

Vol. 21

No 1

2015



# JOURNAL OF THE BALKAN TRIBOLOGICAL ASSOCIATION

## Editorial Board

*Honorary and Founding Editor*  
Prof. Dr. Nyagol Manolov, Bulgaria

*Editor-in-Chief*  
Prof. Dr. Slavi Ivanov, Bulgaria

*Editors*  
Assoc. Prof. Dr. Zh. Kalitchin, Bulgaria  
Mag. Eng. M. Boneva, Bulgaria

*Associate Editors*  
Prof. Dr. Nicolae Napoleon Antonescu,  
Romania  
Prof. Dr. Eng. habil. K.-D. Bouzakis,  
Greece  
Prof. Dr. Branko Ivković, Serbia  
Prof. Dr. Mehmet Karamis, Turkey  
Assoc. Prof. Dr. V. Gecevska,  
FYR Macedonia  
Assoc. Prof. Dr. Mara Kandeva,  
Bulgaria

*International Editorial Board*  
Prof. Dr. Vladimir Andonovic,  
FYR Macedonia  
Prof. Dr. Miroslav Babič, Serbia  
Prof. Dr. G. Haidemenopoulos,  
Greece  
Prof. Dr. H. Kaleli, Turkey  
Prof. Dr. A. Michailidis, Greece  
Prof. Dr. S. Mitsi, Greece  
Prof. Dr. D. Pavelescu, Romania  
Prof. Dr. P. St. Petkov, Bulgaria  
Prof. Dr. Alexander Rač, Serbia  
Prof. Dr. Andrei Tudor, Romania  
Prof. Dr. G. E. Zaikov, Russia  
Assoc. Prof. Dr. Mikolai Kuzinovski,  
FYR Macedonia  
Assoc. Prof. Dr. Fehmi Nair, Turkey  
Assoc. Prof. Dr. V. Pozhidaeva,  
Bulgaria  
Assoc. Prof. Dr. Burhan Selcuk, Turkey  
Assist. Prof. Dr. Afsin Alper Cerit,  
Turkey

Scientific  
Bulgarian  
communications  
Ltd., Co.

## CONTENTS

Vol. 21, No 1, 2015

<i>Tribotechnics and tribomechanics – computer simulation of epoxy resins behaviour</i>	
I. TSIAFIS. Experimental Computational Investigation of Epoxy Resin Behaviour Under Tensile and Torsion Loading .....	1
<i>Tribotechnics and tribomechanics – computer simulations</i>	
QIYIN LIN, ZHENGYING WEI, NING WANG, WEI CHEN. Effects of Large-area Textured/Slip Surface on Slider Bearing .....	12
<i>Tribotechnics and tribomechanics – wear of borided surfaces</i>	
G. KARA, G. PURCEK, Y. ATASOY, E. BACAŞIZ. Microstructure and Tribological Properties of Ti Borided by Electron Beam Evaporation Technique .....	24
<i>Tribotechnics and tribomechanics – tribology in machine elements</i>	
E. DESNICA, A. ASONJA, D. MIKIC, B. STOJANOVIC. Reliability Model of Bearing Assembly on an Agricultural Cardan Shaft ..	38
<i>Computer simulation – wagon series Zans</i>	
S. SLAVCHEV, V. STOILOV, S. PURGIC. Static Strength Analysis of the Body of a Wagon, Series Zans .....	49
<i>Computer simulation – lubricant system</i>	
HAO JIANG, YUHUA BI, LIZHONG SHEN, LI BAO. Lubricant System Optimisation of a Turbocharged Inter-cooler Diesel Engine Based on Network Analysis.....	58
<i>Computer simulation</i>	
A. MIHAILIDIS, E. ATHANASOPOULOS, E. OKKAS. Flash Temperature in Cycloid Reducers .....	76
<i>Static friction and surface roughness</i>	
K. YILDIZLI. Investigation of Static Friction Between Rubber and Modified Aluminum Surfaces Prior to Vulcanisation.....	90
<i>Friction in brake pads</i>	
V. THIYAGARAJAN, K. KALAICHELVAN, K. SRINIVASAN, S. VENUGOPAL, R. VIJAY. Influence of Specific Heat Capacity on Hybrid Non-asbestos Brake Pad Formulation .....	102
<i>Wear of nano-reinforced composites – powder metallurgy</i>	
Y. SAHIN. Wear Analysis of Nano-Al <sub>2</sub> O <sub>3</sub> -reinforced Tini Shape Memory Alloy Composites Under Abrasive Conditions .....	120
<i>Coatings</i>	
V. PETKOV, P. TASHEV, N. GIDIKOVA, M. KANDEVA, R. VALOV. Wear Resistant Chromium Coating with Diamond Nanoparticles upon an Arc Deposited Layer .....	134
<i>Coatings – cutting conditions – fatigue strength-strain rate</i>	
K.-D. BOUZAKIS, P. CHARALAMPOUS, R. PARASKEVOPOULOU, G. SKORDARIS, E. BOUZAKIS, S. KOMBOGIANNIS, G. KATIRTZOGLU, S. MAKRIMALLAKIS. Performance Increase of Hardmetal Cutting Tools Based on Stress-strain Strain Rate Properties of Their Film .....	141
<i>Al-Si alloys – effect of copper</i>	
Y. ALEMDAG, M. BEDER. Dry Sliding Wear Properties of Al-7Si-4Zn-(0-5)Cu Alloys.....	154
<i>Influence of laser beam on surface</i>	
R. ULEWICZ. Hardening of Steel X155CrVMo12-1 Surface Layer .....	166
<i>Wear – finite element analysis</i>	
I. GUNES, S. ULKER, S. TAKTAK, K. ASLANTAS. Finite Element Analysis of Contact Stresses Occurred During Wear of Duplex Surface Treated Steels .....	173
<i>Wear – dry sliding conditions</i>	
A. A. CERIT, F. NAIR, M. B. KARAMIS. Wear Behaviour of Aluminum Matrix SiC particle Reinforced Composite Cam Profile Under Dry Sliding Condition .....	186
<i>Wear – thermal fatigue</i>	
A. C. DRUMEANU. Specific Aspects Concerning the Thermal Fatigue Wear of Die Steels .....	195
<i>Biotribology – dental alloys</i>	
D. KLIMECKA-TATAR, K. RADOMSKA, G. PAWLOWSKA. Corrosion Resistance, Roughness and Structure of Co <sub>64</sub> Cr <sub>28</sub> Mo <sub>5</sub> (Fe, Si, Al, Be) <sub>3</sub> and Co <sub>63</sub> Cr <sub>29</sub> Mo <sub>8</sub> (C, Si, Fe, Mn) <sub>1,5</sub> Biomedical Alloys.....	204
<i>Lubrication – corrosivity of lubricant solutions</i>	
A. C. DRUMEANU, R. G. RIPEANU. Corrosivity of Some Lubricating Solutions Based on Organic Polymers.....	211
<i>Lubrication – regeneration of used oils</i>	
L. BOGATU, I. ONUTU, D. CURSARU. New Alternative for Conditioned Oils Reevaluation .....	222
<i>Machinery breakdown – diagnostics and prevention</i>	
Ch. TSIAFIS, Z. ZAHARIS, M. XANTHOPOULOU, Ch. SKEBERIS, I. TSIAFIS, P. TODOROVIC, Th. D. XENOS. Detection of Non-linear Signal Distortions Due to External Impulse Stimulations in Rolling Bearing Experimental Device .....	233
<i>Anniversary</i>	
S. K. IVANOV. Professor Gennady Efremovich Zaikov. Sixty Years in Science .....	246
Zh. D. KALITCHIN. 80th Anniversary of the Editor-in-Chief of the International Journal of the Balkan Tribological Association, Professor DSc. Slavi Kunev Ivanov .....	254

## WEAR RESISTANT CHROMIUM COATING WITH DIAMOND NANOPARTICLES UPON AN ARC DEPOSITED LAYER

V. PETKOV<sup>a</sup>, P. TASHEV<sup>a</sup>, N. GIDIKOVA<sup>a</sup>, M. KANDEVA<sup>b\*</sup>, R. VALOV<sup>a</sup>

<sup>a</sup> *Institute of Metal Science, Equipment and Technologies, Bulgarian Academy of Sciences, 67 Shipchensky prohod Blvd, 1574 Sofia, Bulgaria*

<sup>b</sup> *Tribology Centre, Faculty of Industrial Engineering, Technical University – Sofia, Sofia, Bulgaria*

*E-mail: kandevam@gmail.com*

### ABSTRACT

A method for applying a thin chromium coating containing nanodiamonds upon an arc deposited layer on steel is developed. The wear resistance of the binary coating is studied. A comparative analysis is performed between the chromium coating containing nanodiamonds and the pure arc deposited layer on steel. The wear resistance of the chromium coating containing nanodiamonds is increased with more than 450% compared to the pure arc deposited layer. The hardness of the binary coating on steel is increased, too.

*Keywords:* nanodiamonds, galvanic coatings, wear resistant coatings, chromium coatings.

### AIMS AND BACKGROUND

The economic crisis of the recent 5–6 years made us consider seriously the decreasing natural resources of the Earth. The metals are used in all fields of industry. Their protection with different surface protective coatings like polymers, ceramic and metallic contribute to their long-term usage in modern industry. In this paper we pay special attention to one new binary coating. The first layer is surfaced arc deposited material and the second layer is composite chromium coating with nanodiamond particles (ND). The nanodiamonds are nanosized diamond particles obtained by detonation synthesis. Their grain size is less than 50 nm with average value of 4 nm. Thus we deem to increase significantly the exploitation properties of the products exposed to wear, erosion, corrosion, etc. This is

---

\* For correspondence.

one of the most important issues of the modern material science. The development of efficient wear resistant coatings is a complicated task since the coatings has to combine high hardness and toughness with low inner tensions, good adhesion to the substrate material and low coefficient of friction.

## EXPERIMENTAL PROCEDURE AND RESULTS

The compositions and their respective electrochemical parameters were selected as a result of previous investigations<sup>1</sup>.

Low carbon construction steel S235 as per EN 10025 with pearlite-ferrite structure was used. An arc deposited wear resistant layer was surfaced with basic electrode IZA – E 300. The content of the surfaced layer is presented in Table 1.

**Table 1.** The content of the surface layer

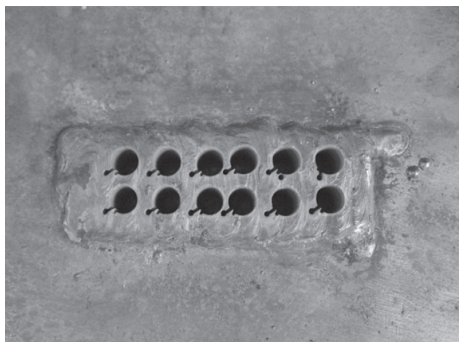
C (%)	Mn (%)	Si (%)	Cr (%)
0.1–0.15	1.6–1.8	0.4–0.8	0.8–1.2

Standard electrolyte was used to prepare the chromium layer with nanodiamond particles. The ratio of the chromium anhydrate to the sulphuric acid was 100:1. This ratio produced the highest yield in relation to the current density. The composition of the chromating electrolyte was  $\text{CrO}_3$  – 220 g/l and  $\text{H}_2\text{SO}_4$  – 2.2 g/l. The used current density was within the range 45–80 A/dm<sup>2</sup>, the duration of the process – 50 min, the temperature of the electrolyte – 50–55°C and the anode was lead. The nanodiamond particles (ND) were added to the electrolyte as a water suspension and their concentrations in the chromating solution were different: 0.25 and 42 g/l. According to some authors, the best wear resistance is achieved when the chromium coatings with nanodiamonds are obtained at a temperature of 55±1°C, current density of 40 A/dm<sup>2</sup> and nanodiamond concentration of 5.0 g/l (Ref. 2).

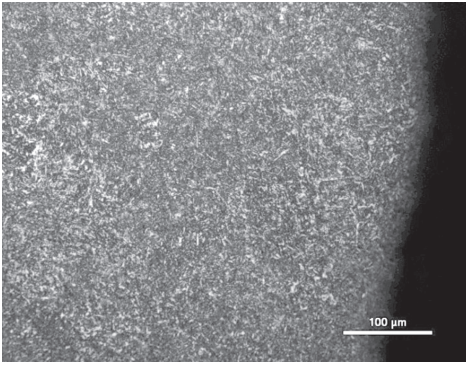
The surfacing was done on rectangular plates with thickness 25 mm out of the chosen steel (Fig. 1) and then the samples for wear resistance tests were prepared by water abrasive cutting machine (Fig. 2). The samples represented cyl-



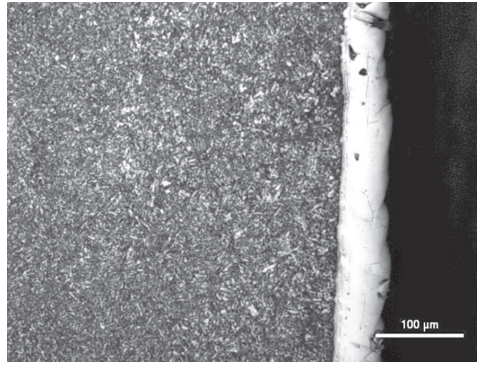
**Fig. 1.** Surfaced layer on steel with 25 mm thickness



**Fig. 2.** Surfaced cylindrical samples cut with diameter of 8 mm



**Fig. 3.** Microstructure of surfaced layer martensite type without coating,  $\times 200$



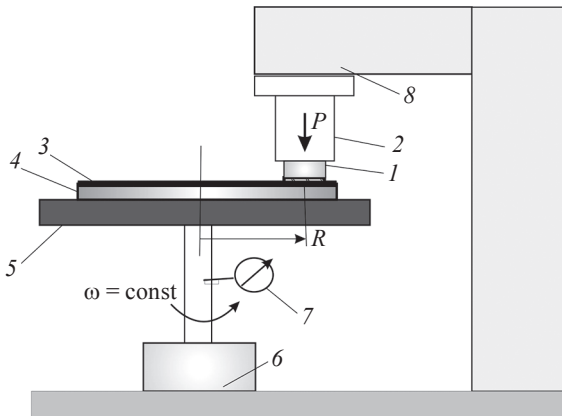
**Fig. 4.** Microstructure of chromium coating with nanodiamonds,  $\times 200$

inders with their axis along the thickness of the plate. Their dimensions were diameter  $d - 8$  mm and length  $h - 25$  mm. The surfaced part was about 10 mm along the length of the sample.

Microstructure of electric arc surfaced layer on steel is shown in Fig. 3 and chromium coating with nanodiamonds with thickness of about  $50 \mu\text{m}$  deposited on the steel – in Fig. 4.

A procedure for accelerated testing has been developed in the Laboratory of Tribology at the Technical University – Sofia and a pin-on-disk tribotester (Fig. 5) device has been used for the experimental study of coatings wear. The procedure matches the operative standards<sup>3,4</sup>.

The studied cylindrical specimen  $1$  with the chromium coating is placed in a holder  $2$  of the loading box  $8$ , so that the coating stays in contact with the abrasive surface  $3$ , fixed on horizontal disk  $4$ . The disk is driven by the motor  $6$  and is rotating around its vertical central axis with rotational speed  $\omega = \text{const}$ .



**Fig. 5.** Scheme of the tribotester for fixed abrasive wear study of coatings

The sliding distance was measured by the number of revolutions read on the revolution counter 7. The device allows sliding speed variation by changing the disk rotational speed through the control unit and/or by changing the distance  $R$  between disk axis and specimen axis.

The abrasive surface 3 is built of impregnated corundum of average grain size  $320\ \mu\text{m}$  and 9.0 Mohs hardness, which meets the standard requirement for over 60% higher hardness than the hardness of the tested coatings.

The procedure included determining the mass wear of the coatings by measuring the specimen mass before and after the preset number of cycles read by the revolution counter 7 (friction duration  $t$ ) using electronic balance of 0.1 mg accuracy. In order to avoid static electricity, the specimens were cleaned with appropriate solution before each measurement. A normal central load  $P$  was performed by a leverage system in the loading box 8. All coatings were tested at one and the same load  $P = 3.92\ \text{N}$  and in this way nominal contact pressure  $P_a = 7.84\ \text{N/cm}^2$  was realised. The wear parameters were determined at a different number of cycles  $N = 100, 150, 250$  and 400. The wear resistance  $I$  was determined as non-dimensional value by the measured mass wear by the formula:

$$I = \frac{\rho A_a S}{m} \quad (1)$$

where  $\rho$  is the density of the coating;  $S$  – the friction distance;  $A_a$  – the nominal contact surface.

The wear of the samples after different number of cycles is presented in Table 2, and the wear resistance of the samples obtained at the same galvanisation conditions – in Table 3.

The relations of the mass wear to the number of cycles of coatings without nanodiamonds and with concentration of the nanodiamonds 25 and 42 g/l obtained at different current density are graphically presented in Figs 6 ( $45\ \text{A/dm}^2$ ), 7 ( $60\ \text{A/dm}^2$ ) and 8 ( $80\ \text{A/dm}^2$ ).

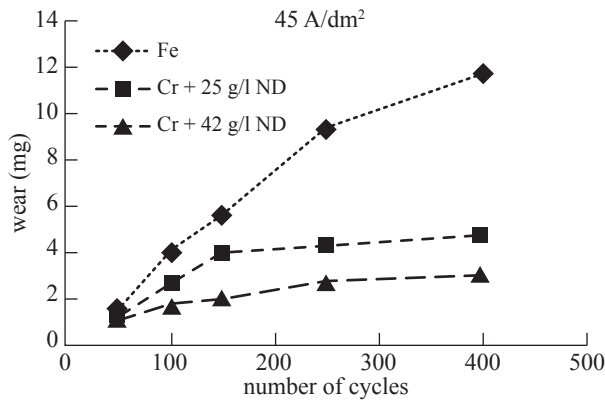
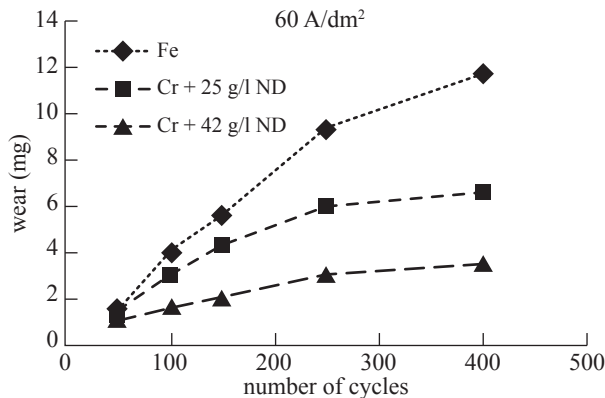
**Table 2.** Wear of samples after different number of cycles (mg)

Sample No	Concentration of ND (g/l)	Current density ( $\text{A/dm}^2$ )	Number of cycles				
			50	100	150	250	400
			wear (mg)				
1	0	0	1.5	4	5.6	9.3	11.7
2	25	45	1.3	2.6	4	4.3	4.8
3	25	60	1.5	2.8	4.3	5.9	6.6
4	25	80	1.8	3.1	5.2	7	7.4
5	42	45	1	1.8	2.1	2.7	3
6	42	60	1	1.5	2	3	3.5
7	42	80	1	1.4	1.9	3.2	3.8

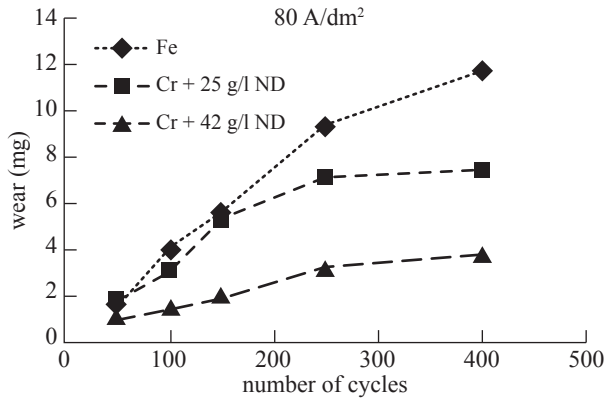
**Table 3.** Wear resistance of samples after different number of cycles  $\times 10^{-6}$ 

Sample No	Concentration of ND (g/l)	Current density (A/dm <sup>2</sup> )	Number of cycles				
			50	100	150	250	400
			wear resistance, $10^{-6}$				
1	0	0	2.71	2.03	2.18	1.75	1.75
2	25	45	3.13	3.13	3.05	3.78	4.23
3	25	60	2.71	2.9	2.84	2.75	3.08
4	25	80	2.26	2.62	2.35	2.23	3.33
5	42	45	4.06	4.52	5.81	5.81	8.13
6	42	60	4.06	5.42	6.1	5.42	5.8
7	42	80	4.05	5.62	6.21	5.32	5.5

From Figs 6, 7 and 8 one may see that the biggest mass wear is in samples without chromium coating, and the least mass wear is in samples with chromium coating with 42 g/l nanodiamonds. The least mass wear is achieved in samples prepared at current density 45 A/dm<sup>2</sup> which is almost 4 times less than the pure arc deposited layer. Similar relation is observed at current densities 60 and 80 A/dm<sup>2</sup>.

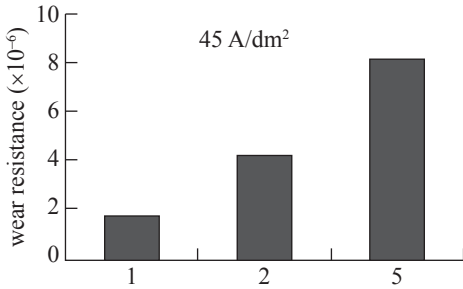
**Fig. 6.** Relation of the wear of coatings with different content of nanodiamonds to the cycles number at constant current density 45 A/dm<sup>2</sup>**Fig. 7.** Relation of the wear of coatings with different content of nanodiamonds to the cycles number at constant current density 60 A/dm<sup>2</sup>

**Fig. 8.** Relation of the wear of coatings with different content of nanodiamonds to the cycles number at constant current density 80 A/dm<sup>2</sup>

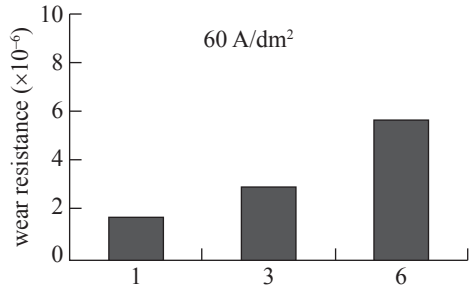


Diagrams of the wear resistance of coatings without and with different nanodiamonds content and at different current density – 45, 60 and 80 A/dm<sup>2</sup> for 400 cycles of friction are presented in Figs 9, 10 and 11.

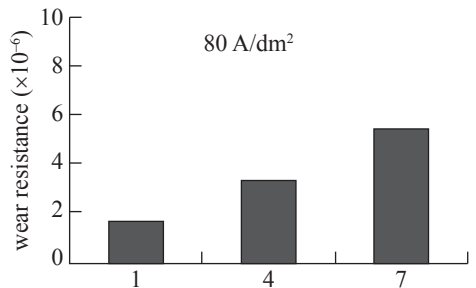
The least wear resistance is observed in samples without chromium coating (Figs 9–11). The biggest wear resistance is achieved in samples with chromium coating with 42 g/l ND and current density 45 A/dm<sup>2</sup>. It is almost 5 times bigger



**Fig. 9.** Diagram of the wear resistance of coatings with different nanodiamonds content (1 – 0, 2 – 25, 5 – 42 g/l) at current density 45 A/dm<sup>2</sup> for number of cycles  $N = 400$



**Fig. 10.** Diagram of the wear resistance of coatings with different nanodiamonds content (1 – 0, 3 – 25, 6 – 42 g/l) at current density 60 A/dm<sup>2</sup> for number of cycles  $N = 400$



**Fig. 11.** Diagram of the wear resistance of coatings with different nanodiamonds content (1 – 0, 4 – 25, 7 – 42 g/l) at current density 60 A/dm<sup>2</sup> for number of cycles  $N = 400$



than the pure arc deposited layer. The similar phenomenon is observed at current density 60 and 80 A/dm<sup>2</sup>.

## CONCLUSIONS

- A method for preparation of wear resistant chromium coating with nanodiamonds on surfaced arc deposited layer is developed.
  - A comparative analysis between pure arc deposited layer and one with chromium coating with ND is performed.
  - With increasing the ND concentration to 42 g/l the wear resistance is increased.
  - The biggest wear resistance is achieved in samples with chromium coating with 42 g/l ND and current density 45 A/dm<sup>2</sup>. It is almost 5 times bigger than the one without chromium. At current densities 60 and 80 A/dm<sup>2</sup> the wear resistance is a little lower.

## REFERENCES

1. M. KANDEVA, N. GIDIKOVA, R. VALOV, V. PETKOV, K. KALCHEVSKA, M. TORBOVA: Wear Resistance of Chromium Composite Galvanic Coating Modified with Nanodiamond Particles. In: Proc. of the 9th International Conference 'THE-A' Coating in Manufacturing Engineering, 3–5 October, Thessaloniki, Greece, 2011.
2. G. K. BURKAT, V. Yu. DOLMATOV, E. OSAWA, E. A. ORLOVA: A Study of Properties of Chromium-diamond Coatings Using Nanodiamonds from Various Producers. *J Superhard Mater*, **32** (2), 98 (2010).
3. ASTM G 99 – 95a: Standard Test Method for Wear Testing with a Pin-on-disk Apparatus.
4. Bulgarian State Standard 14289-77. A Method of Abrasive Wear Testing During Friction on Fixed Abrasive Particles.
5. M. KANDEVA, N. TONCHEV, N. HRISTOV, E. ASSENOVA: Tribological Study of Cladded Bimetallic Coatings. *J Balk Tribol Assoc*, **15** (4), 455 (2009).

*Received 21 October 2014*

*Revised 12 November 2014*