Article citation info:
KAŹMIERCZAK, A., TKACZYK, M. Team durability test of a 1.3 MW locomotive diesel engine with prototype piston rings. *Combustion Engines*. 2021, **187**(4), 77-82. https://doi.org/10.19206/CE-141166

Andrzej KAŹMIERCZAK
Marcin TKACZYK

Combustion Engines
Polish Scientific Society of Combustion Engines

Team durability test of a 1.3 MW locomotive diesel engine with prototype piston rings

ARTICLE INFO

Received: 15 July 2021
Revised: 5 August 2021
Accepted: 10 August 2021
Available online: 12 September 2021

Objective of this work was to realize a test of 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 chromium layer with including of diamond powders 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-piston rings-cylinder unit in internal combustion engine and an analysis of the use of hard materials (diamond powder) in friction pairs. During work of this unit we can observe wear of piston rings, precisely – of coating which is deposited on ring to prolong service life. After testing of the locomotive engine EMD645 on the basis of the collected results are 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.

Key words: *combustion engine, durability test, piston ring, diamond powder, multilayer*

1. Introduction

This paper describes part of a larger program to reduce wear the set working parts (piston, piston ring and bearing surface). The project is implemented through the development of new designs of piston rings with anti-wear coating that contains synthetic diamond in the form of loose embedded in a coating of chromium (PRS). The main purpose of coating is to reduce ring wear while maintaining or reducing wear cylinder sleeve. Application for said part of the research is EMD 645 engine. The engine used in this study was manufactured by the Electro-Motive Division of General Motors Corporation (EMD). This engine is available in both naturally aspirated and turbocharged configurations, and in V-8, V-12, V-16, and V-20 configurations [1]. It is popular for locomotive applications in North America, as well as in marine, industrial and power generation applications. For this program, the EMD 12-645-E engine was chosen because it is commonly found in switcher and road-switcher locomotive applications in North America, in power ranges from 750 kW to 1,500 kW. Roughly 3,000 of these switcher locomotives are in operation in North America. Figure 1 shows an EMD GP38-2 road-switcher locomotive, which is equipped with an engine like the one tested in this program. Specifications for the EMD 12-645-E engine are given in Table 1. The EMD 645-E engine is a uniflow-scavenged, two-stroke, direct-injected diesel. Figure 2 shows a power assembly from the EMD 645-E engine. Figure 2 shows that the power assembly has four compression rings on the piston crown and two oil control rings at the piston skirt. Prior to testing, the model engine was rebuilt, and equipped with a set of commercially available power assemblies, and broken in for 85 hours of operation.

Fig. 1. EMD GP38-2 road-switcher locomotive

Fig. 2. EMD 645-E power assembly [2]

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

Cylinders	V-12
Bore	230 mm
Stroke	254 mm
Displacement/cylinder	10.6 dm^3
Compression ratio	16:1
Power	1,100 kW
BMEP	5.9 bar @ 900 rpm
BSFC@ rated power	254 g/kWh
Air charging	Gear driven roots – blower
Fuel injection	Cam driven unit – injectors
Crankcase ventilation	Crankcase fumes are returned into the blower
Engine condition	About 100 hours break-in upon complete engine overhaul
Emission certification	EPA Tier 0 – switcher Cycle 2

2. Finite-element simulation

Finite element as such is a simple geometric shape – flat or spatial, for which are set out special points called nodes, and certain functions of interpolation, called functions shape. The nodes are located at the vertices of the finite element may also be placed against its sides, this is called the higher order components [4, 5]. If the nodes are only the vertices of the finite element is called a linear component or element of the first row. The Government of the element is always equal to the rank shape function, while the number of functions in a single component shape corresponds to the number of its nodes [3, 8]. All finite elements and nodes must be numbered, usually seeks to ensure that the numbering will guarantee a minimum bandwidth of non-zero coefficients matrix of equations [4, 8]. FEM concept assumes that any quantity, for example, stress or strain described by a continuous function, approximated discrete model. Discrete model is composed of a set of continuous functions defined in a finite number of subdivisions called elements, to which divided the region [4, 8].

Individual continuous functions of the subdivisions is determined by the value of the primary functions of a finite number of points called nodes. To obtain a discrete model should therefore:

- distinguish a finite number of nodes,
- nodes to determine physical quantities, subject to approximation – such as stress or displacement,
- divide the area in question on a finite number of elements,
- approximate size of the physical elements using polynomial approximation, for example, ranks, or strings [4].

Now that the finite element method is used widely, there are many types and kinds of finite elements. In order to determine the type of finite element makes the following basic criteria characterizing featured item [6]:

- dimension of the element: one-dimensional – 1D, two-dimensional – 2D, three-dimensional – 3D,
- geometric shape,
- the degree and type of shape function adopted,
- number of nodes in the element,
- constraints imposed on the item [5].

Due to the size of finite elements can be divided into one-dimensional, two-dimensional and three-dimensional, exemplary diagrams of data elements are presented below [8]. Of the three-dimensional elements, which describe the three-dimensional space, we can distinguish volume elements such as TETRA, PENTA, HEXA, and elements axially – symmetrical. Due to the geometrical shape can distinguish the following finite elements [2, 8].

In some cases, the mapping area of the curved lines use elements with curved contours – isoparametric elements. For ease of description of the geometry of the curved elements is transformed to the geometry of the core. We can distinguish 3 classes of curved elements:

- isoparametric,
- superparametric,
- subparametric [8].

By constraints imposed on the finite element meant to receive the possibility of movements in different directions points that belong to this element. The element arises field strains and stresses. In the space generally occurs 6 degrees of freedom, while the number of degrees of freedom of the finite element is presented below [4, 5, 8]:

- rod elements 2D and 3D {ux, uy, uz},
- Beam Elements 2D and 3D {ux, uy, uz, αx, αy, αz},
- membrane elements {ux, uy},
- disc elements {ux, uy, αz},
- plate elements {u, αx, αy} or {u, αx, αy, αxy},
- coating elements {ux, uy, uz, αx, αy, αz},
- volume elements {ux, uy, uz}.

During the execution of the strength calculations band of piston rings were carried out in order to calculate the state of stress in the piston rings whose method of implementation and the scope can be reduced to:

1. Develop calculation module piston rings (Fig. 3).
2. Carry out calculations for the three engines of the Rings: EMD 645, I0470, according S359 of Computing Module Piston Rings.

Developed and implemented Piston Rings Calculation Module is compatible with the idea of numerical computational methods is to say: functionally consists in carrying out a calculation of the desire to achieve the exact solution (the nearest is real) by conducting and receiving intermediate solutions (the next). Shown in Fig. 3, a block diagram of a computing unit piston ring contains the names of the functionality of each of the stages in the quest to achieve the final effect, which is to define the geometry and material of piston rings. Presented a block diagram of a computing unit piston rings (Fig. 4) has a sub-module implemented in the rump.

„Load calculation in the model assembly TPC combustion engines using the MES”. Said sub-module is marked in red and will be described in the task of work.

Spreadsheet – Data input at this stage, collected all available data measurement in the piston ring grooves and measurements of the diameters of cylinders, as well as data on the materials from which the consortium member FPT "Prima" SA can make piston rings. Then made estimates based on empirical formulas and pre-defined geometry and material of piston rings. The preprocessor – construction geometry at this stage been set in the previous step geometry of the rings. The construction geometry was carried out in the preprocessor to the program Ansys CFD, construction geometry was based on coordinates of points then combined their curves, which were spread on surfaces which were then sealed in volume and given boundary condition "solid".

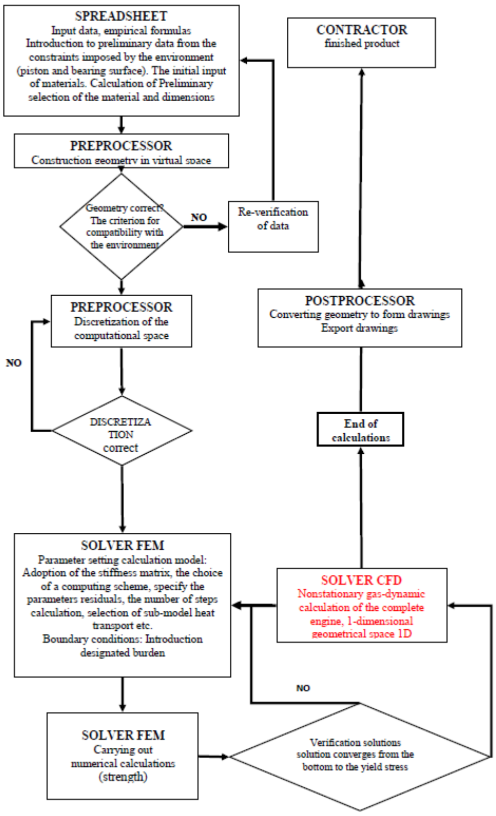

Fig. 3. A block diagram of the computing unit of piston rings

Geometric correct – at this stage was inspected by checking whether the geometry of the virtual rings are located in annular grooves of the pistons. Preprocessor – Discretization computing space, at this stage in the software Ansys CFD made discretization or the distribution of geometry into a finite number of elements, choosing cubic higher-order elements (Fig. 4).

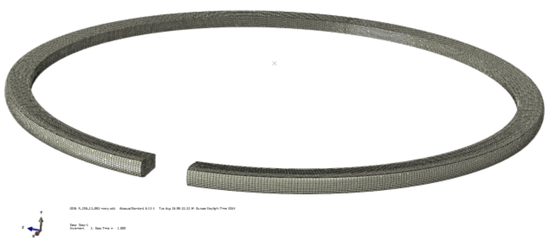

Fig. 4. The discreet form a ring geometry of an exemplary EMD 645E - mesh FEM

Discretization correct – at this stage was made to verify the quality of discrete area of scanning all the elements of the criterion: volume differences, differences in diagonals, differences in lengths of the sides. SOLVER FEM – Abaqus, at this stage, carried out all the necessary steps to build a numerical model of the above/in the system; adoption of stiffness matrix, the choice of a computing scheme, specify the parameters of convergence, the number of steps calculation, selection of sub-model heat transport etc. One of the most important things was the introduction of boundary conditions through proper task force vector. Verification solution – at this stage completed the task of receiving the first targets as a result of stress in the rings under two conditions of load: compression (Fig. 5) and stretching (Fig. 6) for each of the rings. After the analysis for each of the rings to give the results. In Fig. 5 and Fig. 6 have been included distribution of stresses and displacements for the individual rings.

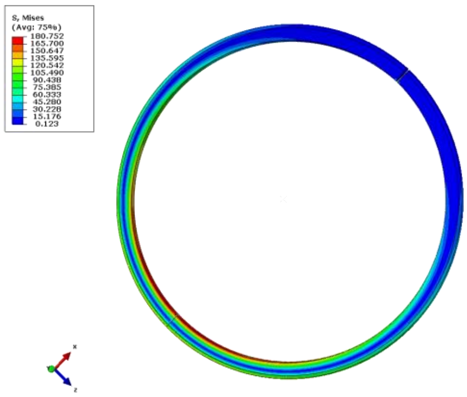

Fig. 5. View of the state of stress in the compression ring engine EMD645

The state in which the rings are shown in the figures k = 1.2 for the material. Noticeable is the accuracy of the highest stresses experienced during assembly ("expansion" of the ring) are found in the most remote from the slot assembly, a similar tendency appears in the case of compression to close the lock.

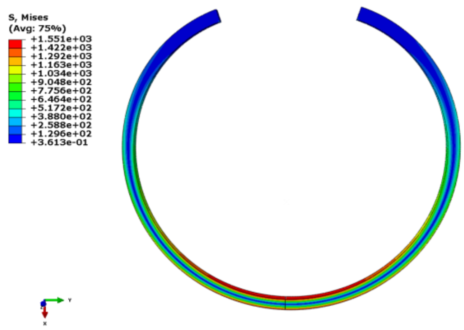

Fig. 6. View of the state of stress in the tension ring exemplary engine EMD 645E

3. Team durability test

The next subject of the research work was to test the durability of internal combustion engine with self-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 [7, 9–12]. 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 Pacific 3450 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 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. 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 roughness's between the ring and the cylinder is accompanying increase in temperature causes the transition of diamond into graphite. This occurs even at 973 K and higher. Thanks to this phenomenon this hardest known mineral becomes a kind of grease. The coating consists of twenty-two layers.

4. Measurement of the rings before and after the test

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 power of the engine varies between 0.6 MW for the six-cylinder unit (10 engine weight 10,000 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 liters. We found a place where the motor was installed on the chassis dynamometer. It is a Southwest Reasearch 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 (Table 3, 4). The measurements were made in accordance with the diagram in Fig. 7.

The average wearing value of the radial thickness, and therefore the wearing of the chrome coating ring with PCD is equal to: 13 μm. The average wearing value of the radial thickness of the rings is equal to a standard: 19 μm. With a measurement accuracy equal to 1 μm differences between the wearing of new rings and standard rings are very important.

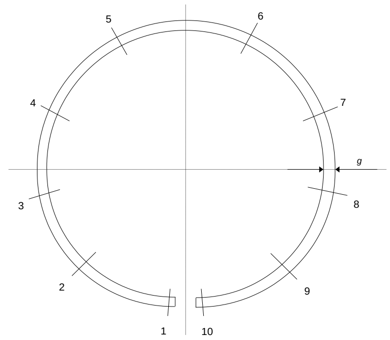

Fig. 7. Measurement diagram of the piston ring

Table 3. Value of the axial height wearing of the rings after the test

Ring	Value of the axial height wearing of the rings after the test [μm]									
Num.	1	2	3	4	5	6	7	8	9	10
1b	–5	9	4	5	4	7	7	4	7	9
2	14	3	10	0	9	11	13	17	9	10
3b	12	1	1	4	1	8	8	6	1	8
4	0	0	–5	1	2	7	2	4	3	8
5b	3	3	0	4	6	2	7	0	3	0
6	0	4	7	1	–2	14	4	2	3	5
7	–2	–3	–1	1	11	17	10	–7	–5	–3
8b	–2	2	3	4	6	3	15	20	11	7
9	1	1	0	–6	-6	–1	5	0	–1	–5
10b	2	16	–2	8	9	–3	18	0	0	3
11	–7	3	–2	-8	1	1	–1	5	5	8
12b	0	4	0	0	6	4	2	–1	5	5

Table 4. Value of the radial thickness wearing of the rings after the test

Ring	Value of the radial thickness wearing of the rings after the test [μm]									
Num.	1	2	3	4	5	6	7	8	9	10
1b	13	11	14	13	8	8	10	12	17	4
2	18	9	73	10	13	8	11	13	12	20
3b	13	11	10	10	11	12	9	7	6	12
4	24	18	24	26	27	23	22	28	18	21
5b	33	13	14	17	15	12	9	12	11	11
6	11	12	11	25	27	10	8	13	23	24
7	27	27	26	30	19	19	18	24	17	22
8b	19	16	15	13	15	14	17	15	14	14
9	8	9	14	18	22	12	13	19	15	10
10b	15	15	16	18	14	11	11	13	14	12
11	13	10	20	24	14	12	14	18	16	19
12b	15	13	13	18	14	12	14	17	12	10

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.

5. Measurements of emissions of exhaust components

During the tests, the emissions of exhaust components were also measured. Measurements were made before the start of the test in the zero state and after its completion. The values of sulfur dioxide (SO_2) emissions, particulate matter emissions, carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x) were measured. These values are summarized in Table 5 as emissions per 1 liter of consumed fuel. As the load during the group durability test was constant, the values of the content of the said toxic components in the exhaust gases were measured many times and converted in relation to the amount of fuel consumed in the test, creating the emission values. An exception is the value of sulfur dioxide emissions, which is the result of the consumption of lubricating oil when using sulfur-free fuel. In this case, the results are given in ppm.

Table 5. Emission value of the toxic exhaust components of an EMD 645 engine before and after the team endurance test

Chemical compound measured	Emission before test	Emission after test
Sulfor dioxide, SO_2, ppm	0.15	0.18
Particulate matter, 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 oxide, NO_x, g/dm^3	81.02	90.5

The emission values were referenced to the amount of fuel consumed in order to be a benchmark for the emission limit of individual compounds, which in the US (target market of the FPT Prima S.A. project consortium) is usually given in grams per gallon of fuel consumed. In summary, it can be stated that the tested emissions are within the standards applicable to the EMD645 engine in the USA.

Throughout the test, many engine performance indicators were discreetly measured. The measurement was performed every 3 seconds of the subject operation during the 85 hours of the team endurance test. As a result, a very rich research material was obtained. The engine is running around its maximum torque value. Due to the fact that the measurement of engine performance indicators was performed, every 3 seconds, it is a large database consisting of 102,000 records collected in the so-called running; here is an example screen with Run055. The analysis of all the collected material allowed for the drawing of a number of utilitarian conclusions.

6. Summary and conclusion

In conclusion obtained maxima strain ring, which comes to maximum stress. On this basis it was concluded that the rings meet designed in terms of strength required Formed during both compression and installation pistons [8].

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 [14]. 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.

Acknowledgements

This work was supported by the National Research Centre of Poland.

Bibliography

[1] REIF, K., DIETSCHE, K.H. *Automotive Handbook*. Robert Bosch GmbH. Karlsruhe 2014.

[2] FROELUND, K., FRITZ, S., SMITH, B. Ranking lubricating oil consumption of different power assemblies on an EMD16-645-E locomotive diesel engine. *CIMAC Congress* 2004, Kyoto.

[3] CORCIONE, F.E., VAGLIECO, B.M., CONSALES, S. et al. Temporal and spatial evolution of radical species in the experimental and numerical characterization of diesel autoignition. *Proceedings of the Fifth International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines* (COMODIA 2001), 2001, 355-363. https://www.jsme.or.jp/esd/COMODIA-Procs/Html/005.html

[4] RUSIŃSKI, E., CZMOCHOWSKI, J., SMOLNICKI, T. Zaawansowana metoda elementów skończonych w konstrukcjach nośnych. *Wydawnictwo: Oficyna Wydawnicza Politechniki Wrocławskiej*. Wrocław 2000.

[5] RUSIŃSKI, E. Zasady projektowania konstrukcji nośnych pojazdów samochodowych, *Oficyna Wydawnicza Politechniki Wrocławskiej*. Wrocław 2002.

[6] https://www.mimuw.edu.pl/~lmarcin/lab/nrr/wyklad.pdf (update 12.07.2021)
[7] BESSLER, W.G., SCHULZ, C., LEE, T. et al. Laser-induced fluorescence detection of nitric oxide in high-pressure flames with A-X (0,1) excitation. *Proceedings of the Western States Section of the Combustion Institute*. Spring Meeting, 145-156, Oakland 2001.
[8] BUCKMASTER, J., CLAVIN, P., LINAN, A. et al. Combustion theory and modelling. *Proceedings of the Combustion Institute*. 2005, **30**(1), 1-19. https://doi.org/10.1016/j.proci.2004.08.280
[9] POULON-QUINTIN, A., FAURE, C., TEULE-GAY, L. et al. microstructure coating influence for optimized diamond deposition. *Material Science Forum*. 2012, **706-709**, 2898-2903. https://doi.org/10.4028/www.scientific.net/MSF.706-709.2898
[10] ALDWELL, B., TRIMBLE, D., YIN, S. et al. Enabling diamond deposition with cold spray through the coated particle method. *Material Science Forum*. 2017, **879**, 1194-1199. https://doi.org/10.4028/www.scientific.net/MSF.879.1194
[11] OZOMAKI, E.T., LAMBERT, C.S., BELANGERO, W.D. et al. Biocompatibility of titanium based implants with diamond-like carbon coatings produced by plasma immersion ion implantation and deposition. *Key Engineering Materials*. 2017, **361-363**, 677-680. https://doi.org/10.4028/www.scientific.net/KEM.361-363.677
[12] MOULIN, D., RAYMOND, O., CHEVRIER, P. et al. CVD diamond coatings for machining. *Material Science Forum*. 2006, **526**, 55-60. https://doi.org/10.4028/www.scientific.net/MSF.526.55
[13] MELLOR, B.D. Surface coatings for protection against wear. *Woodhead Publishing*. CRC Press 2006. https://doi.org/10.1533/9781845691561.1

Prof. Andrzej Kaźmierczak, DSc., DEng. – Faculty of Mechanical Engineering, Wroclaw University of Science and Technology.
e-mail: *andrzej.kazmierczak@pwr.edu.pl*

Marcin Tkaczyk, DEng. – Faculty of Mechanical Engineering, Wroclaw University of Science and Technology.
e-mail: *marcin.tkaczyk@pwr.edu.pl*