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RESEARCH AND ANALYSIS OF THE RESULTS OF THE INTERNAL COMBUSTION ENGINE LOCOMOTIVE DURING THE 85-HOUR ENDURANCE TEST

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Abstract

Piston – ring – cylinder assembly of combustion engine has many friction pairs examples, also one of them which decide about fastness to wear, it means first sealing ring – cylinder, called further very simply ring – cylinder unit. During work of this unit, we can observe wear of piston, precisely – of coating which is deposited on ring to prolong service life. Objective of this work was to realize a test of set durability of railway engine EMD645 with power about 1300 kW. Within the framework of this test were investigated a prototyped piston's rings with diamond embankment. Piston rings are made of diamond coating technology with a porous chromium coating, where in pores is deposited on said diamond powder with a grain size about 1 micron. The work will be carried out of an analysis of collaboration piston – rings – cylinder unit in internal combustion engine and an analysis of the use of hard materials in friction pairs, including powders. Will be performed research of material and description of diamond powder, which will be applied to the piston rings. After stability, testing in the locomotive engine EMD645 on the basis of the collected results will be developed conclusions of the wearing intensity on piston ring and relating them to the requirements for coatings. The work aims to show the possibilities and benefits of the application of new protective coatings on structural elements of the internal combustion engine in order to reduce their wearing, which is consistent with the observed trend of technology development.

Keywords: *friction pair, internal combustion engine, piston, ring, cylinder, tribological properties, coating, EMD645, endurance test, diamond powder*

1. Test

The subject of the research work was to test the durability of internal combustion engine with spark ignition, also equipped with steel piston rings made in the technology of diamond coating of the first groove. The purpose was to check the quantity of piston rings wearing with the diamond-derivative coating on the external surface. The scope of work included the geometric measurements and a description of the cylinders surfaces with whom they cooperated.

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.

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”.

2. Technology

Chrome plating working surfaces of the piston rings is a technology used successfully for many years and it is very popular. FPT “Prima” SA also successfully used technology chrome piston rings. As a part of the R&D project was prepared a multi-layer chrome plating as PCD (Fig. 1) with a diamond coating.

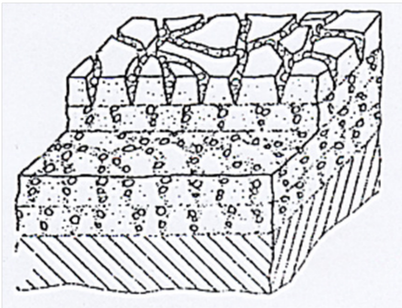

Fig. 1. Schematic of chromium porous technology introduced in FPT “Prima” SA

This technology can successfully compete in many markets of the world with other coatings produced by global corporations.

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. In the case of boundary friction and contact with surface asperities, in the similar technology, hard alumina particle was deposited and getting to the top of cylinder imbalances caused the intensive use, of a considerable abrasive wear in high temperature conditions. Elaborated coating is devoid of this defect [1, 2]. Diamond as the hardest known mineral ensures a significant increase hardness of the coating in total. At the same time in the case of boundary, friction caused by the contact of surface roughnesses between the ring and the cylinder is accompanying increase in temperature causes the transition of diamond into graphite. This occurs even at 873 K (700°C) and higher. Thanks to this phenomenon, this hardest known mineral becomes a kind of grease. The coating consists of twenty-two layers [3].

The final composition of the coating is the result of optimization work carried out in the framework of research and it is illustrated in Tab. 1.

Tab. 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

3. Measurement before and after the test

The research project achieved by an 85-hour endurance test used, inter alia, by the company Federal Mogul like a continuous motor work at the specified torque. The result is the intensification of thermal and mechanical loads, leading also intensification of wearing particularly in the piston – – rings – cylinder set. 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 litters. The power of the engine varies between 0.6 MW for the six-cylinder unit (10 engine weight 1000 kg) supplied by the Roots compressor, to 3.1 MW unit twenty-cylinder (19 engine weight 500 kg) powered by turbocharger. The tests were powered by turbocharged engine EMD 645E3 (V12) with a capacity of 1200 kW and a torque of 12 000 Nm. Displacement volume is 124.2 litters. We found a place where the motor was installed on the chassis dynamometer. It is a Southwest Research Institute in San Antonio, USA. The tested engine EMD 645 is a typical power unit used in the US market to drive diesel locomotive. The result of the implementation of the sample was measurable wear on the radial thickness and axial height of rings and cylinders and pistons wear.

Tab. 2. Measurement of the axial height of the rings before testing

Ring number	Value of measurement of the axial height of the rings before testing [mm]									
	1	2	3	4	5	6	7	8	9	10
1b	4.783	4.781	4.784	4.784	4.789	4.792	4.785	4.78	4.79	4.797
2	4.812	4.801	4.8	4.781	4.785	4.786	4.794	4.808	4.807	4.809
3b	4.787	4.781	4.786	4.793	4.79	4.79	4.802	4.798	4.786	4.789
4	4.805	4.804	4.799	4.791	4.791	4.795	4.795	4.806	4.812	4.816
5b	4.789	4.804	4.803	4.807	4.81	4.807	4.801	4.784	4.788	4.795
6	4.784	4.788	4.796	4.8	4.79	4.807	4.798	4.792	4.79	4.794
7	4.786	4.782	4.785	4.793	4.796	4.797	4.801	4.792	4.786	4.788
8b	4.796	4.801	4.807	4.801	4.799	4.79	4.788	4.798	4.81	4.813
9	4.788	4.786	4.784	4.77	4.766	4.776	4.796	4.796	4.794	4.795
10b	4.8	4.807	4.782	4.799	4.799	4.786	4.804	4.792	4.786	4.791
11	4.787	4.795	4.788	4.775	4.771	4.774	4.786	4.793	4.793	4.801
12b	4.806	4.808	4.817	4.811	4.812	4.809	4.79	4.788	4.806	4.817

Tab. 3. Measurement of the radial thickness of the ring before testing

Ring number	Value of measurement of the radial thickness of the rings before testing [mm]									
	1	2	3	4	5	6	7	8	9	10
1b	7.484	7.467	7.476	7.468	7.492	7.492	7.489	7.492	7.482	7.492
2	7.643	7.587	7.601	7.626	7.647	7.666	7.662	7.646	7.613	7.642
3b	7.39	7.417	7.43	7.411	7.411	7.394	7.391	7.39	7.391	7.388
4	7.703	7.657	7.644	7.669	7.676	7.668	7.682	7.689	7.668	7.7
5b	7.492	7.476	7.498	7.508	7.522	7.506	7.48	7.476	7.465	7.471
6	7.552	7.531	7.546	7.586	7.622	7.603	7.592	7.566	7.542	7.566
7	7.566	7.543	7.564	7.587	7.565	7.544	7.509	7.49	7.505	7.551
8b	7.481	7.477	7.475	7.464	7.47	7.484	7.501	7.506	7.49	7.49
9	7.609	7.594	7.588	7.605	7.625	7.597	7.599	7.606	7.6	7.612
10b	7.404	7.389	7.398	7.387	7.398	7.41	7.409	7.428	7.415	7.411
11	7.614	7.587	7.587	7.616	7.606	7.598	7.601	7.607	7.607	7.597
12b	7.36	7.374	7.382	7.379	7.371	7.368	7.344	7.35	7.359	7.368

Tab. 4. Measurement of the axial height of the rings after testing

Ring number	Value of measurement of the axial height of the rings after testing [mm]									
	1	2	3	4	5	6	7	8	9	10
1b	4.788	4.772	4.78	4.779	4.785	4.785	4.778	4.776	4.783	4.788
2	4.798	4.798	4.79	4.781	4.776	4.775	4.781	4.791	4.798	4.799
3b	4.799	4.78	4.785	4.789	4.78	4.782	4.794	4.792	4.785	4.781
4	4.805	4.804	4.804	4.79	4.789	4.788	4.793	4.802	4.809	4.808
5b	4.786	4.801	4.803	4.803	4.804	4.805	4.794	4.784	4.785	4.795
6	4.784	4.784	4.789	4.799	4.792	4.793	4.794	4.79	4.787	4.789
7	4.788	4.785	4.795	4.792	4.785	4.78	4.791	4.793	4.791	4.791
8b	4.798	4.799	4.804	4.797	4.793	4.785	4.783	4.79	4.799	4.806
9	4.787	4.785	4.784	4.776	4.772	4.777	4.791	4.796	4.795	4.8
10b	4.798	4.791	4.784	4.791	4.79	4.789	4.786	4.792	4.786	4.788
11	4.794	4.792	4.79	4.783	4.77	4.773	4.787	4.788	4.788	4.793
12b	4.806	4.804	4.817	4.811	4.806	4.795	4.788	4.789	4.801	4.812

Tab. 5. Measurement of the radial thickness of the ring after testing

Ring number	Value of measurement of the radial thickness of the rings after testing [mm]									
	1	2	3	4	5	6	7	8	9	10
1b	7.471	7.456	7.462	7.455	7.484	7.484	7.479	7.48	7.465	7.488
2	7.625	7.578	7.528	7.616	7.634	7.658	7.651	7.633	7.601	7.622
3b	7.377	7.406	7.42	7.401	7.4	7.382	7.382	7.383	7.385	7.376
4	7.679	7.639	7.62	7.643	7.649	7.645	7.66	7.661	7.65	7.679
5b	7.459	7.463	7.484	7.491	7.507	7.494	7.471	7.464	7.454	7.46
6	7.541	7.519	7.535	7.561	7.595	7.593	7.584	7.553	7.519	7.542
7	7.539	7.516	7.538	7.557	7.546	7.525	7.491	7.466	7.488	7.529
8b	7.462	7.461	7.46	7.451	7.455	7.47	7.484	7.491	7.476	7.476
9	7.601	7.585	7.574	7.587	7.603	7.585	7.586	7.587	7.585	7.602
10b	7.389	7.374	7.382	7.369	7.384	7.399	7.398	7.415	7.401	7.399
11	7.601	7.577	7.567	7.592	7.592	7.586	7.587	7.589	7.591	7.578
12b	7.345	7.361	7.369	7.361	7.357	7.356	7.33	7.333	7.347	7.358

Tab. 6. Value of the axial height wearing of the rings after the test

Ring number	Value of the axial height wearing of the rings after the test [mm]									
	1	2	3	4	5	6	7	8	9	10
1b	–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
3b	–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
5b	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
8b	–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
10b	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
12b	0	0.004	0	0	0.006	0.014	0.002	–0.001	0.005	0.005

Tab. 7. Value of the radial thickness wearing of the rings after the test

Ring number	Value of the radial thickness wearing of the rings after the test [mm]									
	1	2	3	4	5	6	7	8	9	10
1b	0.013	0.011	0.014	0.013	0.008	0.008	0.01	0.012	0.017	0.004
2	0.018	0.009	0.073	0.01	0.013	0.008	0.011	0.013	0.012	0.02
3b	0.013	0.011	0.01	0.01	0.011	0.012	0.009	0.007	0.006	0.012
4	0.024	0.018	0.024	0.026	0.027	0.023	0.022	0.028	0.018	0.021
5b	0.033	0.013	0.014	0.017	0.015	0.012	0.009	0.012	0.011	0.011
6	0.011	0.012	0.011	0.025	0.027	0.01	0.008	0.013	0.023	0.024
7	0.027	0.027	0.026	0.03	0.019	0.019	0.018	0.024	0.017	0.022
8b	0.019	0.016	0.015	0.013	0.015	0.014	0.017	0.015	0.014	0.014
9	0.008	0.009	0.014	0.018	0.022	0.012	0.013	0.019	0.015	0.01
10b	0.015	0.015	0.016	0.018	0.014	0.011	0.011	0.013	0.014	0.012
11	0.013	0.01	0.02	0.024	0.014	0.012	0.014	0.018	0.016	0.019
12b	0.015	0.013	0.013	0.018	0.014	0.012	0.014	0.017	0.012	0.01

The average wearing value of the radial thickness, and therefore the wearing of the chrome coating ring with PCD is equal to 0.013 mm. The average wearing value of the radial thickness of the rings is equal to a standard: 0.019 mm. With a measurement accuracy equal to 0.001 mm differences between the wearing of new rings and standard rings are very important.

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 superhard 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.

The value of cylinders wearing is determined on the basis of realized spot in the US diametrical measurements made by the employees of the Technical University of Wroclaw. Measurements were made at three levels of measurement; in External Return (ZZ) of the first sealing ring (including coated PCD), in the middle of the piston stroke (corresponding to the pitch of the first sealing ring) and Internal Return (ZW) of the first sealing ring. The results of the wear was measured to the nearest 0.01 mm using a suitable bore hole gauge capable of measuring the diameter. Measurements were carried out in two directions of measurement; along the longitudinal axis of the motor and transverse to this axis. Of course, due to the fact that the motor is formed as a V system is along and across the rows of cylinders. The numbering cylinders conform to Polish. Cylinder numbers from 1 to 6 on the left cylinder row looking at the motor axis on the side opposite to the output carrier power and cylinder numbers from 7 to 12 relate to the order of the right looking to the side opposite to the side the output carrier power. These measurement results are given in table 8. Wherein the measurement height ‘0’ (measured in mm) means ZZ of the first sealing ring, the measurement height ‘127’ means a stroke of the first sealing ring and the measurement height ‘254’ is a first sealing ring ZW.

The measured wearing values in cylinders are in the range of measuring error of test bore hole gauge. This means the proper working of these piston rings and cylinders. The confirmation of proper co-operation developed in the project piston rings and cylinders are caused cracks what evidence of little or no utilization of cylinder.

During the research also measured emissions of toxic exhaust. The measurements were performed before attempting able to zero and after its completion. Measured values for emissions of sulphur dioxide (SO_2), particulate emissions, carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x). These values are summarized in Tab. 9 as the emissions per 1 litter of fuel consumed. Since the load during the endurance test was solid, so repeatedly was measured value

Tab. 8. The wearing in cylinder of EMD 645 engine after the durability test

Cylinder No.	Measurement height, mm	Wear of cylinder „longitudinal" of the engine, mm	Wear of cylinder „transverse" of the engine, mm
1	0	0.01	0.00
	127	0.00	0.00
	254	0.00	0.00
2	0	0.00	0.01
	127	0.01	0.00
	254	0.00	0.00
3	0	0.01	0.00
	127	0.00	0.01
	254	0.00	0.00
4	0	0,00	0.01
	127	0.00	0.00
	254	0.00	0.00
5	0	0.00	0.01
	127	0.01	0.00
	254	0.00	0.00
6	0	0.01	0.00
	127	0.00	0.00
	254	0.00	0.01
7	0	0.01	0.01
	127	0.00	0.00
	254	0.00	0.00
8	0	0.01	0.01
	127	0.01	0.00
	254	0.00	0.01
9	0	0.01	0.01
	127	0.01	0.00
	254	0.00	0.01
10	0	0.01	0.00
	127	0.00	0.00
	254	0.01	0.01
11	0	0.01	0.00
	127	0.00	0.00
	254	0.00	0.00
12	0	0.01	0.00
	127	0.00	0.01
	254	0.00	0.00

Tab. 9. The value of toxic exhaust emissions engine EMD 645 before and after the durability test team

Substance	Emission before the test	Emission after the test
SO_2, ppm	0.15	0.18
particulates, g/l	2.16	2.15
CO, g/l	9.46	9.85
HC, g/l	4.32	4.55
NO_x, g/l	81.02	90.5

of the contents of these toxic components in the exhaust gas and converted by reference to the amount of fuel consumed in the test, forming emissions. The exception is the value of the sulphur dioxide, which is the result of consumption of the lubricating oil when using sulphur-free fuel. In this case, the results are reported in ppm.

Emission values were related to the quantity of fuel consumed to make the reference level emission permitted content of individual compounds, which in the USA (target market consortium member project FPT Prima S.A.) is usually given in grams per gallon of fuel consumed. In summary, the values are in the standards applicable to the motor EMD645 in the United States.

4. Summary

Studies show that with % increasing of the carbon in the coating composition and decreasing of the hydrogen amount is related to improved strength and wear resistance at the time of no lubricating function of the lubricant. The use of diamond – derivative coatings is a new direction in the development of technology for internal combustion engines. Replacement of worn parts of the piston – ring – cylinder set would decrease considerably their properties and their improvement has a definite dimension, so the use of such modern shells prolonging the life could change a lot on what evidence may be carried out research and very promising results. These the hardest coatings available on the market today are increasingly used, mainly in the automotive and electronic equipment. The properties of these coatings and getting their increased popularity also contribute to the decrease in costs associated with their production, and the problem of their insufficient thickness will likely be solved with the most modern methods of hardfacing on components.

Solution to the given research problem is based on the results of these studies of 85-hour endurance test. They allow you to acquire new knowledge and skills in the manufacture of coatings PCD, in particular the constitution layers of diamond coating with a specific weight percentage composition. Positive test results realized in Southwest Research Institute in San Antonio in the US pose a real chance to increase the quantities of produced rings with diamond coating for large combustion engines powering locomotives and small inland waterway vessels in the US and in the future perhaps for small internal combustion engines for use in vehicles like a cars, thus extending their life.

Diamond – derivative coatings can be applied to elements 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, low coefficient of friction and excellent wear resistance.

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