Journal of the Balkan Tribological Association *Vol. 26, No 2, 193–205 (2020)*

Wear

ABRASIVE WEAR RESISTANCE OF MICRO- AND NANO-DIAMOND PARTICLES

M. KANDEVA[a,c]*, N. STOIMENOV[b], B. POPOV[b], Zh. KALITCHIN[d], V. POZHIDAEVA[e]

[a] *Faculty of Industrial Engineering, Tribology Center, Technical University – Sofia, 8 Kl. Ohridski Blvd, 1000 Sofia, Bulgaria,*
E-mail: kandevam@gmail.com
[b] *Institute of Information and Communication Technologies – BAS, Acad. G. Bonchev str., bl. 2, 1113 Sofia, Bulgaria,*
E-mail: nikistoimenow@gmail.com
[c] *South Ural State University, 76 Prospekt Lenina, Chelyabinsk, Russia,*
[d] *SciBuCom 2 Ltd., P.O.Box 249, 1113 Sofia, Bulgaria*
E-mail: kalitchin@gmail.com
[e] *Department of Engineering Mechanics, University of Mining and Geology 'St. Ivan Rilski', 2A, Prof. Boyan Kamenov Str., 1700 Sofia, Bulgaria,*
E-mail: vpojidaeva@abv.bg

ABSTRACT

In the present paper a comparative study of innovative diamond coatings with included micro- and nano- sized particles are investigated. The coatings are sintered with high-heat treatment and high-tech WC-12Co coating, applied with supersonic jet plasma (HVOF process) for use under extreme operating conditions.

The results for mass wear, the intensity of wear and wear resistance under the same dry friction modes on the surface of rigidly abrasive particles are obtained.

It has been found out that the highest wear resistance has a coating with included micro-diamond particles, which is about one order of magnitude higher than the wear resistance of a coating with included nano-diamond particles.

The WC-12Co wear resistance coating is 3–4 order of magnitude lower than the wear resistance of diamond coatings with included nano- and micro- sized particles.

Keywords: tribology, abrasive wear, coatings, nano/micro particles, diamond.

* For correspondence.

AIMS AND BACKGROUND

The main task of the tribology is to increase the energy efficiency and life cycle of the machines in accordance with the high requirements for environmental protection by managing the processes of friction, wear and lubrication. It is known that 30% of the world's energy losses are due to friction in the contact joints, and 80-90% of the failures are due to wear. More than 50% of the cost of overcoming wear is due to the abrasive wear of the surfaces of the working bodies and the contact joints in the machines[1÷8].

Tribotechnology is an area in tribology that is focused on the development and study of methods, materials, and technologies for the management of tribological processes[9÷12].

There are three main trends in tribology for overcoming wear:

– development of new and improvement of existing structural materials and coatings with increased physicomechanical and tribological parameters;

– development of new and improvement of existing lubricants;

– study of self-organizing processes in tribological systems to achieve a minimum of friction and wear, and in some cases to achieve non-wear friction.

The first tendency is directly related to parts and machines operating under extreme conditions of exploitation – abrasion, corrosion, erosion, shock and vibration loads, corrosive chemical environment, etc. Such conditions are encountered in agriculture, energy, mining, and road transport equipment. In the mining industry, the most common extreme conditions are encountered in the grinding and milling processes. These processes are carried out in mills, which are divided into three main types: autogenous, semi-autogenous and ball mills. Autogenous and semi-autogenous mills operate with the presence of lifters. Mills are most widely used in various technological continuous processes in metallurgy, mining, cement, and other industries.[13–15].

For the last 10 years, the main approach for increasing the wear resistance of parts has been the development of new composite coatings including in the matrix micro- and / or nano- sized particles – silicon carbide, boron, tungsten, diamond, titanium nitride, boron and other elements, and their compounds[16–21]. For example, the high-tech super-alloy of tungsten and super-alloy of nickel matrix coated with supersonic jet plasma, which finds place under extremal working conditions. Their high performance – density, hardness, and durability make them a serious competitor to galvanic chrome coatings, which in their production create serious environmental and human health problems[22].

The aim of the authors in this publication is to investigate the wear resistance of innovative diamond coatings with included micro- and nano- sized particles, obtained by high-temperature sintering for usage in extremal applications.

MATERIALS

Samples of two types of diamond coatings are examined with micro- sized diamonds (C-DM), with nano- sized diamonds (C-DN), and one type of WC-12Co, coated with supersonic jet plasma (HVOF). The diamond samples were obtained by the method of liquid-phase bonding of diamond beads on a metal surface of steel. The method is known as 'birch' and has been widely used in recent years for coatings of tools for cutting, drilling, shaping, grinding and polishing of rock materials, etc. [23÷24].

The tested coatings were obtained from a multicomponent nickel-based system and content of 5 to 15% chromium, 2,4-2,6% boron, 3,5-3,7 silicon and up to 5% iron. From these components, the use of nickel double-borne and silicon produces a melt, which is triturated with a stream of nitrogen. A granular fraction of 0,07 to 0,05 μm is obtained. The need to use a powder of the chosen granularity is to use it in an aqueous suspension containing up to 1,5% polyvinyl alcohol. The suspension is used for layering on metal, usually steel base, and the individual layers, deposited with a brush, are being dried and then a subsequent layer is applied. The thickness of the generally applied layers of the suspension corresponds to the size of the diamond intended for a particular type of specimen. The sample sintering temperature is from 1040 to 1080 °C. This is a necessary condition, in which the resultant multi-component eutectic liquid phase moistens the surface of the diamond grains and, upon their interaction, produces a chromium carbide microlayer that enhances the cohesive strength of the diamond grains with the metal matrix.

For metallic bonding, a nickel-based mixture containing 13,2% Cr, 2,43% B, 3,56% Si and up to 2,71% Fe with average particle size – 60 ÷ 40 μm, determined by particle size analysis, is used. According to the data, the occurrence of a liquid phase as a result of a eutectic interaction between the alloy components is at a temperature of about 980°C. The optimal sintering temperature is 1040÷1060°C at different retention times for maximum of wetting and anchoring of the diamond (5; 10; 15 minutes).

The application processes of the diamond is performed on a pre-treated flat surface of cylindrical specimens with a diameter of 15 mm, made of iron 45 (Fig. 1).

Fig. 1. Specimen with diamond coating

A diamond is applied with mesh size 30/40; 100/120; 200/230 and 400. Two types of diamonds are used, produced by two different methods: 'Belt-method' and 'Chechevitsa' (different types of carbide molds and catalysts are used)[23–24]. The influence of sintering time on the performance of diamond birch specimens is the study at a temperature of 1050±10 °C and vacuum of 10^{-3} Pa. The duration is 5, 15 and 25 minutes.

Upon increasing the sintering time, a better wetting of diamond grains is observed, even overlapping with liquid phase. Increasing the sintering time interval increases the thickness of the carbide layer between the diamond and the joint. A greater thickness carbide layer reduces the adhesive strength of the metal base coating, although it reduces the thermal stress between the metal and the diamond. The reason for this is that the coefficient of thermal expansion is about 5 times greater than that of the metal component.

EXAMINATION OF THE APPLIED DIAMOND ADHESION WITH THE SAMPLE

Industrial Computed Tomography (CT) Nikon XT H 225 is used. It allows the study of a wide range of materials and sample sizes with a range of 20 up to 225 KV. The CT tomography is equipped with five-axis positioning system. The maximum of sample weight is 15 kg, and the maximal sample dimensions are 15×15×15 cm. The maximum of resolution of the detector is 1900×1500 with an active area of 467 cm^2, accuracy of 3 μm. The system has also computer software for analysis and 3D reconstruction of the internal structure of the sample.

The examined and scanned sample is shown in Fig. 2. The adhesion between the applied diamond coating and the specimen was analyzed. The sections (images) at the beginning (Fig. 3), in the middle (Fig. 4) and at the end (Fig. 5) of the

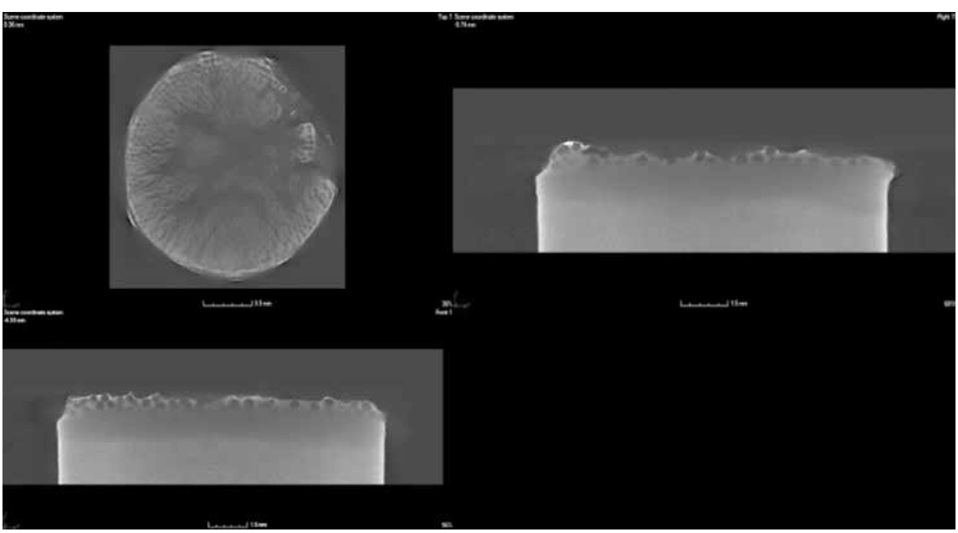

Fig. 2. Overview of the 3D computed tomography of the studied object

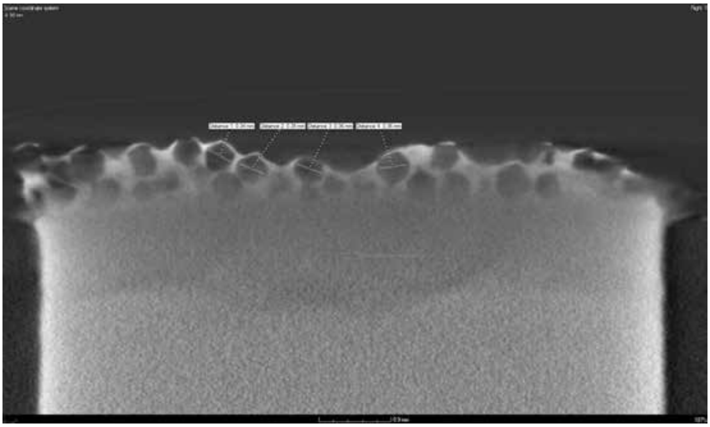

Fig. 3. Beginning of the specimen

Fig. 4. The middle of the specimen

Fig. 5. End of the specimen

specimen are shown, and the tomographic analysis shows good adhesion between the two materials.

DEVICE AND METHODOLOGY

The abrasive wear of the coatings has been studied during dry friction of the surface with fixed solid abrasive particles. The study has been carried out using a tribo-tester of the type ‘Pin on disk’. The functional scheme of the tribo-tester is represented in Fig. 6.

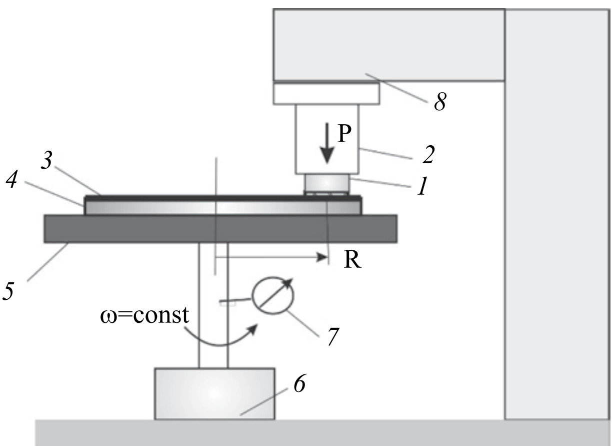

Fig. 6. Schematic diagram of abrasive wear testing on pin-disc tribometer

The studied sample with a coating (1) is attached and fixed firmly in the bed of the holder (2), placed in the loading head (8). The forehead surface of the sample (1) is in contact with the surface of the counterbody (3), fixed firmly on a horizontal disk (4). The disk (4) is being driven by electromotor (6) and it is rotating around its vertical central axis at a constant angular rate ω. The normal loading P is applied in the center of gravity of the contact area between the sample and the surface and it is being driven by the lever system in the loading head (8). The friction path length is set by the number of cycles measured by rotameter 7. The device enables changing of the sliding velocity varying within the limits from 0.55 m/s up to 1 m/s by varying the distance R between the axis of rotation of the disk (4) and the axis of the sample (1).

The methodology for investigation of the characteristics of the wearing off process consists in measuring of the mass amount worn off the samples at a definite friction path length (time interval of friction) under fix set of conditions – loading and sliding velocity. The methodology comprises the following sequence of operations: preliminary preparation of the samples having identical size and measurement of the roughness, thickness and hardness of the coatings; Measurement of the mass m_o of the sample prior to the friction by means of electronic balance WPS 180/C/2 with a precision of 0.1 mg. Before each measurement with the balance the sample is purified from mechanical and organic particles, dried up with ethyl alcohol in order to prevent possible electrostatic effect. The sample is placed in the holder of the loading head, a certain normal loading value P is set and the number of cycles of friction (friction path length) is 500, 1000, 1500; The mass of the sample m_i is measured and the following characteristics of the wearing off process are calculated: mass loss – mg, wear rate – mg/m and wear resistance – m/mg.

RESULTS AND DISCUSSION

The above described device and methodology provide results for mass wear, wear rate and wear resistance for a different number of friction cycles for both micro-particle diamond coatings C-DM, with nano-particle coating C-DN, and with coating WC-12Co, applied by HVOF method. The results are represented in Tables 1, 2, and 3.

A comparison of the wear resistance of the individual coatings is done according to the indicator *relative wear resistance* R_{ij}. Relative wear resistance $R_{i,j}=J_i/J_j$ is calculated as the ratio of the wear resistance of the test coating J_i and the wear resistance of a reference coating accepted for comparison – J_j, obtained under uniform friction conditions.

Table 1. Abrasive wear of tested coatings

Sample	Coating designation	Number of cycles (N)		
		500	1000	1500
		Sliding distance, m		
		116	230	346
		Mass loss, mg		
1	C-DM	0.001	0.002	0.0022
2	C-DN	0.012	0.022	0.0176
3	WC-12Co	2.4	4.6	6.8

Table 2. Wear rate of tested coatings

Sample	Coating designation	Number of cycles (N)		
		500	1000	1500
		Sliding distance, m		
		116	230	346
		Wear rate, mg/m		
1	C-MD	8.6×10^{-6}	8.7×10^{-6}	6.3×10^{-6}
2	C-ND	10×10^{-5}	9.5×10^{-5}	5×10^{-5}
3	WC-12Co	2.0×10^{-2}	2.0×10^{-2}	1.9×10^{-2}

Table 3. Wear resistance of tested coatings

Sample	Coating designation	Number of cycles (N)		
		500	1000	1500
		Sliding distance, m		
		116	230	346
		Wear resistance, m/mg		
1	C-MD	0.12×10^6	0.1×10^6	0.16×10^6
2	C-ND	0.1×10^3	0.1×10^3	0.2×10^5
3	WC-12Co	0.5×10^2	0.5×10^2	0.5×10^2

In Table 4 is repesented the relative wear resistance of the specimens at 1500 number of friction cycles, i.e. 346 m.

Table 4. Relative wear resistance of tested coatings for friction path 346 m

Sample	Coating designation	Wear resistance for friction	Relative wear resistance $R_{i,j}$		
			influence of nano-diamond particles	total comparison	
1	C-MD	0.16×10^6	$R_{1,1} = 1$	$R_{1,1} = 1$	–
2	C-ND	0.2×10^5	$R_{1,2} = 0.8x10$	–	$R_{2,2} = 1$
3	WC-12Co	0.5×10^2	–	$R_{1,3}=0.3 \times 10^4$	$R_{2,3} = 0.4 \times 10^3$

In Figures 7, 8, 9, 10, 11, and 12 the dependences of mass wear and wear intensity on the number of friction cycles for the three types of test pieces are represented graphically C-MD, C-ND, and WC-12Co.

Figures 7 and 9 show that the change in mass wear as a function of the number of cycles/friction path for diamond coatings passes through two sections. The first section of up to 1000 friction cycles is the preparation of the tribo-abrasive surface tribosystem, which shows a sharp increase in wear. This is due to the high friction and high pressure values in the microcontacts.

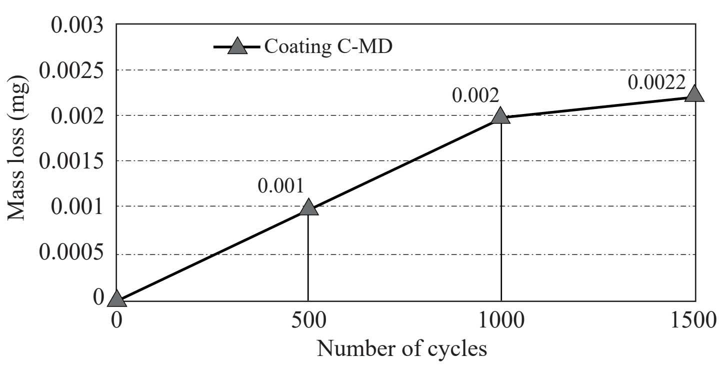

Fig. 7. Change in mass wear from the number of cycles/friction path for coating C-MD

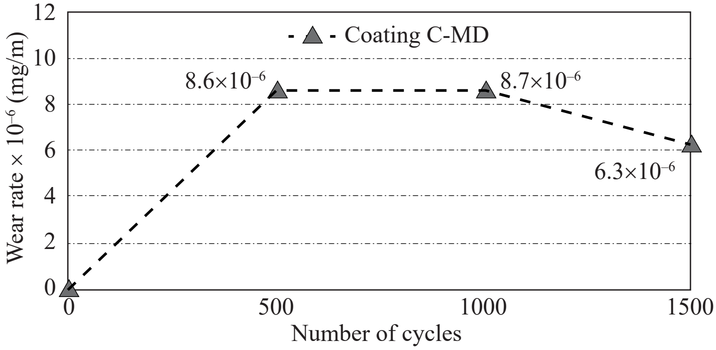

Fig. 8. Change in the wear rate of the number of cycles/friction path for coating C-MD

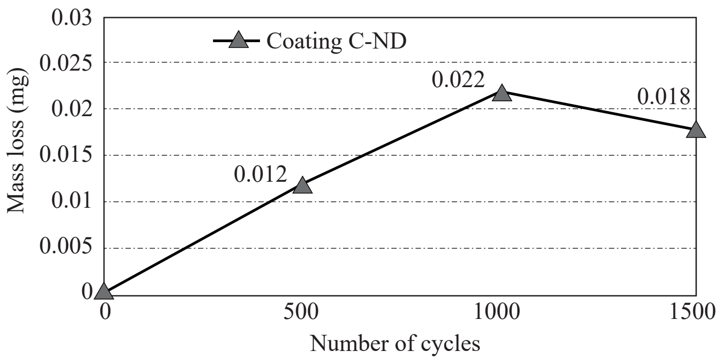

Fig. 9. Change in mass versus from the number of cycles/friction path for coating C-ND

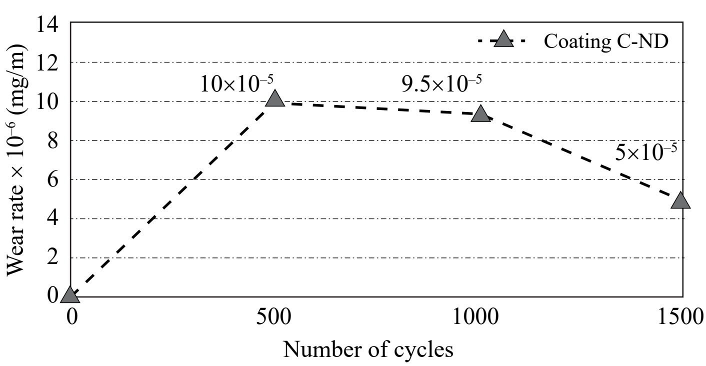

Fig. 10. Change in the wear rate of the number of cycles/friction path for coating C-ND

After friction path of 1000 cycles, there is a gradual decrease in the wear and the system enters in a stationary wear regime. This period is attempted by increasing of the actual contact area of contact, i.e. increasing the number of contact

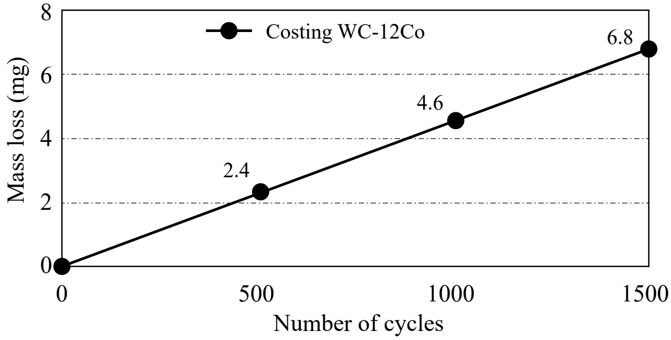

Fig. 11. Change in mass versus from the number of cycles/friction path for coating WC-12Co

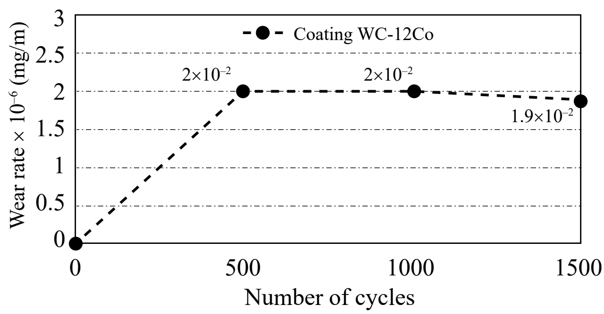

Fig. 12. Change in the wear rate of the number of cycles/friction path for coating WC-12Co

spots and contact pressure coupling. This can be seen clearly in Figures 8 and 10, which show the changing wear rate of diamond coatings. The curves of the two types of diamond coatings have a similar character.

From these figures it can be seen that the wear ratio of diamond micro-particle coatings is less by about one order of magnitude of the wear rate of nano-particle coatings and, with a friction path of 1500 cycles, have corresponding values: for diamond with micro- sized particles – $6.3x10^{-6}$ mg/m, and with nano- sized particles – $5x10^{-5}$ mg/m. This fact can be explained by the higher hardness of the diamond micro-particles themselves, the high cohesive strength between the diamond particles and the binder body of the coating and the high adhesive strength of the coating with the substrate.

The dependence of the mass wear of coating WC-12Co from the friction path is definitely linear in character, without any preparation period (Fig.11), which is evident from the constant intensity (Fig.12) of wear for the tested number of friction cycles.

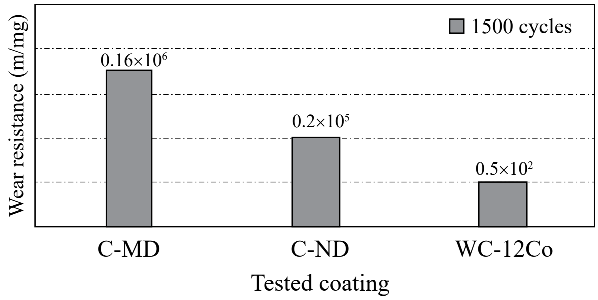

Fig. 13. Comparative diagram of the wear resistance of the tested coatings

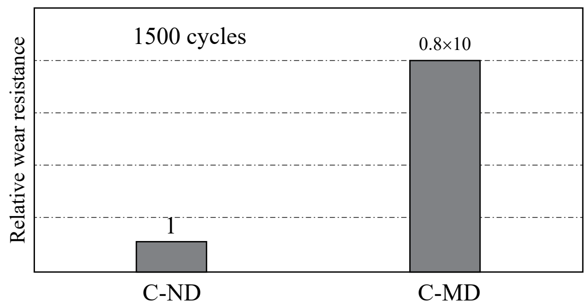

Fig. 14. Influence of diamond particle size on the wear resistance of coatings

Figure 13 shows a comparative diagram of the wear resistance of coatings for the same friction path – 1500 cycles (346 m), and in Fig. 14 – the effect of the size of diamond coatings on the relative wear resistance indicator.

Figure 13 shows that the highest wear resistance is shown by a coating of micro-diamond particles – $0,16x10^6$, which is about one order of magnitude higher than the wear resistance of a coating with nano-diamond particles – $0,2x10^5$ (Fig. 14).

In the tested friction modes, the wear resistance of the WC-12Co – $0,5x10^2$ coating is 3 – 4 orders of magnitude lower than the wear resistance of the diamond coatings with nano- and micro- particles, respectively.

CONCLUSIONS

A comparative study of innovative diamond coatings with included micro- and nano- sized particles obtained by sintering under high heat treatment, as well as high-tech WC-12Co coated with a supersonic jet plasma (HVOF process) for use under extreme operating conditions.

The results for mass wear, the intensity of wear and wear resistance under the same dry friction modes on the surface of rigidly abrasive particles are obtained.

It has been found out that the highest wear resistance has a coating with included micro-diamond particles, which is about one order of magnitude higher than the wear resistance of the coating with the included nano-diamond particles.

The WC-12Co wear resistance is 3 – 4 orders of magnitude lower than the wear resistance of diamond coatings with included nano and microparticles.

ACKNOWLEDGEMENTS

This study and the results are related to the implementation of tasks:

(a) Contract: DM 17/8 – 2017, "Investigation and optimization of milling processes by using innovative grinding environments (lifters)", Grant "Young Scientists – 2017", funded by the National Science Fund at the Ministry of Education and Science, Bulgaria.

(b) Contract: ДН 07/28 "Research and creation of new wear-resistant coatings using composites and nanomaterials", funded by the National Science Fund at the Ministry of Education and Science, Bulgaria.

REFERENCES

1. K. HOLMBERG, A. MATTHEWS: Coatings Tribology: Properties, Mechanisms, Techniques and Applications in Surface Engineering. Amsterdam: Elsevier, (2009).
2. C. M. COTELL, J. A. SPRAGUE: Preface. – In: ASM Handbook, Vol. 5, Surface Engineering, ASM International, Metals Park, 225 (1994).
3. B. BHUSHAN: Principles and Applications of Tribology. New York: John Wiley & Sons, (2013).
4. G. W. STACHOWIAK, A. W. BATCHELOR: Engineering Tribology. Amsterdam: Elsevier, 525 (2014).
5. M. KANDEVA, A. VENCL, D. KARASTOYANOV: Advanced Tribological Coatings for Heavy-Duty Applications: Case Studies, Prof. Marin Drinov, Publishing House of Bulgarian Academy of Sciences, Sofia, (2016).
6. J. GENOV, M. TODOROV: Dynamical Stresses In The High Class Wind Turbine Blades Caused By The Vertical Wind Speed Gradient. Part 1 – Aerodynamical Loads, J Balk Tribol Assoc, **25** (4), 1002 (2019).
7. J. GENOV, I. KRALOV, I. ANGELOV: Llade Element mfmentume Theory adaptation Taking into Account Non-Uniform, Non-Stationary Wind Field, J Environ Prot Ecol, **20** (3), 1270 (2019).
8. I. KRALOV, J. GENOV, I. ANGELOV: Modified BEM Theory Application for Determining the Aerodinamic Forces Acting on the Blade of Wind Turbine, J Environ Prot Ecol, **20** (3), 1255 (2019).
9. N. STOIMENOV, B. POPOV, V. YOSIFOVA: Controlled High-Temperature Sintering of Boron Carbide, MATEC Web of Conferences, **292**, 03005, CSCC 2019, (2019).
10. D. KARASTOYANOV, R. PETROV, M. HARALAMPIEVA: Innovative Technologies for New Materials Using Micro/Nano Elements, MATEC Web of Conferences, **292**, 01007, (2019) CSCC 2019.
11. S. KIROV, R. YANKOVA: Comparative Research of Abrasive Wear of Welded Layers, Journal BulTrib, **6** (06), 209 (2016).
12. T. TODOROV, N. NIKOLOV, R. NIKOLOV, Ya. SOFRONOV, L. KOCHEV: Optimization of Micro-Electro-Mechanical Piezoelectric Energy Harvesters with Interdigitaled Electrode, J Balk Tribol Assoc, **25** (3), 535 (2019).

13. H. TSVETKOV: Mineral processing machines, NP 'Technology', Sofia, Bulgaria (1988).
14. V. MONOV, D. KARASTOYANOV, T. PENCHEV: Advanced Control Methods and Technologies for Two Industrial Processes., Third IEEE International Conference on Information Science and Technology ICIST, March 23–25, 2013; Yangzhou, Jiangsu, China., 978-1-4673-2764-0/13/ ©2013 IEEE., 187 (2013)
15. N. STOIMENOV, N. SABOTINKOV, B. POPOV: Investigation of Materials Behavior in Autogenous Grinding Mill, 8th International Conference on Mechanical Technologies and Structural Materials (MTSM 2018), Split, Croatia, September 27–28, 2018, Croatian Society for Mechanical Technologies, Croatia, ISSN: 1847–7917, 173–176 (2018)
16. D. KARASTOYANOV, T. PENCHEV, G. GAVRILOV: Coating with Nanocomponents for Renovating of Extrusing Shafts. – Problems of Engineering Cybernetics and Robotics, **63**, 49 (2011).
17. D. KARASTOYANOV, V. MONOV: An Advanced Technology for Renovation of Extruding Shafts. – International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, **7** (8), 1679 (2013).
18. M. KANDEVA, D. KARASTOIANOV, B. IVANOVA, V. POJIDAEVA: Influence of Nano-Diamond Particles on the Tribological Characteristics of Nickel Chemical Coatings. – Tribol in Ind, **36** (2), 181 (2014).
19. M. KANDEVA, T. PENYASHKI, G. KOSTADINOV, Zh. KALITCHIN, J. KALEICHEVA: Wear of Electroless Nickel-Phosphorus Composite Coatings with Nanodiamond Particles, J Environ Prot Ecol, **19** (3), 1200 (2018).
20. P. SVOBODA, D. KOSTAL, R. GALAS, I. KRUPKA, M. HARTL: Tribological Behaviour of Ultra Dispersed Diamond-graphite in Liquid Lubricants. J Balk Tribol Assoc., **22** (4), 917 (2018).
21. M. MICHALEC, P. SVOBODA, I. KRUPKA, M. HARTL: Tribological Behaviour of Smart Fluids Influenced by Magnetic and Electric Field – A Review. Tribology in Industry. 2018, **40** (4), 515. DOI: 10.24874/ti.2018.40.04.01. ISSN 03548996.
22. M. KANDEVA, P. SVOBODA, Zh. KALITCHIN, T. PENYASHKI, G. KOSTADINOV: Wear of Gas-Flame Composite Coatings with Tungsten and Nickel Matrix. Part I. Abrasive Wear, Journal of Environmental Protection and Ecology, **20** (2), 811 (2019).
23. J. KONSTANTY, A. ROMAŃSKIAROMANSKI, E. BACZEK, D. TYRALA: New Wear Resistant Iron-Base Matrix Materials For The Fabrication Of Sintered Diamond Tools. **60** (2), (2015)
24. Y. PALYANOV, I. KUPRIYANOV, A. KHOKHRYAKOV, V. RALCHENKO: 17-Crystal Growth of Diamond, Bulk Crystal Growth, Handbook of Crystal Growth, 671 (2015).

Received 18 November 2019
Revised 15 December 2019