Manufacturing Technique and Properties of Condensed Copper-Carbon Composite Materials for Sliding Electrical Contacts

Nikolay Grechanyuk[1], Rimma Minakova[2], Viktor Bukhanovsky[3], Nikolay Rudnitsky[3*]

[1]Eltechmash (Gekont) Science & Technology Company, Vinnitsa, Ukraine
[2]Frantsevich Institute for Problems of Materials Science under the National Academy of Sciences of Ukraine, Kiev, Ukraine
[3]Pisarenko Institute for Problems of Strength National Academy of Science of Ukraine, Kiev, Ukraine
Email: eltecnic@bk.ru, 29min@ipms.kiev.ua, *nadiynist@ipp.kiev.ua

Received 15 April 2014; revised 5 August 2014; accepted 8 September 2014

Abstract

The production technology, structure, electrical conductivity, coefficient of friction, hardness, strength, and plasticity over a temperature range of 290 - 870 K of laminated copper-carbonic composites for sliding electrical contacts of current-collecting devices obtained by electron-beam evaporation and vapor condensation are studied.

Keywords

Copper-Carbonic Condensed Composite, Electron-Beam Technology, Material Structure, Electrical, Tribotechnical and Mechanical Characteristics

Subject Areas: **Physics & Mathematics**

1. Introduction

Now-a-day composite materials (CMs) based on copper and carbon are widely used as electro contact materials for current-collecting devices [1]-[4]. In addition to the conventional powder metallurgy processes for producing these materials, they are also obtained by high rate electron beam evaporation of copper and carbon from individual water cooled crucibles and layer by layer condensation of the mixed vapour flow on a rotating steel disk. The technology of high rate electron beam evaporation-condensation is the alternative for powder metallurgy: in united space, the processes of thermal dispersion of liquid melt and consolidation of dispersed particles flow

*Corresponding author.

How to cite this paper: Grechanyuk, N., Minakova, R., Bukhanovsky, V. and Rudnitsky, N. (2014) Manufacturing Technique and Properties of Condensed Copper-Carbon Composite Materials for Sliding Electrical Contacts. *Open Access Library Journal*, **1**: e371. http://dx.doi.org/10.4236/oalib.1100371

(without special molding for obtaining the high-density material state) with a limited amount of admixtures are observed. The apparent advantages of the electron-beam technology, which makes it possible to develop a new generation of composite materials for electrical contacts, are as follows:

- the possibility to mix the vapor flows of substances that do not dissolve well in each other at the atomic and molecular levels, and obtain composite materials and coatings (facing layers) with the assigned structure, chemical composition and performance characteristics, which cannot be obtained by other methods;
- simplicity and efficiency as compared to the methods based on powder metallurgy, as the material is formed in one technological cycle;
- the possibility to create gradient structures by varying the deposition rate of the components being evaporated in the course of the technological process;
- the possibility to obtain laminated composite materials, which is practically impossible to achieve using traditional methods;
- ecological purity, as this technology eliminates all atmospheric emissions.

The electron beam evaporation and subsequent condensation technology are applied to produce electrical contact Cu-C CMs with specified laminated structures and chemistries within one production cycle. Such a composition determines its unique physico-mechanical and operating properties. The condensed copper-carbon composite materials with carbon contents from 1.2 to 7.5 vol.% in the form of sheets of 3 - 5 mm in thickness have produced by the Eltekhmash (Gekont) Science & Technology Company and, at present, these materials are in series production in Ukraine. Generally, these sheet materials are used in current-collecting devices as operating floors of copper contact clips attached to them by brazing [5]-[9].

The present paper covers data on production technology and experimental investigations of the structure, electrical along with tribotechnical characteristics, strength, hardness, and plasticity of the condensed composite materials of the Cu-C system for current-collecting devices with carbon content from 1.2 to 7.5 vol.% over a temperature range of 290 - 870 K.

2. Material and Methods

One of the advantages of the copper-carbon CMs is the possibility to change their electro conductivity and tribotechnical properties in a wide range with variation in copper and carbon content in the composite. The high-speed electron beam evaporation and condensation is regarded here as the most common and easily implemented manufacturing method.

However, there are almost insurmountable difficulties for obtaining the Cu-C system CMs using the mentioned production process due to a lack of physicochemical interaction between copper and carbon, a very high melting temperature of carbon and the difficulty of its transformation into a vaporous state. In the light of this, the original electron-beam technology of carbon evaporation through molten tungsten mediator has designed by the Eltekhmash (Gekont) Science & Technology Company, and, thus, obtained experimental industrial specimens of Cu-C CMs with the carbon content controlled within a particular range.

The objects for the present investigation were the studies on condensed composites of the Cu-C system, which were produced using electron-beam technology with the carbon content of 1.2, 3.5, 5.0 and 7.5 vol.%.

The electrical-engineering Cu-C composites condensed from the vapor phase were obtained on the L5 electron-beam facility designed at the Eltekhmash (Gekont) Science & Technology Company. The physical configuration and scheme of the facility are given in **Figure 1** and **Figure 2**, respectively. The facility represents technological work chamber 1 (**Figure 2**). The side wall of the work chamber has gun chamber 2 attached to it, which contains electron-beam heaters 3, 4, 5 and 6. The vacuum system, which comprises two fore pumps, two booster pumps and two high-vacuum units, serve to provide dynamic vacuum in the facility chambers for evaporation and condensation of the initial materials.

On the upper flange of the work chamber 1 there is a mechanism 15 that rotates steel substrate 800 mm with diameter 14 mm. The design of this mechanism allows it to be operated for a long time without destroying vacuum at a temperature of 870 ± 50 K. The substrate fixed to the rotation rod 7 was heated to the assigned temperature by 40 kW electron-beam heaters 5 and 6. The initial material was heated to evaporation by 100 kW electron-beam heaters 3 and 4. All heaters have independent cathode-glow and electron-beam controls.

The evaporation unit has crucibles 8, 9 with a diameter of 100 and 70 mm for evaporation of copper and carbon, ingots 10, 11 to be evaporated, and mechanisms that allow the ingots to be put in the evaporation zone 12, 13.

Figure 1. Physical configuration of the L5 electron-beam facility designed at the Eltekhmash (Gekont) Science & Technology Company.

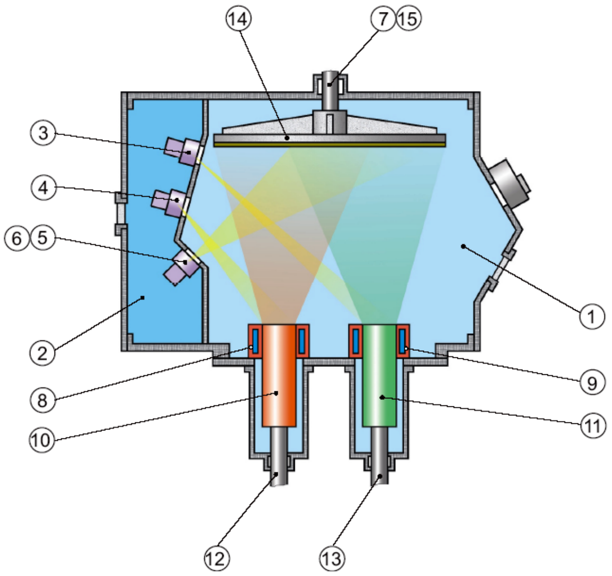


Figure 2. Scheme of the L5 electron-beam facility. Designations: 1—work chamber; 2—gun chamber; 3, 4, 5 and 6—electron-beam heaters; 7—substrate rotation rod; 8—crucible for evaporation of copper; 9—crucible for evaporation of carbon; 10, 11—ingots of copper and carbon, respectively; 12, 13—mechanisms for supplying ingots in the vapor flow zone; 14—steel substrate for condensation of copper and carbon vapor flows; 15—substrate rotation mechanism.

In the present investigation, the copper-carbon condensates are obtained by means of copper and carbon evaporation from separate crucibles followed by their condensation on a rotated steel substrate coated with a separating layer of calcium fluoride. The steel substrate was heated to a temperature of 935 - 965 K. The initial materials were M0 grade copper ingots with 100 mm in diameter after electron-beam remelting and GMZ grade carbon ingots with a diameter of 70 mm.

The process of carbon evaporation involves the following stages. The batch of VA grade tungsten of 400 g weight was put on the surface of the carbon ingot. When a vacuum level of $(1.3 - 4.0) \times 10^{-3}$ Pa is reached in the work chamber, then electron-beam heating of the substrate is performed, on which vapors were to be condensed up to the temperature of 950 ± 15 K. Simultaneously, the surfaces of both ingots with electron beam were heated up to the melting temperature of the base metal—copper and intermediate for carbon technological metal—tungsten at a current of 1.15 - 1.3 A. The melt pools became homogeneous after 15 - 20 minutes of heating. A layer from the crucible for copper evaporation was the first to be condensed on the substrate. At the production stage, evaporation from both crucibles was performed simultaneously at a beam current of 2.2 - 2.4 A for copper and 2.6 - 3.8 A for carbon under acceleration voltage of 20 kV. By varying the beam current one can readily regulate the evaporation rate of carbon and its concentration in the composite over wide ranges.

By maintaining the substrate temperature in the range from 935 to 965 K, the re-evaporation of copper from the surface of the condensed material is prevented. The condensation rate of the tempered vapour flow was 20 μm/min. The resulting condensed materials were 2 - 3 mm thick disks of 800 mm in diameter.

At the end of the technological process, the condensed composite material was separated from the substrate. The obtained condensed material was annealed in the vacuum furnace at 1170 K for 3 hours in order to relieve internal stresses, make the structure stable and enhance the material ductility.

During the study, used research techniques include the macro-and microstructure analysis using optical and scanning electron microscopy, electrical resistance, tribotechnical tests, mechanical tensile tests at room and high temperatures as well as hot hardness measurements.The content of carbon and copper was determined using the mortar method (volumetric analysis).

The structure of the composite materials was investigated by optical and scanning electron microscopy using the “Neophot-2” optical microscope and the “Superprobe 733” raster electron microscope manufactured by “Jeol”. Specimens for metallographic analysis were prepared using chemical etching in a 40% hydrochloric acid solution and ion etching in a glow discharge. The specimen surface and cross section perpendicular to the substrate were studied.

The mechanical characteristics were determined at ambient (outdoors) and elevated temperatures to 870 K (in vacuum not below 0.7 mPa) from the results obtained towards of mechanical tensile tests of standard flat fivefold proportional specimens with a gauge length of 15 mm, width of 3 mm and thickness of ~2 mm using a 1246-R unit [10] according to ISO 6892 [11] and ISO 783 [12], respectively. The specimens were cut from ~2 mm thick composite material after vacuum annealing at 1170 K for 3 h. The content of carbon in the composites varied from 1.2 to 7.5 vol.%. 3 - 5 specimens were tested at each temperature. The deformation rate was 2 mm/min, which corresponded to a relative strain rate of $\sim 2.2 \times 10^{-3}\ s^{-1}$. During the tests deformation diagrams were recorded to determine the proof strength $R_{p0,2}$, the ultimate strength R_m, the percentage elongation after fracture A, and the percentage non-proportional elongation at the maximum force A_g. In addition, the percentage reduction of cross-sectional area Z was evaluated.

The Cu-W composite hardness was estimated in the temperature range from 290 to 870 K by the Vickers indentation in the plane parallel to the surface of condensation. The pyramidal point was made of a synthetic corundum single crystal. Indentation loads were 10 N. The tests were carried out at a pressure not more than 0.7 mPa on a UVT-2 unit [13] [14] according to the DSTU 2434-94 [15].

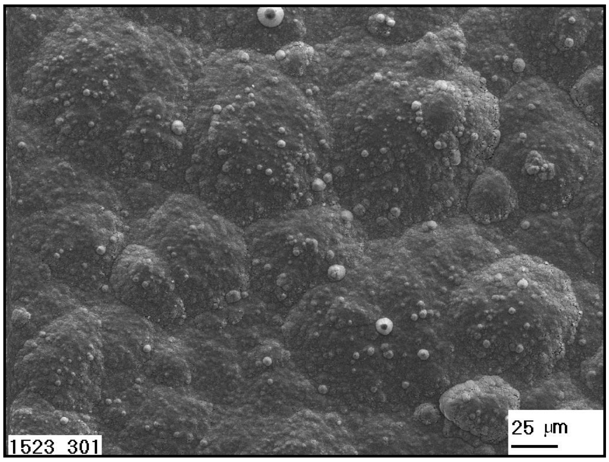
The experimental data, obtained by hardness measurement, were statistically processed. The average specimen value (mathematical expectation) x, the specimen standard deviation S, the coefficient of variation w, and the confidence limits Δx for the mathematical expectation were calculated at a significance level of $\alpha = 0.05$.

3. Results and Discussion

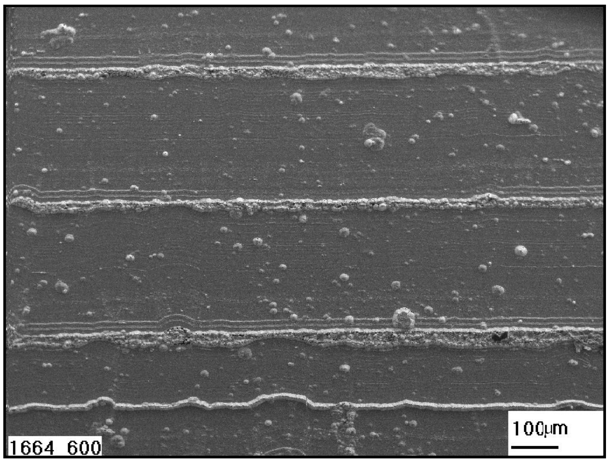
The electron-beam technology provides a specific laminated structure of composites with alternating layers of copper from 150 to 300 μm in thickness with disperse particles of carbon and layers of carbon from 6 to 8 μm in thickness (**Figure 3**). The copper grain size is 0.1 - 0.3 μm, and the mean size of disperse carbon particles in copper matrix does not exceed 200 Å.

The results on investigation of the tribotechnical characteristics of the condensed Cu-C CMs together with a copper contact wire show that the friction coefficient for the composites with 4.0 - 7.0 vol.% C decreases by 3 -

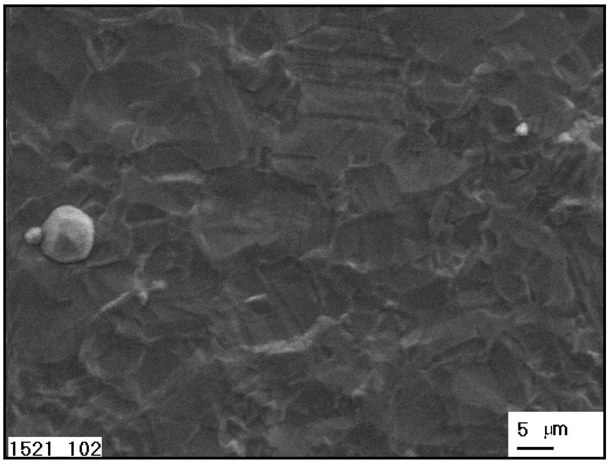
4 times as compared with the tough-pitch copper.



(a)



(b)



(c)

Figure 3. Microstructure of the Cu-5.0 vol.% C composite (scanning electron micrograph): (a) composite surface microstructure (without etching); (b) micro-layer structure of the composite, observed after ion etching; (c) polygonal structure of the layers, observed after ion etching.

The electrical conductivity of the investigated condensed CMs depending on the carbon content (from 1.2 to 7.5 vol.%) varies in the range from 34,850,000 to 40,700,000 SC/m, which is from 60% to 70% of that of copper. The electrical conductivity of the condensed CMs is almost one and a half as much as that of the known Cu-C powder compositions.

At the same time, the electrical conductivity of the condensed composites decreases naturally with an increase in carbon content. The maximum magnitude of the transferred current (up to 3000 A) for the condensed Cu-C CMs is two times higher than that of silver.

In operation, the materials of current-collecting devices are subjected not only to intensive wear and electrical erosion, but also to mechanical loads at elevated temperatures. Therefore, studies on their mechanical properties over operating temperature ranges are of definite scientific and practical interest.

Strength and plasticity characteristics of the investigated copper-carbon composites over a temperature range of 290 - 870 K are presented in **Table 1**. As follows from **Table 1**, its strength loss due to heating is of monotonous nature. The tensile strength and proof strength of the material decrease monotonically from 250 - 260 MPa and 180 - 235 MPa at room temperature to 30 - 60 and 32 - 53 MPa at 870 K, respectively. Moreover, the strength properties of Cu-C CMs decrease with an increase of the percentage carbon content in the composite within the entire temperature range.

Temperature dependences of CMs plastic properties are of more complicated nature with peaks caused by hot brittleness typical of copper and its alloys. In particular, a sharp decrease in plasticity values is observed at 570 K. An increase of the carbon content in composites facilitates decrease of their plastic characteristics at all investigated temperatures.

Hardness variations due to heating of the copper-carbon composites are shown in **Table 2**. With an increase in temperature, hardness monotonically decreases from maximum values of 805 - 951 MPa at room temperature to minimum values of 74 - 138 MPa at 870 K. Moreover, hardness of the condensed CMs as well as their strength characteristics decrease naturally with an increase in the carbon content in composites over the entire investigated temperature range.

Owing to their specific laminated structure the condensed CMs surpass the known Cu-C powder composites of the similar composition in mechanical characteristics (including strength, plasticity and hardness) [4].

Due to high tribotechnical, electrotechnical, mechanical and operating characteristic the condensed Cu-C CMs produced by the Eltekhmash (Gekont) Science & Technology Company are used for the manufacture of sliding contacts for current-collecting devices of electric transport (**Figure 4**). These materials exhibit high operating characteristics and are successfully used in Ukraine.

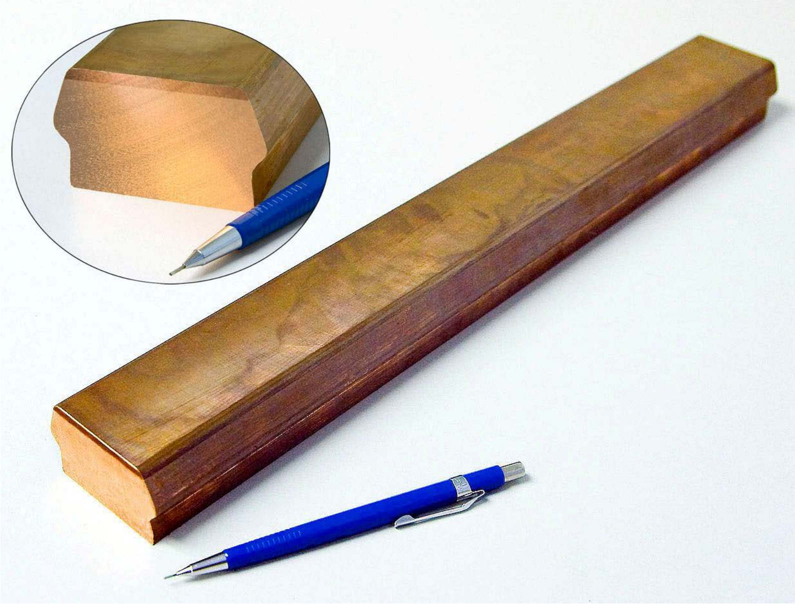


Figure 4. Production specimen of sliding contact for current-collecting device of electric transport made on basis of Cu-C condensed CMs.

Table 1. Strength and plasticity characteristics of the Cu-C composites in the 290 - 870 K temperature range.

T, K	R_m, MPa	$R_{p\,0.2}$, MPa	A, %	A_g, %	Z, %
Composite Cu-1.2 vol.% C					
290	260	235	27.8	20.2	70.5
370	233	196	21.0	15.2	59.0
470	194	153	16.7	11.3	40.0
570	165	136	14.9	9.0	34.4
670	127	107	20.7	12.0	35.0
770	93	86	29.3	4.8	36.5
870	60	53	40.4	20.2	40.2
Composite Cu-3.5 vol.% C					
290	257	225	24.7	20.3	42.3
370	216	186	20.0	16.4	35.4
470	185	145	16.5	12.1	34.5
570	145	128	14.5	10.0	33.0
670	107	100	11.3	7.8	30.5
770	83	75	10.5	3.2	27.0
870	50	47	9.2	2.0	23.2
Composite Cu-5.0 vol.% C					
290	253	186	8.5	5.5	28.2
370	213	173	6.7	4.3	24.6
470	167	140	4.6	4.1	22.0
570	127	117	4.5	4.2	20.2
670	104	96	6.0	3.2	18.3
770	65	59	6.6	2.0	17.4
870	37	34	8.2	2.5	17.0
Composite Cu-7.5 vol.% C					
290	250	180	7.5	4.5	25.0
370	210	167	5.7	4.0	22.5
470	155	133	4.1	3.7	20.0
570	107	100	4.0	3.6	19.2
670	95	90	4.5	3.0	17.3
770	55	49	5.5	2.5	16.4
870	30	32	7.0	2.0	16.0

Table 2. Hardness of the Cu-C composites in the 290-870 K temperature range.

T, K	*HV*	Δ*HV*	*HV*	Δ*HV*	*HV*	Δ*HV*	*HV*	Δ*HV*
	MPa		MPa		MPa		MPa	
	Cu-1.2 vol. % C		Cu-3.5 vol. % C		Cu-5.0 vol. % C		Cu-7.5 vol. % C	
290	951	±44.1	926	±27.9	828	±45.3	805	±43.8
370	783	±33.5	724	±43.9	666	±78.3	618	±29.1
470	579	±29.5	571	±23.4	552	±64.5	526	±20.9
570	389	±12.7	381	±11.3	373	±33.7	359	±34.9
670	290	±4.0	263	±5.3	252	±6.4	211	±9.6
770	186	±6.0	177	±3.7	174	±3.4	126	±5.3
870	138	±3.3	127	±2.6	122	±4.0	74	±6.9

4. Conclusions

1) The original technology for obtaining condensed laminated composite materials of the Cu-C system by means of high-speed electron-beam evaporation-condensation is developed. The condensed Cu-C composites with a thickness of 2 - 3 mm and carbon content from 1.2 to 7.5 vol.% are obtained using electron-beam technology for the first time in the word practice.

2) The condensed Cu-C CMs with laminated structure has electrical, tribotechnical and mechanical characteristics, which are significantly different from that of the known powder composite materials of this system.

3) The developed CMs are very promising as materials for sliding contacts of current-collecting devices of electric transport.

References

[1] Shubert, T., Weisgarber, T. and Kieback. B. (2008) Fabrication and Properties of Copper/Carbon Composites for Thermal Management Applications. *Advanced Materials Research*, **59**, 169-172. http://dx.doi.org/10.4028/www.scientific.net/AMR.59.169

[2] Hong, Q., Li, M.W., Wei, J.Z., *et al.* (2007) New Carbon-Copper Composite Materials Applied in Rail-Type Launching System. *JEEE Transactions on Magnetics*, **43**, 137-140. http://dx.doi.org/10.1109/TMAG.2006.887534

[3] Koltsova, T.S., Nasibulina, L.I., Anoshkin I.V., *et al.* (2012) Direct Synthesis of Carbon Nanofibers on the Surface of Copper Powder. *Journal of Materials Science and Engineering B*, **2**, 4240-246.

[4] Shalunov, E.P. and Berent. V.Y. (2004) Uniform Current-Collecting Elements of Dispersion-Hardened Copper with Graphitic Lubrication for Current Collectors of Heavy-Duty and High-Speed Electric Trains. Electrical Contacts and Electrodes. Frantsevich Institute of Materials Science Problems, National Academy of Sciences of Ukraine, Kiev, 202-210.

[5] Movchan, B.A. and Malashenko, I.S. (1983) Vacuum-Deposited Heat-Resistant Coatings. Naukova Dumka, Kiev.

[6] Grechanyuk, N.I., Osokin, V.A., Grechanyuk, I.N. and Minakova, R.V. (2005) Vapour-Phase Condensed Materials Based on Copper and Tungsten for Electrical Contacts. Structure, Properties, Technology. Current Situation and Prospects for Using Electron Beam Physical Vapour Deposition Technique to Obtain Materials for Electrical Contacts. First Announcement. *Modern Electrometallurgy*, **2**, 28-35.

[7] Grechanyuk, N.I., Osokin, V.A., Grechanyuk, I.N. and Minakova, R.V. (2006) Basics of Electron Beam Physical Vapour Deposition Technique Used to Obtain Materials for Electrical Contacts. Structure and Properties of Electrical Contacts, Second Announcement. *Modern Electrometallurgy*, **2**, 9-19.

[8] Bukhanovsky, V.V., Rudnitsky, N.P. and Mamuzich, I. (2009) The Effect of Temperature on Mechanical Characteristics of Copper-Chromium Composite. *Materials Science and Technology*, **25**, 1057-1061. http://dx.doi.org/10.1179/174328408X365829

[9] Bukhanovsky, V.V., Grechanyuk, N.I., Minakova, R.V., *et al.* (2011) Production Technology, Structure and Properties of Cu-W Layered Composite Condensed Materials for Electrical Contacts. *International Journal of Refractory Metals and Hard Materials*, **29**, 573-581. http://dx.doi.org/10.1016/j.ijrmhm.2011.03.007

[10] Klyuev, V.V. (1982) Test Equipment, Handbook. Vol. 2. Mashinostroenie, Moscow.

[11] (1998) Metallic Materials - Tensile Testing at Ambient Temperature. ISO 6892: 1998(E).

[12] (1999) Metallic Materials - Tensile Testing at Elevated Temperature. ISO 783: 1999(E).

[13] Aleksyuk, M.M., Borisenko, V.A. and Krashchenko, V.P. (1980) Mechanical Tests at High Temperatures, Naukova Dumka, Kiev.

[14] Borisenko, V.A. (1984) Hardness and Strength of Refractory Materials at High Temperatures, Naukova Dumka, Kiev.

[15] (1995) Method of Determining High-Temperature Hardness by Pyramidal and Bicylindrical Indentation. DSTU 2434-94.