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Research on the wear of novel sets of piston rings in a diesel locomotive engine

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The paper describes the results of the wear test of innovative sets of piston rings intended, among others, to drive diesel locomotives operated in North America, including the USA. The main subject of research is an innovative set of piston rings, the first sealing ring containing a synthetic diamond embedded in a porous chrome coating. The developed multilayer coating is designed to reduce the wear of the piston rings and the combustion engine cylinder. This technology has been implemented at Piston Rings Manufactory "Prima" S.A. in Łódź. The tests were carried out using a two-stroke diesel engine of the EMD 645 type. This engine is manufactured by General Motors Corporation in the United States. The described research was carried out in the United States in San Antonio, Texas, at the Southwest Research Institute. The EMD 645 engine is widely used in power units of heavy diesel locomotives and inland waterway barges in the United States of America, India, and South Africa.

Key words: *piston ring, cylinder, combustion engines, research, simulation*

1. Introduction

The EMD 12-645-E two-stroke internal combustion engine was tested [24]. This engine is the main source of propulsion for diesel locomotives in the United States. Depending on the type, it has a power of 750 to 1500 kW. The number of locomotives operated in the USA powered by the EMD 12-645-E engine is approximately 3,000. The tests carried out at the Southwest Research Institute were carried out using a two-stroke diesel engine with direct fuel injection and a turbocharger power system [22], of which the data are given in Table 1. The engine piston with a diameter of 9 inches has 6 rings; 4 sealing w mounted on the annular part of the piston and two wipers mounted on the piston skirt (Fig. 1).

Fig. 1. EMD 645-E power assembly and GP38-2 locomotive [6]

Table 1. EMD 12-645-E engine data [2]

EMD 12-645-E	
Number of cylinders	V-12
Bore of the cylinder	230 mm
Stroke of the piston	254 mm
Cylinder displacement	10.6 dm^3
Compression Ratio	16:1
Rated power	1100 kW
Specific fuel consumption	254 g/kWh

2. The durability engine test

The main purpose of the research was to check the durability and determine the wear value of the steel piston rings installed in a two-stroke diesel engine. Rings tested with anti-wear coating were mounted in the first groove of the piston [11]. This coating, which consists of 22 layers [10], was created as a result of a porosity galvanic chrome plating, during which, after the polarity was reversed, diamond dust was deposited in the pores [1]. The chrome coating is multi-layered. Due to the diamond content in the coating, it is characterized by high hardness [17, 18] and good tribological properties [9, 13]. This technology is a development of a similar porous chrome plating technology with aluminum oxide deposited in the pores. Its disadvantage was that under boundary friction conditions, it was possible to cooperate with the peaks of surface roughness of the ring and the cylinder in the presence of hard alumina particles, which caused the intensification of the wear process of the upper part of the cylinder, especially at high temperature [4, 16]. The multilayer coating tested does not have this defect [19, 21], because the diamond at a temperature of 873 K (600°C) and higher changes its crystal lattice, becoming graphite. Graphite is a kind of solid lubricant that significantly reduces the coefficient of friction in rubbing pairs and reduces their wear [8].

The main purpose of the tests carried out was to determine the wear value of the radial thickness of the piston rings with the multilayer coating under test. The tests were carried out as comparative tests with standard rings. Before assembly in the EMD 645-E engine, the rings were geometrically measured by measuring their axial height and radial thickness. The test stand at the Southwest Research Institute is mounted on a Union Pacific 3450 diesel locomotive, equipped with additional resistance devices and cooling sets. After checking the correct operation of the engine, multistage durability tests were carried out during 85 hours of engine operation. This test was carried out at a rotational speed of 550 rpm and a power of 650 kW.

3. Measurement before and after the test and the wear of the tested piston rings

In addition to geometric measurements of the axial height and radial thickness of the piston rings, the diameters of the cylinders were also measured and their surface was described in detail [23]. Geometric measurements of the rings were carried out at 10 points in their circumference according to the measurement scheme shown in Fig. 2.

The ring number consists of a number followed by the letter "b" (Fig. 2) in the case of a test ring with a diamond coating. The number in the nomenclature means the cylinder number from 1 to 12. The numbering of the cylinders is in accordance with the standards, and looking from the front of the engine (the side opposite to the output power), the left row of cylinders is numbers 1 to 6, and the right row of cylinders is numbers 7 to 12. The absence of the letter "b" in the ring designation indicates measurements for an uncoated ring. The test rings on one crank worked with standard comparative rings. The test rings were installed in the left row in the odd-numbered cylinders, and in the right row in the even-numbered cylinders.

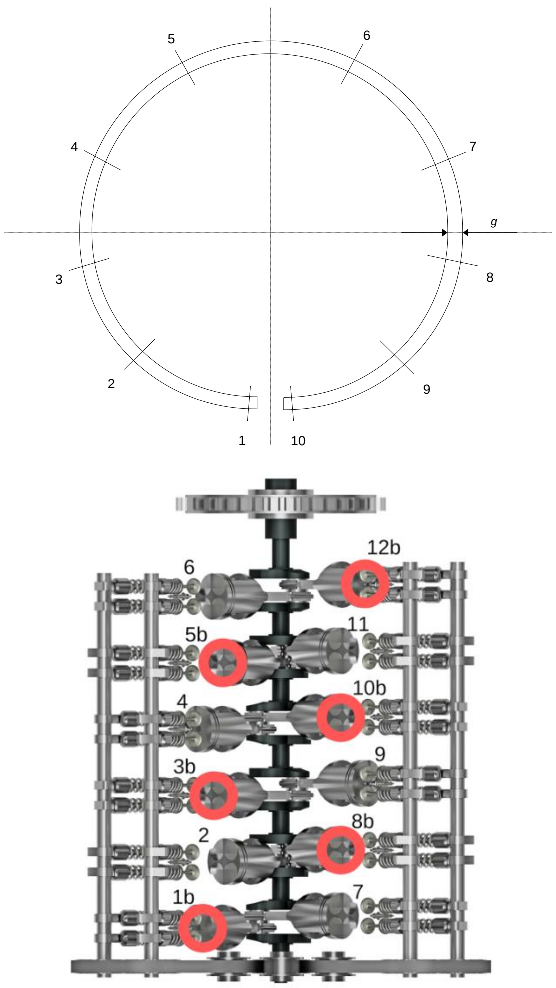

Fig. 2. The measurement scheme of axial high, radial thickness, and the ring number of the EMD 645 engine

The internal combustion engine team durability tests were carried out by implementing the 85-hour test, called the team durability. Such a test is used, among others, by the Federal Mogul. During the test, the engine runs at the rotational speed of the maximum torque value on the external characteristics. This causes an increase in wear as a result of maximising thermal and mechanical loads. The ring-piston assembly is exposed to particularly intensive wear in these conditions. The tests were carried out using the EMD 645-E engine, which has a cylinder diameter of 9.065 inches (230.2 mm). The displacement of one cylinder is equal to 10.35 litres. EMD 645 engines are made in six-cylinder to twenty-cylinder versions with powers ranging from 0.6 MW to 3.1 MW, respectively. whereas a six-cylinder engine is filled with a Roots compressor, and engines with twelve and more cylinders are filled with a turbocharger. The tests were carried out on a turbocharged EMD645-E engine with a rated power of 1200 kW and a maximum torque of 12000 Nm. The cubic capacity of this engine is 124.2 litres [11]. Despite the relatively short duration of the test (85 h), as a result of the intensification of its loads, measurable wear values of the piston rings were found, both in their axial height and radial thickness. To calculate the wear value of the piston rings, the difference in the measurements of their radial thickness and axial height before and after the verification test, lasting 85 hours, was calculated. The results of these calculations are presented in Fig. 3. They are the results of measuring the wear of the axial height and radial thickness, which is the result of the wear process of the diamond-based coating.

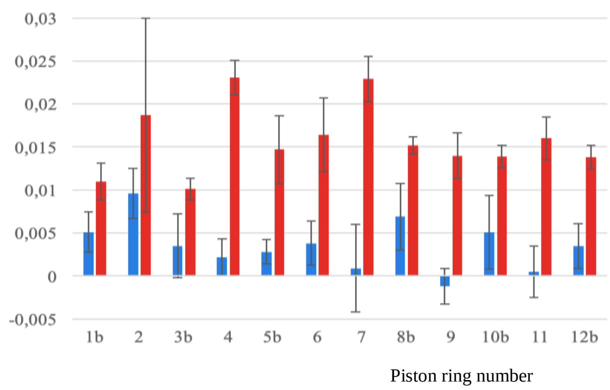

Fig. 3. Average wear of the wear of the ring at axial height (blue) and radial thickness (red)

In cooperation in the piston-cylinder combination, the rings coated with a diamond-based coating were characterised by much lower wear compared to rings that did not have this coating, especially for the wear of the radial width, which is the most heavily loaded working surface of the ring (Fig. 10). The smallest wear of the radial width is about 0.01 mm for the ring with designation 3b with a diamond coating, while the wear of the axial height is low.

The geometric measurements performed showed that the average wear value of the radial thickness of the multilayer porous chrome coating with diamond grit is equal to 0.013 mm. Wear measurements of the radial thickness of the comparative standard rings showed an average wear value of 0.019 mm. The measurement accuracy was 0.001 mm. This means that the differences demonstrated in the average value of the test and standard rings may be significant. Appropriate statistical tests were performed to determine the significance of the differences.

3.1. Statistical analysis

Due to the high variability of the wear values of the rings in their circumference, both in axial height and in radial thickness, the Grubbs test was carried out to determine the existence of outliers. The rejection level of the hypothesis about the lack of outliers was chosen as $p = 0.05$ ("p" values below this value indicate the existence of outliers in the sample population). The test was performed on all 12 rings. In the Table 3 and 4, exemplary results of the test of the wear values of rings 3b and 4 are presented [3].

The test result with a value lower than the assumed significance level of $p = 0.05$ was marked in red [5, 6]. All outliers of the 12 piston rings were identified and removed.

Table 3. Grubbs test for piston ring 3b

Variable	Piston ring 3b Statistics						
	N value	Average	Grubbs-statistic	p-value	Minimum	Maximum	Std. deviation
High-wear axial axis	10	0.004	2.422	0.017	–0.012	0.010	0.0064
Radial thickness wear	10	0.010	1.836	0.440	0.006	0.013	0.0022

Table 4. Grubbs test for piston ring 4

Variable	Piston ring 4 statistics						
	N value	Average	Grubbs-statistic	p-value	Minimum	Maximum	Std. deviation
High-wear axial axis	10	0.002	1.943	0.296	–0.005	0.008	0.0037
Radial thickness wear	10	0.023	1.480	1.000	0.018	0.028	0.0034

Next, using the Shapiro-Wilk test, the normality of the distribution of variables in individual groups (wear of the axial high and radial thickness) was verified for both variables: "axial height wear" and "radial thickness wear". The assumptions for the analysis of variance (ANOVA), i.e. the normality of the distribution for individual ring wear values, were checked. As in the previous test, Fig. 4 and Fig. 5 present the results in the form of histogram plots and fitted normal distributions for rings 3b and 4 regarding the radial thickness.

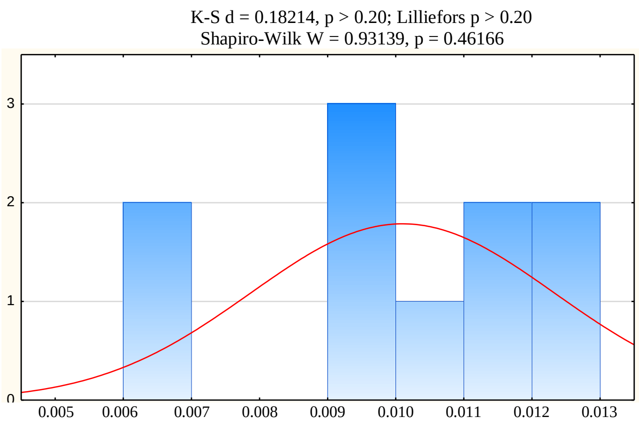

Fig. 4. The histogram of the radial thickness wear of the piston ring 3b [3]

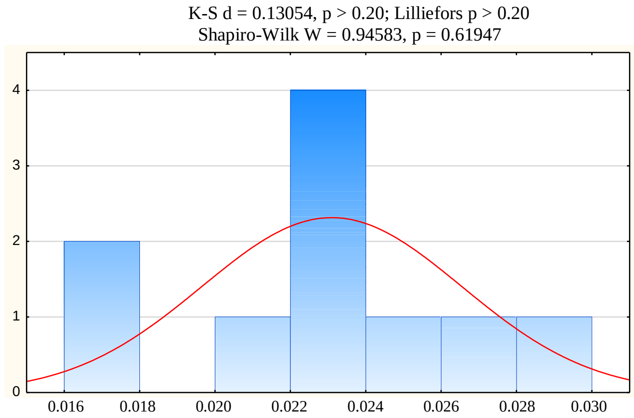

Fig. 5. The histogram of radial thickness wear of the piston ring 4 [3]

Eliminating outliers significantly improved the normality of distribution in individual research groups (wear). With the exception of one study group (ring 6 – "radial thickness wear"), for all others, the value of the Shapiro-Wilk test does not give grounds to reject the null hypothesis about the normality of the distribution.

The assumptions for the analysis of variance (ANOVA), i.e. homogeneity of variance (Levene's test) were also checked, Table 5.

Table 5. Levene's test for all piston rings

Variable	Levene's test, i.e. an analysis of homogeneity of variance Marked effects in red are significant with $p < 0.05$							
	SS effect	Df effect	MS effect	SS misstatement	Df misstatement	MS misstatement	F	p
High-wear axial axis	0.0003	11	0.000029	0.0008	104	0.000008	3.821	0.000126
Radial thickness wear	0.0002	11	0.000022	0.0004	106	0.000004	5.966	0.000000

For both variables, the homogeneity of variance was challenged in Levene's test. Therefore, analysis of variance (ANOVA) with Welch correction was performed. In addition, the results of the analysis will be confirmed by the nonparametric equivalent of ANOVA, the Kruskal-Wallis test.

An analysis of variance (ANOVA) was also performed; see Table 6.

The calculated significance level "p" indicates the rejection of the hypothesis of equal mean values in the groups for both examined variables. In other words, the tested groups (rings) are significantly differentiated in terms of height wear and thickness wear. The "p" value indicates greater variation in thickness wear (lower value – sixth decimal place still 0).

Table 6. Variance analysis with Welch correction

Variable	Variance Analysis with Welch correction Marked effects in red are significant with p < 0.05											
	SS Effect	df Effect	MS Effect	SS Misstatement	df Misstatement	MS Misstatement	F	p	df WelchEffect	df WelchMis-statement	F Welch	p Welch
High-wear axial axis	0.001025	11	0.000093	0.002594	104	0.00003	3.735	0.000165	11	40.837	4.891	0.000086
Radial thick-ness wear	0.001841	11	0.000167	0.001595	106	0.00002	11.1194	0.000000	11	41.480	12.227	0.000000

Due to the undermined homogeneity of variance in the study groups, the nonparametric Kruskal-Wallis test was used to confirm the ANOVA results. The level of rejection of the hypothesis was maintained as for the above tests, i.e. $p = 0.05$ (Table 7 and 8).

Table 7. The Kruskal-Wallis test for variable: axial high of the piston rings

Dependent variable: axial high	ANOVA rang Kruskal-Wallis; axial high wear Grouping independent variable: Kruskal-Wallis piston-ring test: H (11, N = 116) = 33.29436, p = 0.0005		
	N important value's	Summ Rang	Averange Ranga
1b	9	728.00	80.889
2	10	932.00	93.200
3b	9	649.00	72.111
4	10	513.50	51.350
5b	10	547.50	54.750
6	9	490.50	54.500
7	10	414.00	41.400
8b	10	748.50	74.850
9	10	271.50	27.150
10b	10	609.50	60.950
11	10	429.50	42.950
12b	9	452.50	50.278

Table 8. The Kruskal-Wallis test for variable: radial thickness of the piston rings

Dependent variable: radial thick-ness	ANOVA rang Kruskal-Wallis; radial thickness wear Grouping independent variable: Kruskal-Wallis test of the piston ring: H (11, N = 118) = 56.70718, p = 0.0000		
	N important value's	Summ Rang	Average Rang
1b	10	325.50	32.550
2	9	383.00	42.556
3b	10	218.50	21.850
4	10	1034.00	103.400
5b	9	405.00	45.000
6	10	587.50	58.750
7	10	1023.00	102.300
8b	10	707.00	70.700
9	10	538.50	53.850
10b	10	561.00	56.100
11	10	684.00	68.400
12b	10	554.00	55.400

The results of the Kruskal-Wallis test for both verified variables unequivocally confirmed the ANOVA results: wear on the axial height and radial thickness of the tested piston rings are significantly different. This means that the rings wear unevenly around the circumference. At the same time, there is no strictly preferred wear direction.

3.2. Analysis of test results

The engine was found to have consumed 22,400 dm^3 of diesel oil and 45.42 dm^3 of lubricating oil during the 85-hour verification test. Considering the size of this drive unit and comparing it with the results of other studies conducted at the Southwest Research Institute, it was found that these were the correct sizes. The consumption of lubricating oil was small and was 0.2% of the fuel consumption [9]. Whereas, based on the available source data, oil consumption in relation to fuel consumption for a turbocharged EMD 645 engine is equal to 0.5 ±0.2%. This means significant savings in lubricating oil consumption resulting from the use of an innovative piston ring solution with a diamond-based coating [9].

Based on Tables 2 and 3, pie charts were prepared showing the wear of the radial thickness at each of the 10 measurement points on the circumference of the rings for rings coated with and without a diamond-based coating (Fig. 6, 7).

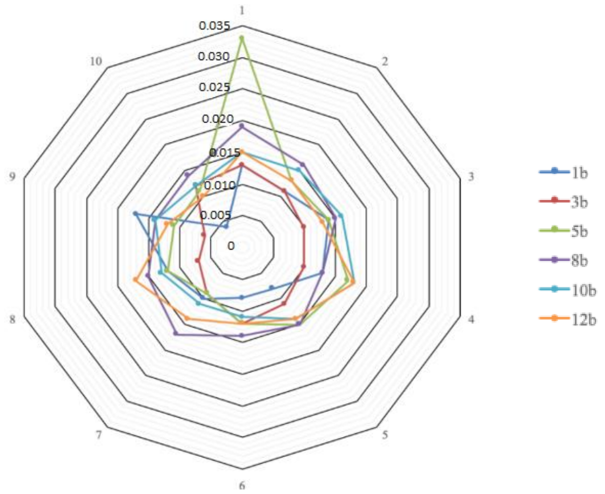

Fig. 6. Wear of the radial thickness of the diamond-coated rings at each of the 10 measurement points [3]

Figure 6 shows the wear of rings at the radial thickness with a diamond coating. The highest wear value was at the measurement point no. 1 on the circumference of the ring marked 5b and was 0.033 mm. The smallest wear value was observed at the measurement point no. 9 at the circumference of the ring marked 1b, which was 0.004 mm. The distribution of wear on the radial width was even, and for all measurement points the wear value did not exceed 0.02 mm, except for measurement point No. 1 on the circumference of the ring marked 5b, which could have been a measurement error.

Figure 7 shows the wear of the rings on the radial width without the diamond coating. The highest wear value was at the measurement point no. 3 on the circumference of the ring marked 2 and amounted to 0.073 mm. This point was outside the area in Fig. 6, due to the adopted scale, which was introduced to maintain similarity to Fig. 5. The smallest wear value was observed at the measurement point no. 7 in the circumference of the ring marked 6, which was 0.008 mm [7].

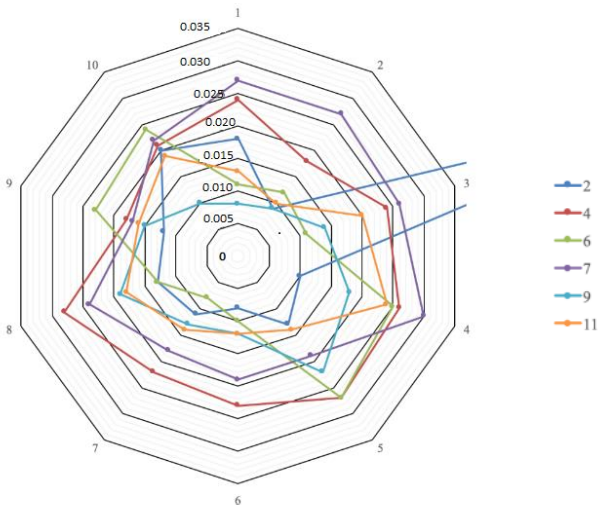

Fig. 7. Wear of the radial thickness of the rings without the diamond coating at each of the 10 measurement points [3]

Cylinder wear values were determined on the basis of completed diameter measurements. Measurements were made at three measurement levels:

– in the Top Dead Centre (TDC) of the first sealing ring (including diamond-coated),
– in the middle of the piston stroke (corresponding to the stroke of the first sealing ring),
– and in the Bottom Dead Centre (BDC) of the first sealing ring.

Measurements were made in two measuring directions: along the longitudinal axis of the engine and across this axis [5]. Due to the fact that the engine is made as a V-shaped arrangement, this is along and across the rows of cylinders. The numbering of the cylinders is in accordance with the Polish standard. Cylinder numbers 1 through 6 apply to the left row cylinders when looking at the engine along the axis opposite the power output side, and cylinder numbers 7 to 12 apply to the right row also when viewed opposite the power output side. If the diamond-based coating in question was made incorrectly, then the indicated measurement accuracy was sufficient to determine such a fact during the tests described in the previous point. The measurement results discussed are presented in Table 9, where the measuring height "0" (measured in mm) is the ZZ of the first sealing ring, the measuring height "127" is the centre of the piston stroke of the first sealing ring, and the measuring height "254" is the ZW of the first sealing ring.

The measured cylinder wear values were within the measurement error range of the bore gauge used for testing, which was 10 micrometres. The bore gauge measurement was a control. If there was excessive wear to the cylinder, a bore gauge with a measuring accuracy of 10 micrometres would show excessive wear. This meant the correct cooperation of the piston rings with the cylinders. The confirmation of the correct cooperation of the developed piston rings with the cylinders is the photograph of the ZZ area of the cylinders No. 3, 5 and 9 in Fig. 8, in which the sealing ring with a diamond coating worked. The honing scratches visible in the photo show little or even no wear of the cylinders.

Table 9. EMD 645 engine cylinder wear values after the verification test

Cylinder No.	Measurement height, mm	Cylinder wear in the longitudinal axis of the engine, mm	Cylinder wear in the cross section 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

Fig. 8. Photograph of the surface of cylinders no. 3, 5 and 8 after the engine verification test

During the implementation of the 85-hour team durability test, the concentrations of harmful components of the exhaust gases and the emissions of selected components were also measured. These tests were performed at the beginning of the trial and after its completion. Sulphur dioxide (SO_2), particulate matter, hydrocarbon content in exhaust gases (HC) and nitrogen oxides (NO_x) measurements were performed. The results of the measurement of these components are presented in the form of concentrations per 1 litre of fuel consumed. The sulphur dioxide concentration was also measured, even though sulphur-free fuel was used. It is normal for a two-stroke engine to consume significant amounts of lubricating oil. For this reason, the presence of sulphur dioxide is found in the exhaust gases, despite the use of sulphur-free fuel. In this case, the results are given in ppm.

Table 10. The value of the emission and concentration of the toxic exhaust components of the EMD 645 engine before and after the verification test

Chemical to be measured	Before test	After test
Sulphur dioxide, SO_2, ppm	0.15	0.18
Solid particles, g/dm^3	2.16	2.15
Carbon monoxide, CO, g/dm^3	9.46	9.85
Hydrocarbons, HC, g/dm^3	4.32	4.55
Nitrogen oxides, NO_x, g/dm^3	81.02	90.5

The concentration limits for harmful compounds in the United States are given in grammes per gallon of used fuel. Therefore, in order to reference these standards, the described measurement of the concentration per litre of fuel was used. The measured concentrations of harmful compounds in the exhaust gases are within the standards applicable in the USA for EMD 645 series engines, introduced by the Environmental Protection Agency (EPA), according to the NSPS standard for the engine category with the designation 1/2 (for ships and locomotives), updated in 2008, which dates back to 1999.

During the 85-hour test, a number of engine performance indicators were discreetly measured. The engine worked at parameters close to the maximum torque value. Measurements of the engine operation indicators were performed every 3 seconds, thanks to which a significant database was obtained, that is, 102,000 records stored in the form of 16 gears corresponding to the engine starts during the test. The analysis of the collected material allowed us to draw conclusions of a utilitarian nature. Figures 9 and 10 show power and hourly fuel consumption curves as examples.

Figure 9 shows the changes in power in particular hours of the verification test. There were no visible differences in the values in the individual hours of the 85-hour test and in the settings. This value was on average at the level of 650 kW–700 kW. Only a change was noticeable at the very beginning of engine operation, but this is caused by the running-in of the TPC unit and the associated load reduction.

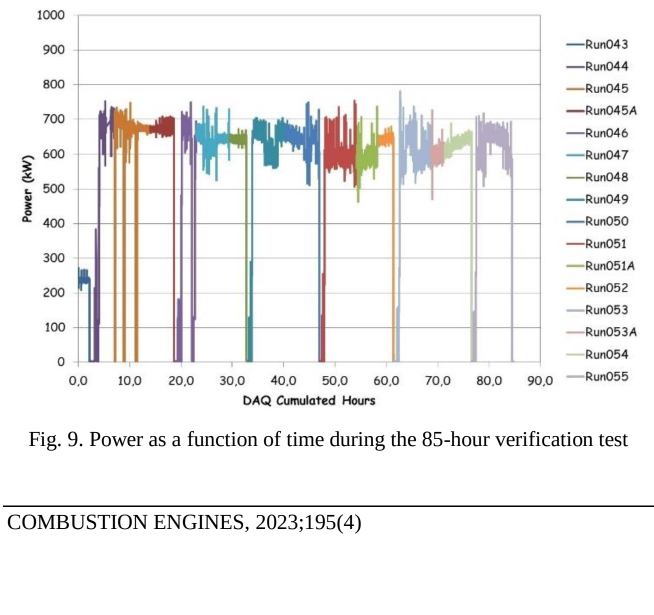

Fig. 9. Power as a function of time during the 85-hour verification test

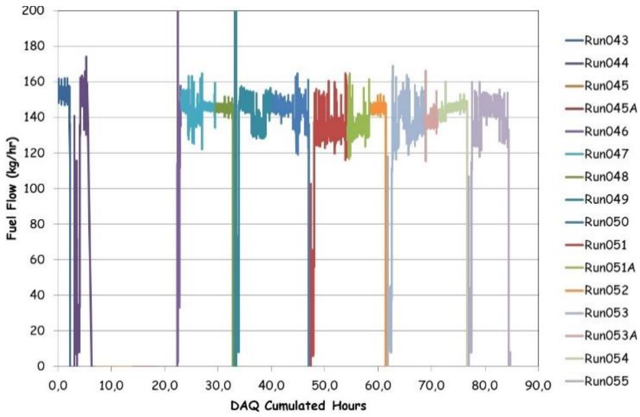

Fig. 10. Hourly fuel consumption as a function of time during the 85-hour verification test

Figure 10 shows changes in the hourly fuel consumption in individual hours of the verification test for each of the controller settings. From about 34.00 hours, the wear showed no signs of disturbance and remained at an even level. However, at 34:00, jumps in these values were observed; they may have been caused by the engine running. Two characteristic peaks were also observed: one to the value of 200 kg/h around the 22nd hour and the other to the value of 200 kg/h around the 32nd hour of the test. Also very characteristic was the moment of lack of fuel consumption measurement between the 6th and 22nd hour of the test, which was caused by a failure of the measuring device.

4. Summary and conclusion

Based on research, among others, presented in [21], it was found that the coefficient of friction of an element with a coating made in a technology based on diamond-containing layers is lower, especially in cooperation with steel and cast iron surfaces. Another extremely important feature of these coatings is wear resistance, manifested by its lower value, which was also found based on the presented research [14]. The use of these coatings becomes particularly important in the event of an intensification of loads, which is, for example, the case in the drive engines of diesel locomotives and inland waterway vessels. They are subjected to extreme loads and are most often operated with maximum torque settings [15]. The tests carried out confirm the desirability of using coatings containing synthetic diamond in their composition. This may be a new direction of research on their wider use for components of internal combustion engines, especially for sealing piston rings [25–27]. The wear values obtained of the radial thickness of the rings tested with coatings containing synthetic diamonds allow us to conclude that their use in highly loaded two-stroke diesel engines is justified [10]. The developed and tested diamond coatings show high adhesion to the steel piston ring substrate despite being subjected to a complex load condition, which is a characteristic feature of the operation of piston rings while ensuring very good tribological properties. Diamond-containing coatings are also characterised by high hardness, even up to 70 GPa [12]. They also have a high electrical resistance value and a low specific mass [20, 28].

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