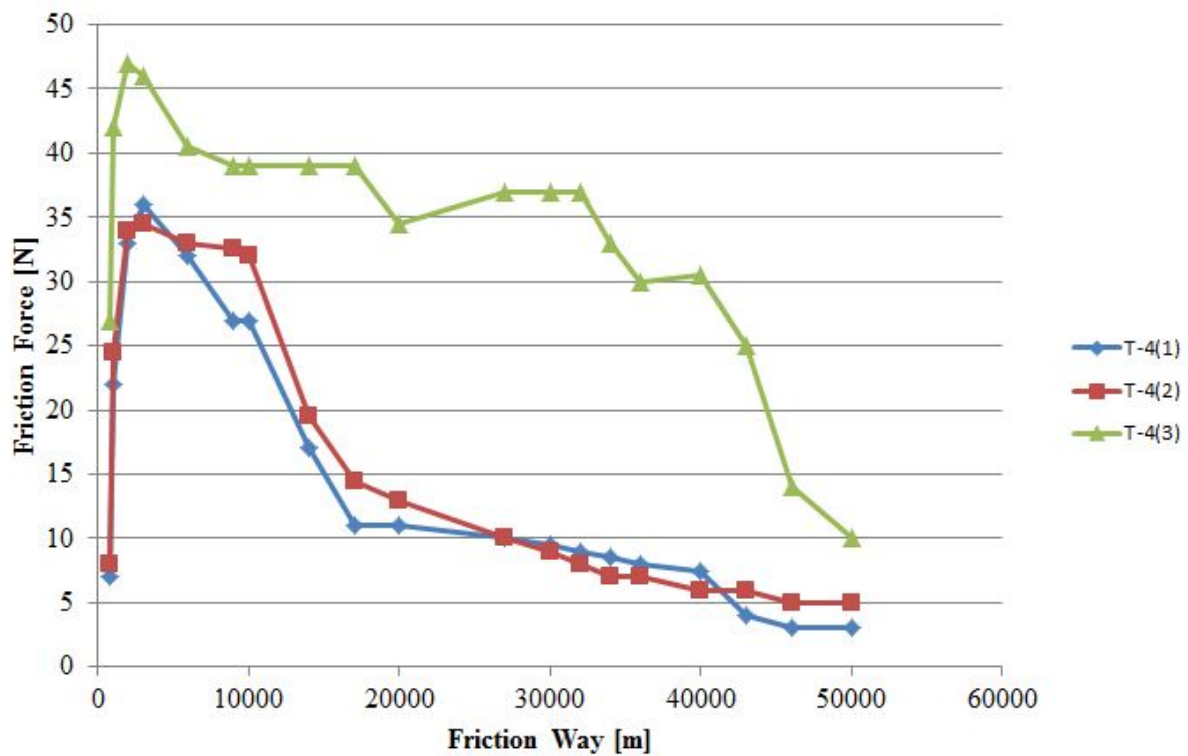


Figure 6. The variation course of the friction force from the road for samples marked T–4

What needs to be mentioned here and it's important is that the T-4 sample has lower value of mass percentage of diamond powder in coating and with that there is no any stabilization of the friction force on a certain value after crossing the linear path.

Difference in the wearing presented in Figure 7 and Figure 8 is significant.

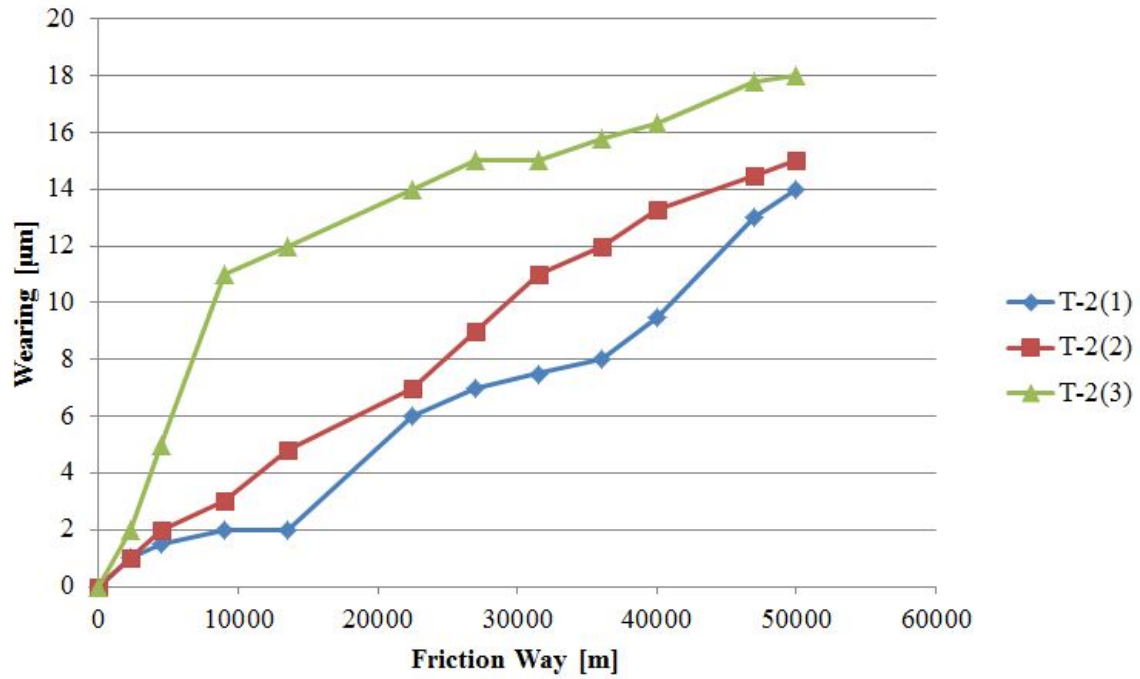


Figure 7. Sum of wearing graph for T-2 friction node in 3 trials

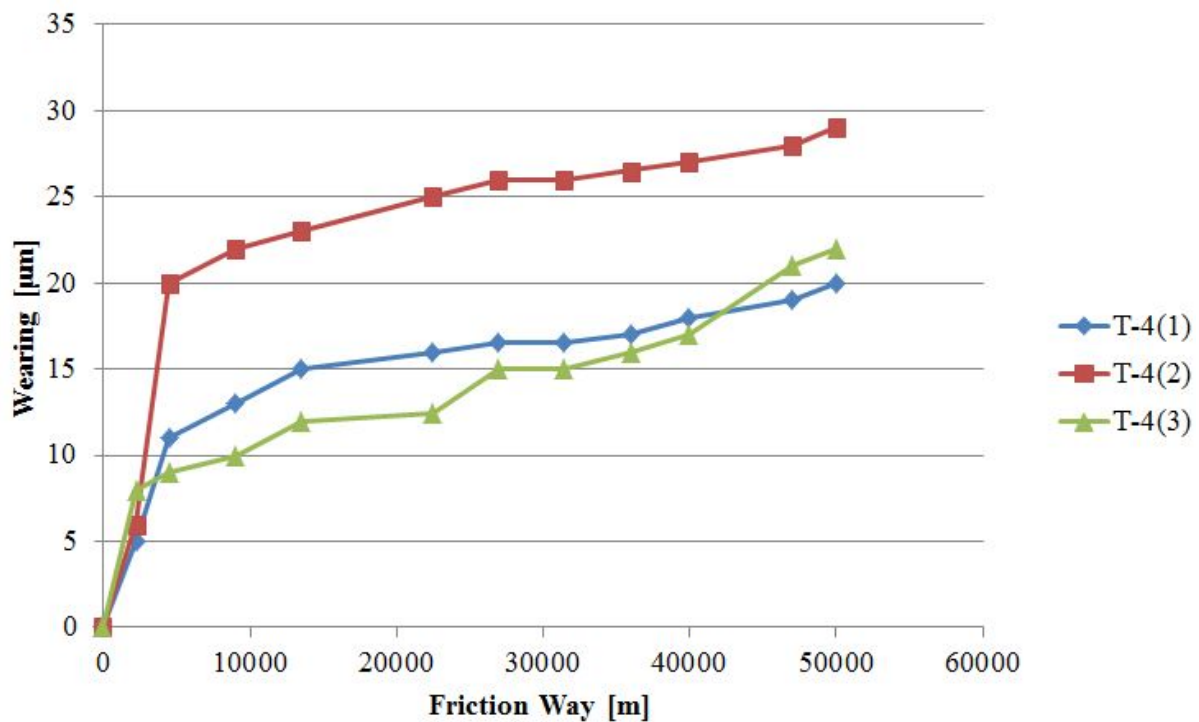


Figure 8. Sum of wearing graph for T-4 friction node in 3 trials

Difference in the wearing of two specimens shows that the value of the diamond powder in the coating has important influence on the wearing of components.

Of course presented results are only the small part of the whole research work, but it's obvious with tests results described in this article that diamond derivating coating can be considered like a potential solution in reducing friction and wearing in friction pairs.

3. Summary

The main and also the most important features of a diamond derivating coatings are lower friction forces and much greater resistance for wearing comparing that to rings that are not covered by such coatings. Without a doubt, the application of such coatings will have an impact not only to extend the life of system piston - ring - cylinder, but also will have influence on engine efficiency what will reduce fuel consumption and emission even under the most strenuous conditions of work of the unit.

Solution to the given research problem is based on the results of these studies of 85 - hour endurance test and tribotester test for six specimens with different chemical composition.

Endurance test shows that the wearing of the piston rings mounted in EMD645 engine is negligible. The wearing of the axial height of the piston after the test is slight and is oscillating between the minimum value which is 0 and the maximum value which is 0.017 mm. The cases of negative consumption shows that instead of wearing there appears the phenomenon of deposition of material – most likely coming from the cylinder.

In the tribotester test we choose two specimens with different percentage mass of diamond powder to check the influence on wearing and friction forces. Presented results show that the higher value of diamond in the coating significantly reduces the friction forces and wearing. The specimen T-2 with higher value of diamond after the completed test shows 62% lower wearing than the specimen T-4.

Additionally, the specimen T-2 demonstrates lower about 20% friction forces at the end of the test in comparison to specimen T-4. Except that specimen T-2 shows much faster stabilization of friction forces in the process of the running-in.

Diamond - derivative coatings can have an application for components which are working in high-speed diesel engines and because of the opportunity to work at very high temperatures. They also exhibit good adhesion to the substrate steel and cast iron, and less stress their own, so they seem to be a breakthrough in the use of materials with excellent tribological properties. A complete set of advantages of applying diamond – derivative coatings contains very high hardness (70 GPa), high value electrical resistance, relatively low weight, and most importantly, lower coefficient of friction and excellent wear resistance.

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