The effect of temperature on mechanical characteristics of copper-carbonic composite

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Abstract

The structure, hardness, strength, and plasticity of a copper-carbonic composite for current-collecting devices obtained by electron-beam evaporation and vapour condensation over a temperature range of 290–870 K are studied. Correlation between the hardness and strength of the composite was established.

Key words: electro-contact material, copper-carbonic composite, mechanical properties, correlation, thermodynamic activation analysis

List of notation

A – percentage elongation after fracture (%)
A_g – percentage non-proportional elongation at maximum force (%)
H – hardness (MPa)
HV – hardness by Vickers (MPa)
R – strength characteristics (MPa)
R_m – the tensile strength (MPa)
$R_p0.2$ – the proof strength (MPa)
T – thermodynamic temperature (K)
U – activation energy (enthalpy) of plastic strain (eV)
Z – percentage reduction of area (%)
A – the function of material parameters and strain rates
a, b – regression coefficients
c – proportionality constant
k – Boltzmann constant
S – sample standard deviation
α – significance level
x – average sample value (mathematical expectation)
Δx – the confidence limits for the mathematical expectation
w – coefficient of variation

1. Introduction

Nowadays composites based on copper and carbon are used as electrocontact materials for current-collecting devices. These materials are formed by high-rate electron-beam vacuum evaporation and condensation of a mixed vapour flow on a rotating disk. Such a composition determines their unique physicomechanical and operating properties. Copper-carbonic composite materials with carbon contents from 1.2 to 7.0 vol.% are currently manufactured at Gekont Science&Technology Company (Ukraine) [1–3].

In operation, the materials of contacting pairs in heavy-duty current-collecting devices are subjected not only to intensive attrition, corrosion 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.

The present publication covers data on experimental investigations of the structure, strength, hardness, and plasticity of the current-collecting composite of the Cu-C system with a carbon content of 5.0 ± 0.2 vol.% over a temperature range of 290–870 K.

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2. Material, treatment and testing

The structure of the composite material was investigated by optical and scanning electron microscopy. Mechanical characteristics were determined from the results of tensile tests in vacuum on standard sheet specimens with a 15 mm gauge length using a 1246-R unit [4] according to ISO 783 [5]. The specimens were cut from the prepared composite 0.6–1.3 mm thick as-received (after vacuum annealing at 1170 K for 3 h). The tests were performed on 3–6 specimens at 100 K intervals. Their deformation rate was 2 mm min^{-1}, 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 $R_{\mathrm{p}}0.2$, the tensile strength R_{m}, the percentage elongation after fracture A, and the percentual non-proportional elongation at maximum force A_{g}. Moreover, the percentual reduction of cross-sectional area Z was evaluated.

Hardness was estimated by Vickers indentation. The pyramidal point was made of a synthetic corundum single crystal. Indentation loads were 10 N. The tests were carried out in vacuum at a pressure no more than 0.7 MPa on a UVT-2 unit [6] according to DSTU 2434-94 [7].

Experimental data were statistically processed. The average sample value (mathematical expectation) x, the sample 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 composite technology provides a specific layered structure typical of nanomaterials [8] (Fig. 1). Copper grain size is 0.1–0.3 μm, and the mean size of disperse particles of carbon does not exceed 200 Å.

Strength and plasticity characteristics of a copper--carbon composite as-received over a temperature range of 290–870 K are presented in Table 1. As follows from Table 1, its strength loss on heating is of monotonous nature. The tensile strength and proof strength of the material decrease monotonously from 257 and 225 MPa at room temperature to 37 and 34 MPa at 870 K, respectively.

Temperature dependences of 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.

Hardness variations on heating of a copper-carbon composite are shown in Table 2.

With an increase in temperature, hardness decreases from maximum values of 951 ± 45.3 MPa at room temperature to minimum values of 127 ± 4.0 MPa at 870 K.

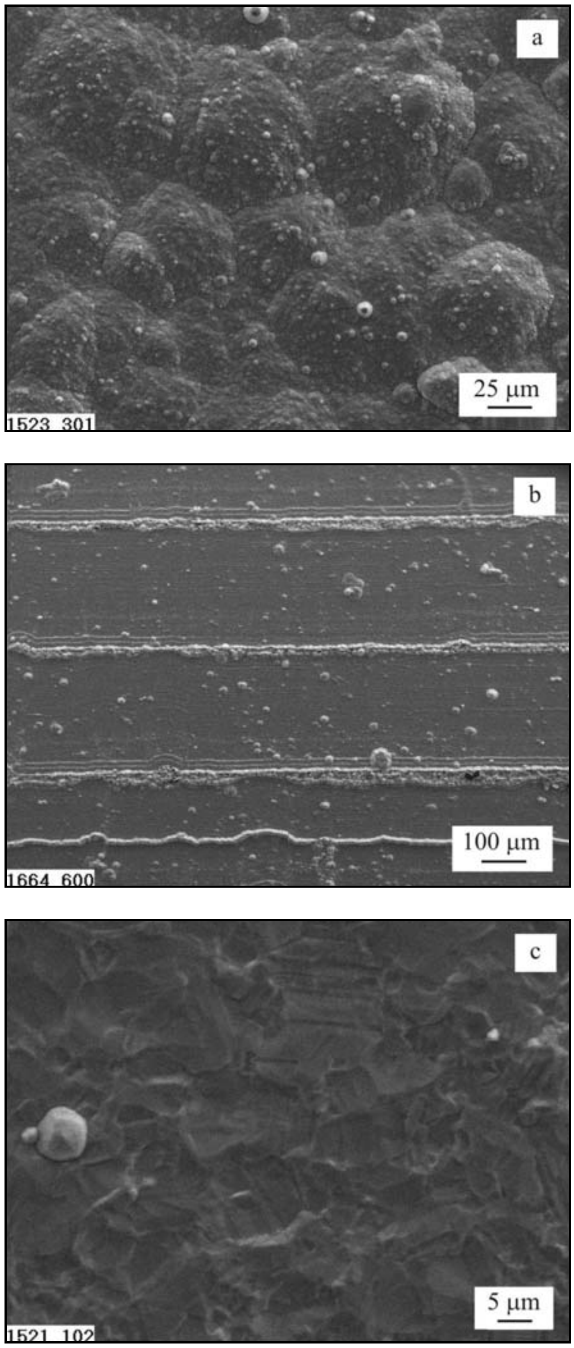

Fig. 1. Microstructure of a Cu-C composite (scanning electron micrograph): a – composite surface microstructure (without etching), b – micro-layer structure of the composite, observed after ion etching, c – polygonal structure of the layers.

Thermodynamic activation analysis of the composite was used to estimate its strength and hardness variations with temperature by a procedure presented earlier [9, 10]. To establish basic strength variation patterns over the temperature range under study, the

T a b l e 1. Strength and plasticity characteristics of a Cu--C composite in the 290–870 K temperature range

T (K)	R_{m} (MPa)	$R_{\mathrm{p}}0.2$ (MPa)	A (%)	A_{g} (%)	Z (%)
290	257	225	8.5	5.5	28.2
370	213	186	6.7	4.3	24.6
470	167	153	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

T a b l e 2. Hardness of a Cu-C composite in the 290–870 K temperature range

T (K)	HV_{av} (MPa)	S	w (%)	ΔHV (MPa)
290	951	75.3	7.9	±45.3
370	724	93.6	12.9	±78.3
470	571	77.1	13.5	±64.5
570	381	40.3	10.6	±33.7
670	290	39.9	13.8	±33.4
770	177	4.0	2.3	±3.4
870	127	6.0	4.7	±4.0

exponential equations describing temperature dependences of strength and hardness were used

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

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

where T is the thermodynamic temperature (K), U is the activation energy (enthalpy) of plastic strain (eV), k is the Boltzmann constant, A is the function of material parameters and strain rates, and c is the proportionality constant, $c = H/R$.

In Fig. 2 the data obtained are presented in the $\ln R_{\mathrm{p}}0.2$, $\ln R_{\mathrm{m}}$, $\ln HV - 1/T$ coordinates. As is seen, the temperature dependences of strength and hardness consist of several portions, within the latter they are linear and obey Eqs. (1) and (2). Each of these portions corresponds to a certain plastic strain mechanism. Equations (1) and (2) were used to determine activation energies of plastic strains from experimental strength and hardness data for different temperature intervals $(0.2\text{–}0.6)T_{\mathrm{m}}^{\mathrm{Cu}}$ (Table 3). They correspond to medium strain rates of $10^{-3}\,\mathrm{s}^{-1}$ under applied stresses, exceeding a 10^{-4} shear modulus.

The analysis and comparison of activation energies of plastic strains for copper and copper-based composite (Table 3) as well as earlier theoretical and experimental data on deformation, internal friction, creep, and self-diffusion of copper [9, 10] allow the conclusion about the plastic flow development accompanied by significant activation energy variations in passing from one temperature interval to another. This points to a progressive change of active (controlling), thermally activated plastic strain mechanisms. Possible domin-

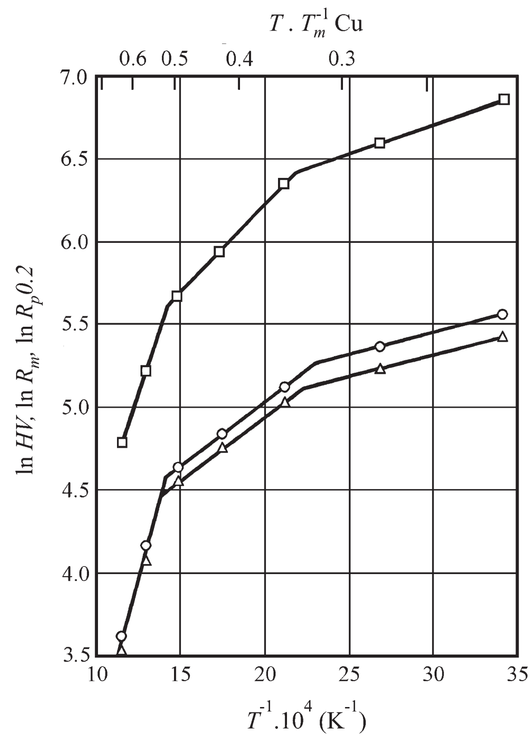

Fig. 2. Temperature dependences of the tensile strength R_{m}, the proof strength $R_{\mathrm{p}}0.2$, and the hardness HV of a copper-carbon composite over a temperature range of 290–870 K: (△) R_{m}; (○) $R_{\mathrm{p}}0.2$; (□) HV.

T a b l e 3. Activation energies of plastic strains of a Cu-C composite and commercially pure copper

Material	Strength characteristic	U (eV) in the temperature interval (K)		
		290…420	420…700	700…900
Cu-C	HV	0.09	0.26	0.84
	R_{m}	0.06	0.20	1.02
	$R_{\mathrm{p}}0.2$	0.06	0.20	1.06
		290…470	470…720	720…920
Cu	HV	0.05	0.22	0.93

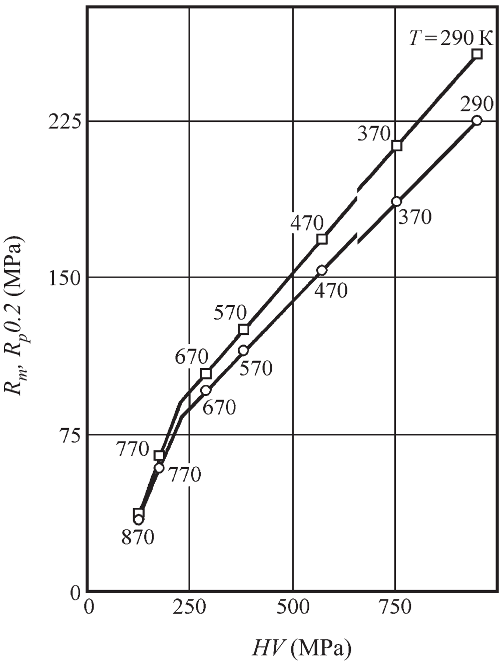

Fig. 3. Correlation field and strength-hardness regression lines for a Cu-C composite at different temperatures: (□) $R_{\rm m} \rightarrow HV$; (○) $R_{\rm p}0.2 \rightarrow HV$.

Table 4. Empirical regression coefficients a and b for strength-hardness correlation of a Cu-C composite

Correlation	T (K)	a	b	Correlation coefficient
$R_{\rm m} \rightarrow HV$	290…420	0.194	73	1.0
	420…700	0.222	41	0.999
	700…900	0.56	−34	1.0
$R_{\rm p}0.2 \rightarrow HV$	290…420	0.172	62	1.0
	420…700	0.201	39	0.999
	700…900	0.5	−30	1.0

ant mechanisms for metals are presented elsewhere [9–12]. The patterns of strength-temperature and hardness-temperature curves are similar, they obey general relationships of their variations with temperature.

The analysis of experimental and calculated data demonstrated that the above strength characteristics were 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 a Cu-C composite these intervals are 290–420 K, 420–700 K, and 700–900 K).

The correlation analysis is aimed at establishing the functional relation between the hardness HV and the tensile strength $R_{\rm m}$ and the proof strength $R_{\rm p}0.2$. Empirical distributions of $R_{\rm m}$ and $R_{\rm p}0.2$ (Fig. 3) 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. 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.

Calculation results for correlation coefficients and regression coefficients of the linear function $y = ax+b$, describing the empirical distribution areas, are summarized in Table 4.

4. Conclusions

Static strength and hardness variation patterns over a wide temperature range for a composite of the copper-carbon system as well as correlations between these properties were experimentally established.

The variation of strength characteristics (tensile strength, proof strength and hardness) upon heating is controlled by the same mechanisms, with their temperature intervals being coincident.

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

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