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VAPOUR-PHASE CONDENSED COMPOSITE MATERIALS BASED ON COPPER AND CARBON

KOMPOZITI NA OSNOVI BAKRA IN OGLJIKA, KONDENZIRANI IZ PLINSKE FAZE

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The production technology, structure, electrical conductivity, coefficient of friction, hardness, strength, and plasticity over a temperature range of 290–870 K of copper-carbonic composites with laminated structures and carbon contents from 1.2 to 7.5 % of volume fractions for sliding electrical contacts of current-collecting devices obtained by electron-beam evaporation and vapor condensation are studied. Thermodynamic activation analysis of the hardness and strength of the composites was carried out. Correlations between the hardness and strength of the composites were established.

Keywords: condensed composites, electron-beam technology, electrical, tribotechnical and mechanical characteristics, correlation

Študirana je tehnologija izdelave, struktura, električna prevodnost, koeficient trenja, trdota, trdnost in plastičnost v temperaturnem območju 290–870 K kompozita baker-ogljik s plastovito strukturo in vsebnostjo ogljika od 1,2 do 7,5 % volumenskega deleža, za drsne električne kontakte za prenos tokov, dobljene z izparevanjem v elektronskem curku in s kondenzacijo par. Izvedena je bila analiza termodinamične aktivacije trdote in trdnosti kompozitov.

Ključne besede: kondenzirani kompoziti, tehnologija elektronskega curka, električne, tribotehnične in mehanske značilnosti, korelacija

1 INTRODUCTION

Nowadays composite materials (CMs) based on copper and carbon are widely used as electrocontact materials for current-collecting devices.[1–6] 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, with layer by layer condensation of the mixed vapour flow on a rotating steel disk.[7–13] The technology of high rate electron beam evaporation-condensation is the alternative to powder metallurgy: the thermal dispersion of the liquid melt and consolidation of dispersed particles flow (without special molding to obtain a high-density material state) with a limited amount of admixtures within a closed space. The apparent advantages of the electron-beam technology, which makes the development of a new generation of composite materials for electrical contacts possible, are as follows:

- the possibility of mixing the vapor flows of substances that do not dissolve well within each other at the atomic and molecular levels, to create composite materials and coatings (facing layers) with the desired structure, chemical composition and performance characteristics, which cannot be obtained by other methods;
- simplicity and efficiency compared to 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 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.

Electron beam evaporation and condensation technology is used to produce electrical contact Cu-C CMs with specific laminated structures and chemistries within one production cycle. The composition determines its unique physical-mechanical and operational properties. Condensed copper-carbon composite materials with carbon contents from 1.2 to 7.5 % of volume fractions in the form of sheets of 3 to 5 mm in thickness were produced by the Gekont (Eltekhmash) Science &

Technology Company and, at present, these materials are in series production in Ukraine. These sheet materials are used in current-collecting devices as the operating floors of copper contact clips which are attached to them by brazing.

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

2 MATERIALS AND EXPERIMENTS

One of the advantages of copper-carbon CMs is the potential to vary their electroconductive and tribotechnical properties over a wide range by changing the copper and carbon contents in the composite. 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 with obtaining Cu-C CMs using the aforementioned production process, i.e. a lack of physicochemical interaction between copper and carbon, a very high melting temperature of carbon, and the difficulty of its transformation into a vapor state. Taking these issues into consideration, the original electron-beam technology of carbon evaporation through a molten tungsten mediator was designed by the Eltechmash (Gekont) Science & Technology Company, and experimental industrial specimens of Cu-C CMs with the carbon contents within a particular range were obtained.

The principle of the method of evaporation through a molten tungsten mediator is as follows. Tungsten carbide is formed upon contact between molten tungsten and carbon, which is thermodynamically unstable under the given temperature conditions, decomposing into atomic tungsten and carbon on the surface of the molten tungsten mediator. As the elasticity of the carbon vapour is two orders of magnitude lower than the elasticity of the tungsten vapour, it is mainly carbon which evaporates from the surface. This process ensures the atomic transfer of carbon to the rotating steel substrate and makes it possible to obtain the condensed Cu-C CMs with the specified laminated structure.

The materials for study were condensed composites of the Cu-C system, which were created using electron-beam technology with carbon contents of (1.2, 3.5, 5.0 and 7.5) % of volume fractions.

The Cu-C composites condensed from the vapor phase were obtained using the L5 electron-beam facility designed at the Eltechmash (Gekont) Science & Technology Company. The physical configuration and a schematic diagram of the equipment are given in **Figures 1** and **2**, respectively. The equipment comprises work chamber 1 (**Figure 2**), which on its side wall has gun chamber 2 connected to it, which contains electron-beam heaters 3, 4, 5 and 6. The vacuum system, comprised of two fore pumps, two booster pumps and two high-vacuum units, serves to provide a dynamic vacuum in the evaporation and condensation chambers.

On the upper flange of the work chamber 1 there is mechanism 15 (**Figure 2**) that rotates the 800 mm diameter steel substrate 14. The mechanism design allows it

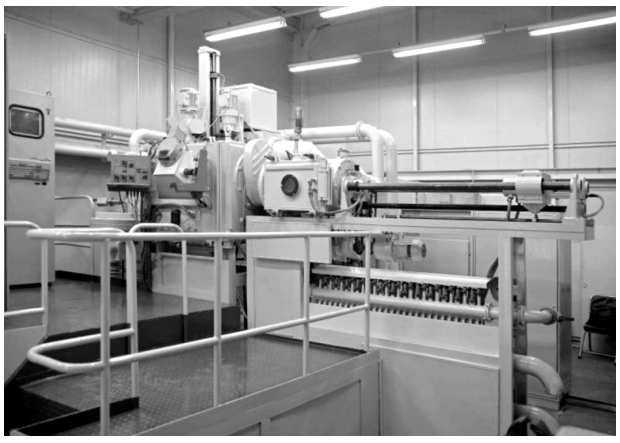

Figure 1: Physical configuration of the L5 electron-beam facility designed at the Eltechmash (Gekont) Science&Technology Company

Slika 1: Konfiguracija naprave z L5 elektronskim curkom, postavljena v Eltechmash (Gekont) Science&Technology podjetju

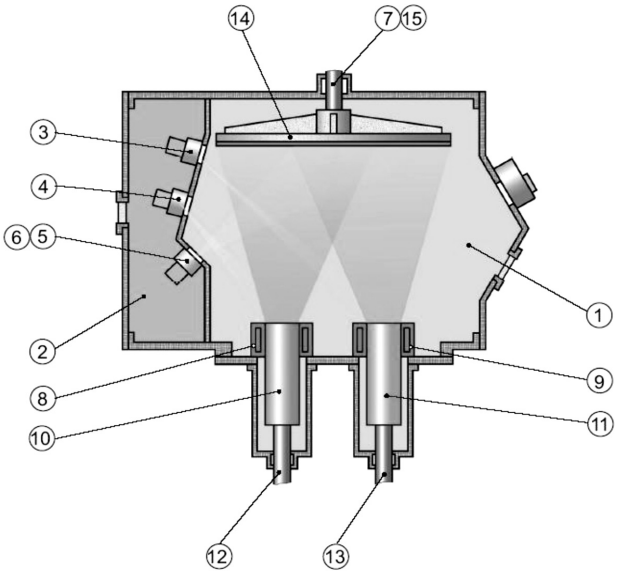

Figure 2: Scheme of the L5 electron-beam facility. Designations: 1 – work chamber; 2 – gun chamber; 3, 4, 5 and 6 – electron-beam heaters; 7 – substrate rotation rod; 8 – crucible for evaporation of copper; 9 – crucible for evaporation of carbon; 10, 11 – ingots of copper and carbon, respectively; 12,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

Slika 2: Shema L5 naprave z elektronskim curkom. Oznake: 1 – delovna komora; 2 – komora s puško; 3, 4, 5 in 6 – grelci elektronskega curka; 7 – palica za vrtenje podlage; 8 – lonček za izparevanje bakra; 9 – lonček za izparevanje ogljika; 10, 11 – ingota bakra in ogljika; 12, 13 – mehanizma za podajanje ingotov v področje toka par; 14 – podlaga iz jekla za kondenzacijo par bakra in ogljika; 15 – mehanizem za rotacijo podlage

to be operated for a long time at a temperature of 870 ± 50 K without destroying the vacuum. The substrate, fixed to the rotating rod 7 was heated to the required temperature by 40 kW electron-beam heaters 5 and 6. The original 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 and 9 with diameters of 100 and 70 mm for evaporation of copper and carbon, ingots 10 and 11 for evaporation, and mechanisms 12 and 13 that allow the ingots to be put in the evaporation zone.

In the present study, the copper-carbon condensates are obtained by means of copper and carbon evaporation from separate crucibles followed by their precipitation on a rotating steel substrate coated with a layer of calcium fluoride. The steel substrate was heated to a temperature of 935–965 K. The original materials were M0 grade copper ingots, 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. A batch of VA grade tungsten of 400 g weight was placed on the surface of the carbon ingot. When a vacuum level in the region of $1.3–4.0\times10^{-3}$ Pa is reached in the work chamber, electron-beam heating of the substrate to a temperature of 950±15 K is performed. Simultaneously, the surfaces of both ingots are electron beam heated to the melting temperature of the base metal – copper, and intermediate for the carbon – tungsten with a current of 1.15–1.3 A. The melt pools became homogeneous after 15–20 min of heating. A layer from the copper evaporation crucible was the first to be precipitated 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 an 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 935 K 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 condensed material obtained was annealed in a vacuum furnace at 1170 K for three hours to relieve internal stresses, stabilise the structure, and enhance its ductility.

In this study, the authors used the characterisation techniques that include macro-and microstructure analysis using optical and scanning electron microscopy, electrical resistance methods, tribotechnical tests, mechanical tensile tests at room and high temperatures, and hot hardness measurements. The carbon and copper contents were determined using the mortar method (volumetric analysis).

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

The electrical conductivity of the Cu-C CMs was determined by indirect bridge method measurements according to GOST 7229-76.[14]

The coefficient of friction of Cu-C CMs with copper was determined by the measurement of moment of friction and the determination of adhesion bond strength at the contact of copper specimen rotating under load with a composite counter-specimen according to GOST 27640-88.[15]

The mechanical characteristics were determined at ambient (outdoor) and elevated temperatures up to 870 K (in vacuum not below 0.7 mPa) from the results of mechanical tensile tests on standard flat fivefold proportional specimens with a gauge length of 15 mm, 3 mm width and ~2 mm thickness, using a 1246-R unit [16] according to ISO 6892[17] and ISO 783[18], respectively. The specimens were cut from ~2 mm thick composite material after vacuum annealing at 1170 K for 3 h. The carbon content in the composites varied from 1.2 to 7.5 % of volume fractions. Three to five specimens were tested at each temperature. The deformation rate was 2 mm/min, which corresponded to a relative strain rate of $\sim2.2\times10^{-3}$ 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-C composite hardness was estimated in the temperature range from 290 K to 870 K by Vickers indentation in the plane parallel to the surface of condensation. The pyramidal indenter was made of a synthetic corundum single crystal. Indentation loads were 10 N. The tests were carried out at a pressure no more than 0.7 mPa on a UVT-2 unit[19,20] according to DSTU 2434-94.[21]

3 RESULTS AND DISCUSSION

The electron-beam process provides a particular laminated composite structure with alternating copper layers, containing dispersed carbon particles, of 150 μm to 300 μm in thickness with carbon layers of 6 to 8 μm thickness (**Figure 3**). The copper grain size is 0.1–0.3 μm. The mean size of the dispersed carbon particles in the copper matrix does not exceed 20 nm.

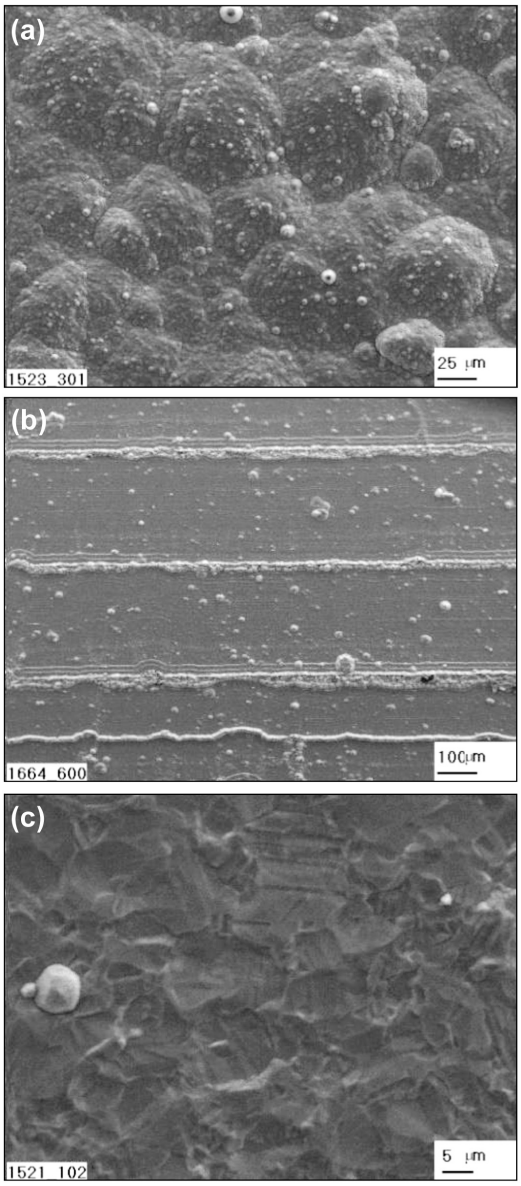

Figure 3: Microstructure of the Cu-5.0 % of volume fractions of C composite (scanning electron micrograph): a) composite surface microstructure (without etching), b) micro-layer structure of the composite, observed after ion etching (wide dark layers – copper, narrow light layers and spots – carbon), c) polygonal structure of the layers, observed after ion etching

Slika 3: SEM posnetek mikrostrukture kompozita Cu-5,0 % volumenskega deleža C; a) mikrostruktura površine kompozita (brez jedkanja), b) struktura kompozita z mikro plastmi, opažena po ionskem jedkanju (širok temni pas je baker, ozke svetlejše plasti in točke so ogljik), c) poligonalna struktura plasti, opažena po ionskem jedkanju

The electrical conductivity of the CMs with carbon contents from 7.5 to 1.2 % of volume fractions varies in the range from 3.49×10^7 to $4.07\cdot10^7$ S/m, which is 60 to 70 % of that of copper. Generally the electrical conductivity of the condensed CMs is almost one and a half times that of the many known Cu-C powder compositions.[1–6] 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.

The results of the 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 % of volume fractions of C decreases by 3 – 4 times as compared with the tough-pitch copper.

In operation, current-collecting device materials 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 the operating temperature ranges are of clear scientific and practical interest.

Hardness, strength and plasticity characteristics of the copper-carbon composites over the temperature range 290 – 870 K are presented in **Table 1**. From **Table 1**, the hardness and strength losses due to heating are continuous. With increasing temperature, the hardness decreases monotonically from maximum values of 805–951 MPa at room temperature to minimum values of 74–138 MPa at 870 K. The tensile strength and proof

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

Tabela 1: Značilnosti trdnosti in plastičnosti kompozita Cu-C, v temperaturnem področju 290–870 K

T, K	HV (MPa)	R_m (MPa)	$R_{p\,0,2}$ (MPa)	A (%)	A_g (%)	Z (%)
Composite Cu = 1.2 % of volume fractions of C						
290	951	260	235	27.8	20.2	70.5
370	783	233	196	21.0	15.2	59.0
470	579	194	153	16.7	11.3	40.0
570	389	165	136	14.9	9.0	34.4
670	290	127	107	20.7	12.0	35.0
770	186	93	86	29.3	4.8	36.5
870	138	60	53	40.4	20.2	40.2
Composite Cu = 3.5 % of volume fractions of C						
290	926	257	225	24.7	20.3	42.3
370	724	216	186	20.0	16.4	35.4
470	571	185	145	16.5	12.1	34.5
570	381	145	128	14.5	10.0	33.0
670	263	107	100	11.3	7.8	30.5
770	177	83	75	10.5	3.2	27.0
870	127	50	47	9.2	2.0	23.2
Composite Cu = 5.0 % of volume fractions of C						
290	828	253	186	8.5	5.5	28.2
370	666	213	173	6.7	4.3	24.6
470	552	167	140	4.6	4.1	22.0
570	373	127	117	4.5	4.2	20.2
670	252	104	96	6.0	3.2	18.3
770	174	65	59	6.6	2.0	17.4
870	122	37	34	8.2	2.5	17.0
Composite Cu = 7.5 % of volume fractions of C						
290	805	250	180	7.5	4.5	25.0
370	618	210	167	5.7	4.0	22.5
470	526	155	133	4.1	3.7	20.0
570	359	107	100	4.0	3.6	19.2
670	211	95	90	4.5	3.0	17.3
770	126	55	49	5.5	2.5	16.4
870	74	30	32	7.0	2.0	16.0

strength of the material decrease from 250–260 MPa and 180–235 MPa at room temperature to 30–60 MPa and 32–53 MPa at 870 K, respectively. Moreover, the hardness and the strength of Cu-C condensed CMs decrease with increasing carbon content in the composite over the entire temperature range.

The temperature dependences of CMs plastic properties are of a 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 the decrease of their plastic characteristics at all investigated temperatures.

Owing to their particular structure the condensed CMs surpass the tough-pitch cast copper and most of known Cu-C powder composites of similar composition in mechanical characteristics (including strength, plasticity and hardness).[1–6]

Thermodynamic activation analysis of the composites was used to estimate its strength and hardness variations with temperature by a procedure presented earlier.[20,22] To establish basic strength variation patterns over the temperature range under study, the exponential equations describing temperature dependences of strength and hardness were used:

$$R = A' \exp\left(\frac{U}{3kT}\right) \quad (1)$$

$$H = cA' \exp\left(\frac{U}{3kT}\right) \quad (2)$$

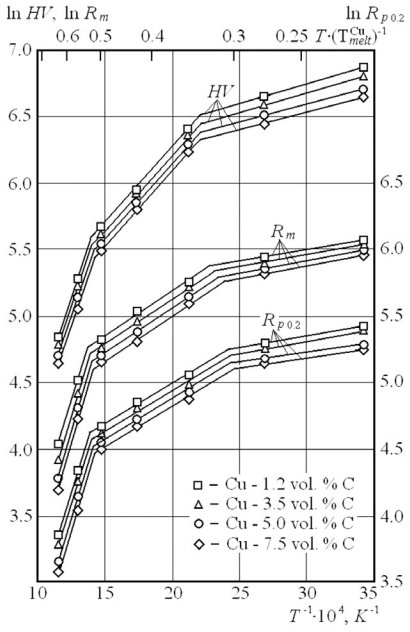

Figure 4: Temperature dependences of the hardness *HV*, the tensile strength R_m, and the proof strength $R_{p0,2}$ of copper-carbon composites over the temperature range 290–900 K

Slika 4: Temperaturna odvisnost trdote *HV*, natezne trdnosti R_m in meje plastičnosti $R_{p0,2}$ kompozita baker-ogljik v območju 290–900 K

where *R* is strength characteristic, MPa; *HV* is Vickers hardness, MP; *T* is the temperature, K; *U* is the activation energy (enthalpy) of plastic strain, eV; *k* is the Boltzmann constant; *A'* is a constant function of the material parameters and strain rates, and *c* is the proportionality constant, *c* = *H/R*.

In **Figure 4** the data obtained are presented as a function of ln $R_{p0,2}$, ln R_m, ln *HV-1/T* coordinates. As is seen, the temperature dependences of strength and hardness of Cu-C CMs consist of several regions, corresponding to the temperature intervals 290–460 K, 460–710 K, and 710–900 K, which are (0,20–0,35), (0,35–0,52), and (0,52–0,65) T^{Cu}_{melt}. Within these intervals they parameters vary linearly, obeying Equations (1) and (2). Moreover, within each of the intervals the temperature dependences of strength and hardness are parallel to each other for all the composites studied.

Each of these regions corresponds to a certain plastic strain mechanism. Equations (1) and (2) were used to determine the activation energies of plastic strains from experimental strength and hardness data for different temperature intervals in the range from 0.20 to 0.65 T^{Cu}_{melt}. They correspond to average strain rates of 10^{-3} s^{-1} under applied stresses, exceeding a 10^{-4} shear modulus. As is clear from **Table 2**, the values of activation energy obtained for all the investigated Cu-C CMs within each assigned temperature interval virtually coincide, and are in a range from 1.5 to 3 times lower than those of tough-pitch copper. The latter is evidence for the fact that the intensity of thermal softening of Cu-C system composites decreases significantly in comparison with that of tough-pitch copper, in particular at temperatures higher than 0,52 T^{Cu}_{melt}.

Table 2: Activation energies of plastic strains of a Cu-C composites and commercially pure copper

Tabela 2: Aktivacijske energije plastične deformacije kompozita Cu-C in komercialno čistega bakra

Material	Strength characteristic	*U*, eV in the temperature interval (K)		
		290...460	460...710	710...900
Cu-1.2 % of volume fractions of C	*HV*	0,03	0,12	0,30
	R_m	0,02	0,07	0,31
	$R_{p0,2}$	0,02	0,07	0,30
Cu-3.5 % of volume fractions of C	*HV*	0,03	0,12	0,30
	R_m	0,02	0,07	0,33
	$R_{p0,2}$	0,02	0,06	0,32
Cu-5.0 % of volume fractions of C	*HV*	0.03	0.11	0.30
	R_m	0.02	0.07	0.33
	$R_{p0,2}$	0.02	0.06	0.32
Cu-7.5 % of volume fractions of C	*HV*	0.03	0.11	0.34
	R_m	0.02	0.07	0.34
	$R_{p0,2}$	0.02	0.06	0.33
Cu [14, 17]	*HV*	0.05	0.22	0.91
	R_m	0.03	0.14	0.93
	$R_{p0,2}$	0.03	0.13	0.90

In this respect, the plots of the strength and hardness temperature dependences are diagrams of the Ashby

deformation mechanisms[23]. According to Ashby, for bcc metals of group IB under the conditions investigated, the mechanisms of dislocation sliding are acting at temperatures below 0.5 T_{melt} and the mechanisms of dislocation creep at higher temperatures. At present, the concept of thermally activated dislocation motion across the local barriers is commonly accepted as a mechanism which controls the rate of the plastic flow process for many types of crystalline solid bodies. During deformation of commercially pure copper in the temperature range from 0.2 to 0.3 T_{melt}, the process of blocking dislocations by impurities takes place. In the temperature range from 0.35 to 0.55 T_{melt}, the strength of copper is governed by the processes of release of Cottrell and Suzuki atmospheres.[24]

The analysis and comparison of activation energies of plastic strains in copper and copper-based composites (**Table 2**) as well as earlier theoretical and experimental work on deformation, internal friction, creep, and self-diffusion of copper[21,22] allow a conclusion about plastic flow development accompanied by significant activation energy variations in passing from one temperature interval to another. This result points to a progressive change of active (controlling), thermally activated plastic strain mechanisms. Possible dominant mechanisms for metals are presented in[22–24]. The patterns of strength-temperature and hardness-temperature curves are similar, obeying general relationships in their variations with temperature.

The analysis of experimental and calculated data demonstrated that the above strength characteristics were

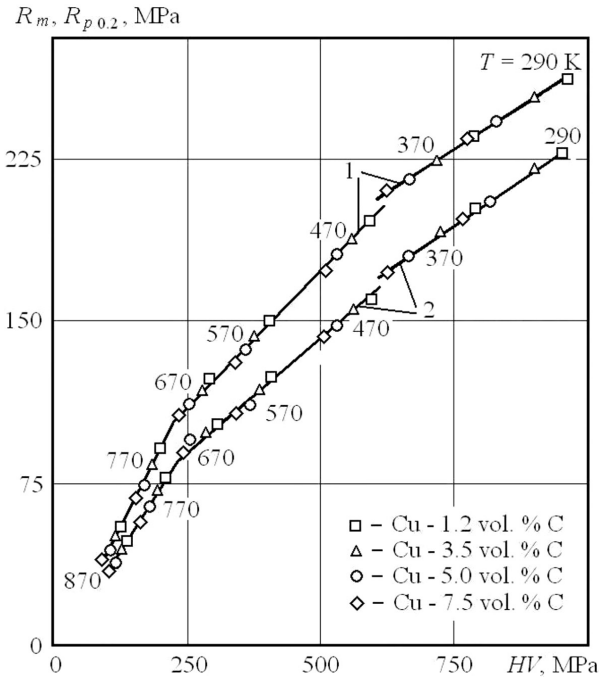

Figure 5: Correlation field and strength-hardness regression lines for Cu-C composites at different temperatures: 1 – $R_m \rightarrow HV$; 2 – $R_{p0,2} \rightarrow HV$

Slika 5: Korelacijsko polje regresijskih linij trdnost-trdota za kompozit Cu-C pri različnih temperaturah: 1 – $R_m \rightarrow HV$; 2 – $R_{p0,2} \rightarrow HV$

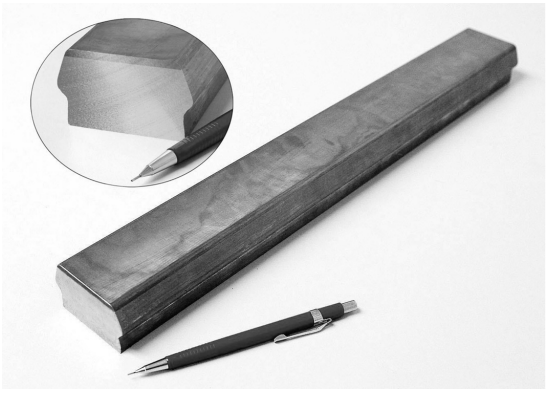

Figure 6: Production specimen of sliding contact for current-collecting device in electric transport made with Cu-C condensed CMs

Slika 6: Izdelan vzorec drsnega kontakta za napravo za zbiranje toka v električnem transportu, narejen na osnovi kondenziranih Cu-C kompozitov

controlled by the same plastic strain mechanisms and their temperature intervals were coincident. Therefore, correlations between strength characteristics should be established within the temperature intervals where strength is controlled by the same mechanisms or at least the latter do not change (for Cu-C composites these intervals are 290–460 K, 460–710 K, and 710–900 K).

The correlation analysis is aimed at establishing the functional relation between the hardness *HV,* the tensile strength R_m, and the proof strength $R_{p0,2}$ of Cu-C composites. Empirical distributions of R_m and $R_{p0,2}$ (**Figure 5**) are the aggregate of points on the plane whose coordinates correspond to the values of the above characteristics at different fixed temperatures.

As is seen, correlation fields possess several regions that are adequately described by the linear regression function. This function is common for all the investigated Cu-C CMs within each region. Such a form of the function is in full agreement with theoretical calculations of the linear hardness-strength relation. Temperature intervals for these regions, as expected, are coincident with the intervals of dominant plastic strain mechanisms.

The results of calculations of the correlation and regression coefficients of the linear function $y = ax + b$ or R_m ($R_{p0,2}$) = $aHV + b$ describing the empirical distribution areas, are summarized in **Table 3**.

Table 3: Empirical regression coefficients *a* and *b* for strength-hardness correlation of a Cu-C composites

Tabela 3: Empirična regresijska koeficienta *a* in *b* za korelacijo trdnost-trdota kompozita Cu-C

Correlation	*T* ()K	*a*	*b*	Correlation coefficient
$R_m \rightarrow HV$	290...460	0.14	125	1.0
	460…710	0.22	63	0.99
	710…900	0.51	–10	1.0
$R_{p0.2} \rightarrow HV$	290...460	0.16	71	1.0
	460…710	0.15	63	0.99
	710…900	0.42	–6	1.0

Due to excellent tribotechnical, electrotechnical, mechanical and operating characteristics, the condensed Cu-C CMs produced by the Eltechmash (Gekont) Science & Technology Company are used for the manufacture of sliding contacts for current-collecting devices in electric transport (**Figure 6**). These materials exhibit excellent operating characteristics and are successfully used in Ukraine.

4 CONCLUSIONS

1) An original technology for obtaining condensed laminated composite materials of the Cu-C system by means of high-speed electron-beam evaporation-condensation was developed. Condensed Cu-C composites with a thickness of 2–3 mm and carbon content from 1.2 to 7.5 % of volume fractions were obtained using electron-beam technology for the first time.

2) The electrical conductivity of Cu-C CMs varies with the carbon content in the range from 3.49×10^7 S/m for Cu-7.5 % of volume fractions of C to 4.07×10^7 SC/m for Cu-1.2 % of volume fractions, which is from 60 % to 70 % of that of copper. Generally the electrical conductivity of the CMs is almost one and a half times that of the many known Cu-C powder compositions.

3) The friction coefficient of Cu-C composites with 4.0 – 7.0 % of volume fractions of C with a copper contact wire decreases by 3 – 4 times compared with tough-pitch copper.

4) Owing to their particular structure the CMs surpass tough-pitch cast copper and many known Cu-C powder composites of similar composition in mechanical characteristics (including strength, plasticity and hardness).

5) Static strength and hardness variation behaviour and correlations between these properties were experimentally established over a wide temperature range .

6) Thermodynamic activation analysis of hardness and strength characteristics were carried out. The variation of the tensile strength, proof strength, and hardness of composites upon heating is controlled by the same mechanisms, with their temperature intervals being coincident.

7) The coefficients of regression equations relating hardness to other strength characteristics of Cu-C composites were determined for each temperature interval.

8) The CMs developed are very promising materials for sliding contacts in current-collecting devices for electric transport.

List of notation:

A – percentage elongation after fracture, %
A_g – percentage non-proportional elongation at maximum force, %
H – hardness, MPa
HV – Vickers hardness, MPa
R – strength characteristics, MPa
R_m – the tensile strength, MPa
$R_{p0.2}$ – the proof strength, MPa
T – thermodynamic temperature, K
T_{melt} – melting temperature, K
T_{melt}^{Cu} – melting temperature of copper, K
U – activation energy (enthalpy) of plastic strain, eV
Z – percentage reduction of area, %
A' – constant being the function of material parameters and strain rates
a, b – regression coefficients
c – proportionality constant
k – Boltzmann constant

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