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Electrical-Contact Properties of a Composite Material with a Copper Matrix Reinforced by Superelastic Hard Carbon

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Abstract—The electrical contact resistance and the electric-erosion wear resistance of the composite material consisting of a copper matrix reinforced by superelastic hard carbon are studied. The reinforcing of CM by carbon particles, which have a unique combination of mechanical properties (high microhardness of 30–35 GPa, elastic modulus of 180–200 GPa, and a high ratio of microhardness to elastic modulus ($HV_{50}/E > 0.15$)), ensures good contact characteristics of the material. The minimum electrical contact resistance of CM is comparable with the electrical contact resistance of a reference sample made of gold. The electric-erosion wear resistance of the CM is more than threefold that of chrome bronze, which is a widely used for high-current electrical contacts.

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INTRODUCTION

Electrical contacts are widely used in many modern technical devices. As electric circuit elements, electrical contacts are diverse in design, switched power, and operating conditions. Their reliability often determines the service life of complex technical systems; therefore, to ensure their stable and reliable operation is one of the most important problems of power machine building and instrument engineering.

Severe operating conditions of modern electrical-contact devices at high electrical and mechanical loads in an aggressive medium make it necessary to design new electrical-contact materials having the required set of properties.

The application of composite materials (CMs) is thought to be the only method to ensure the required set of service properties in an electrical-contact material. The principle of separation of functions between material components can be accomplished in CMs. As a rule, electrical-contact CMs consist of a high-conductivity matrix, which provides a low electrical contact resistance and good heat removal from the contact zone, and functional fillers [1, 2]. Depending on the purpose of an electrical-contact material, a functional filler ensures, e.g., a low friction coefficient (sliding contacts), high mechanical and electric-erosion resistance (sliding and interrupting contacts), high mechanical strength, and low weldability.

For example, successive experience of introducing functional fillers, such as disperse diamonds [3, 4] and tungsten and chromium carbides [4], exists for the materials of interrupting electrical contact. New CMs based on metals reinforced by hard superelastic carbon particles produced from fullerenes under pressure are promising materials [5]. For such materials to be designed and effectively used in electrical contacts, it is necessary to study their service properties.

EXPERIMENTAL

Copper-based CMs, the volume of which was reinforced by carbon particles, were synthesized from a mixture of copper and 10 wt % fullerene (C_{60+70}) powders at a pressure of 8 GPa and a temperature of 800°C. They were held at fixed parameters p and t for 45 s. Samples in the form of pellets 5 mm in diameter and 2.5 mm in height were synthesized in a "Toroid-15" high-pressure chamber. The experimental technique at high pressures was described in detail in [6]. The sample synthesis parameters correspond to the conditions of collapse of fullerene molecules with the formation of a hard carbon phase [7–9].

The microstructure of CMs was analyzed on an Olympus optical microscope. The microhardness of carbon phases was measured with a multifunctional UMT-3MO (CETR) testing device, and loading–unloading curves were recorded at a load of 0.5 N (50 gf). Microhardness HV_{50} and elastic modulus E of the carbon phase was calculated by the Oliver–Pharr method from the loading–unloading curves [10].

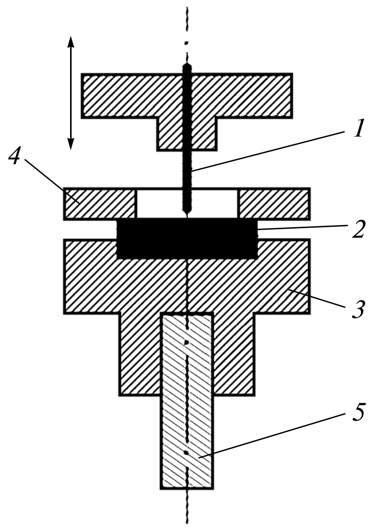

Fig. 1. Schematic diagram of the working unit of the device used for electric-erosion wear resistance tests: (*1–5*) see text.

The density of carbon particles was determined using flotation in heavy liquids, namely, mixtures of diiodomethane and acetone taken at various concentrations. The density of carbon particles after synthesis was 2.2–2.4 g/cm^3.

Indentation hardness H_{IT} of CM samples (GOST R 8.748–2011), which is also known as Meyer hardness, was measured at a load of 100 N applied to an indenter. The indentation diameter was 150–300 μm, which was larger than the carbon particle sizes. Thus, H_{IT} characterizes the total hardness of the samples with allowance for the contributions of carbon particles and the copper matrix.

Electrical resistivity ρ of the samples was measured by the Van der Pauw method [11]. The electrical-contact properties of the CMs were estimated using the ASTM technique [12]. The electrical contact resistance of the material was estimated in a pair with a reference probe (1 mm in diameter, radius of tip curvature of 0.5 mm) made of a gold-coper alloy (80% Au, 20% Cu) using the dc four-probe method. In all cases the load applied to a probe was 1 N. The electrical contact resistance was measured at a voltage of ≤50 mV applied to a open contact. The measurements were repeated 15–20 times along the pellet diameter in two mutually perpendicular directions. For comparison, this technique was used to measure the contact resistance of the reference probe with a sample made of pure gold.

The technique and the apparatus used to estimate the electric-erosion wear resistance of the materials were described in [13]. The schematic diagram of the working unit of the device is shown in Fig. 1. Cylindrical tungsten electrode *1* 1 mm in diameter is in periodic contact with sample *2* made of the material to be studied and placed in brass casing *3*. The sample is fixed in the casing by clamping plate *4* with a hole. The casing is fastened to fine adjustment screw *5*, which can be used to control the contact opening and the press force. The switching frequency (number of switching on–switching off cycles) was 0.33 Hz (20 switchings per minute). The maximum switched charge per switching was 66 mC. The press force on a probe 1 was 0.5 N.

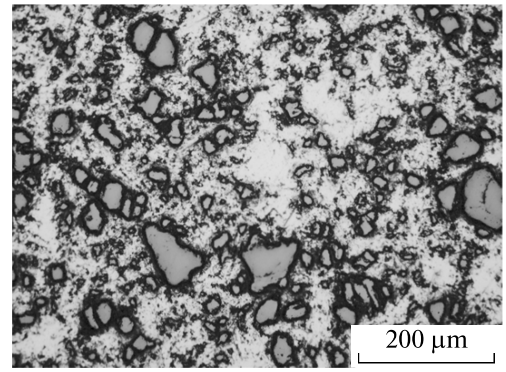

Fig. 2. Microstructure of copper-based CM reinforced by carbon particles.

As a reference probe, tendency electrode *1* was used in all experiments as a constant element of a contact pair. Tungsten was chosen as the probe material due to its high electric-erosion wear resistance. In experiments, sample *2* served as an anode, since the wear of the anode sample is usually higher than the wear of this sample used as a cathode.

The test time corresponded to 100 switching cycles. After tests, we measured the linear wear, namely, the crater depth in a CM sample, accurate to 0.01 mm. Since the decrease in the tungsten probe length was insignificant, it was neglected. As the wear resistance characteristics, we used the linear wear per switching cycle I_c (μm/cycle) and the specific linear wear per switching charge I_q (μm/C). For comparison, we used the described technique to determine the wear resistance of chrome bronze, which is a widely used as an electrical-contact material for high-current contacts.

RESULTS AND DISCUSSION

Structure and Properties of CM and the Reinforcing Carbon Phase

The microstructure of the synthesized CM is shown in Fig. 2. Reinforcing carbon phase particles are 3–100 μm in size, do not create a skeleton in the copper matrix, and are uniformly distributed in the material volume. Their volume fraction is ~30 vol %.

The reinforcing carbon particles synthesized from fullerenes have a unique combination of mechanical properties: the microhardness is 30–35 GPa and the elastic modulus is 180–200 GPa. The ratio of the

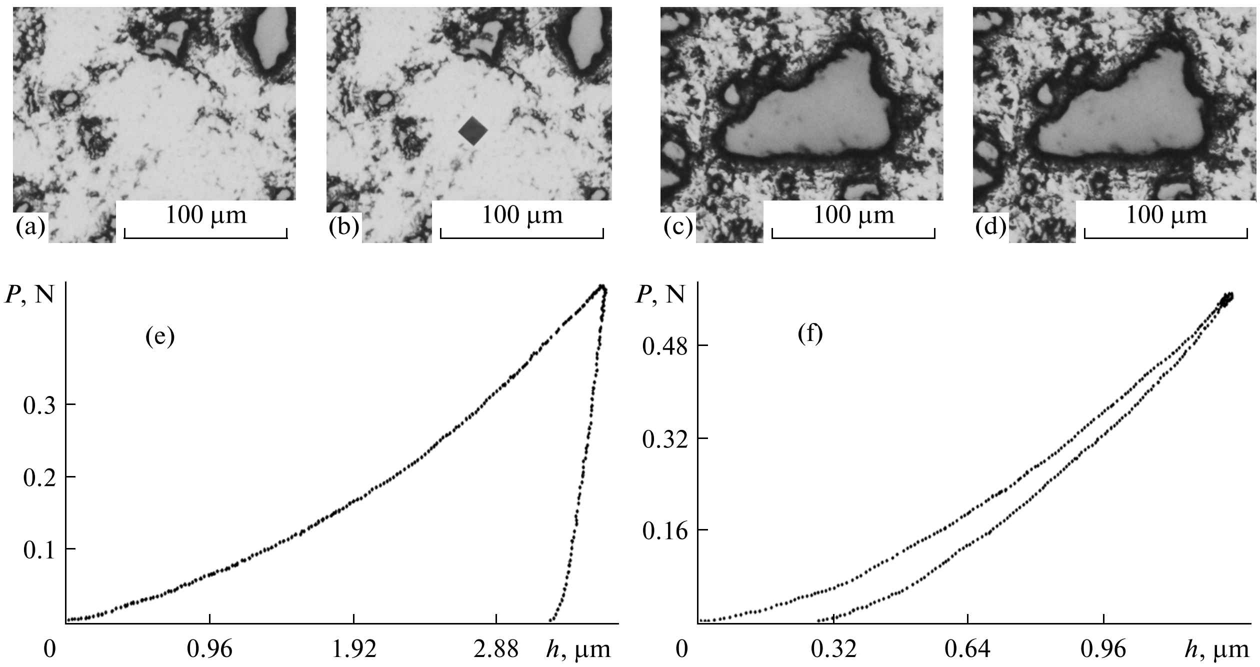

Fig. 3. Microstructures of CM (a, c) before and (b, d) after indentation and the loading–unloading curves for (e) copper matrix and (f) carbon particle. *P* is the load and *h* is the indentation depth.

microhardness to the elastic modulus (HV_{50}/E) is used in contact mechanics as an index of the deformation characteristics of the contact material [14]. Moreover, according to [15], ratio HV_{50}/E correlates with the elastic recovery of the material during indentation (ratio of the elastic deformation to the total deformation during indentation). The reinforcing hard carbon particles synthesized from fillerenes under pressure can be considered as superelastic particles, since they have $HV_{50}/E > 0.15–0.18$ [15]. The elastic recovery of the carbon particles and the copper matrix are 80–83 and 11.5%, respectively. The microstructures of the CM before and after indentation are shown in Figs. 3a–3d, and the indentation curves of the copper matrix and the carbon phase are depicted in Figs. 3e and 3f.

Reinforcing carbon particles have a high fracture toughness, which is important for interrupting electrical contacts [16]. Below, we present some characteristics of the reinforcing carbon phase and CM:

Properties of the carbon phase	
microhardness HV_{50}, GPa	30–35
elastic modulus E, GPa	180–200
elastic recovery during indentation R_e, %	80–83
Properties of CM	
indentation hardness H_{IT}, GPa	1.43–5.73
electrical resistivity ρ, 10^{-8} Ω m	1.7–12

Electrical Contact Resistance of the Materials

This parameter is one of the most important characteristics of any electrical-contact device. In contrast to electrical resistivity, contact resistance is not solely a function of a material: it also depends on the design of an electrical-contact device, the roughness of the contacting surfaces, and the presence of contamination on the contact surface. Therefore, to estimate the electrical-contact properties and to choose a material for a certain device, researchers use probe measurements of contact resistance. Since Russian normative documents do not regulate such measurements, we use the requirements of standard ASTM B 667 to develop an experimental technique [12].

The electrical contact resistance was measured at a voltage of at most 50 mV across open contact, and the average current through the contact was 30 mA, which approaches dry circuit conditions [12]. In this case, the probability of an electrical breakdown (fritting) of the surface films on the contacting parts is minimized due to a low voltage across the contact, and heating of the surfaces in contact is excluded.

The results of measuring the electrical contact resistance of CM are presented in Table 1 and Fig. 4. The histogram of contact resistance has a pronounced asymmetry. The most probable electrical contact resistance is shifted to low values. The distribution of the electrical contact resistance, which is a random quantity, is far from a normal (Gaussian) distribution.

The high values of the coefficient of variation indicate a nonuniformity of the sample of the values of R_c.

Table 1. Statistical characteristics* of the electrical contact resistance of the CM samples

Sample	R_c	σ_R	R_{min}	R_{max}	$V = \sigma_R/R_W$, %
	Ω				
CM (Cu + 10% C)	1.80 ± 0.31	2.62	12×10^{-3}	10.6	145
Au	$10.4 \times 10^{-3} \pm 1.62 \times 10^{-3}$	5.13×10^{-3}	4.6×10^{-3}	19.7×10^{-3}	49

* Designations: R_c is the electrical contact resistance; σ_R is the root-mean-square deviation; R_{min} and R_{max} are the minimum and maximum electrical resistances, respectively; and V is the coefficient of variation.

This fact seems to be natural, since the contact area could be located in the regions of the copper matrix, the carbon phase, or both phases.

For comparison, Table 1 gives the electrical contact resistance of the reference sample made of gold of 99.99% purity, which was measured by the same technique under the same conditions. Naturally, the values of R_c of the gold sample are lower than those of the CMs under study, since gold is resistant to air oxidation under natural conditions. In other words, only a monolayer of adsorbed gases exists on its surface. Much thicker oxide films form on the copper surface under natural conditions. These films significantly increase the electrical contact resistance of the material.

It should be noted that the minimum rather than the average electrical resistance is of particular interest for the electrical-contact properties of the materials under study. It is obvious that the conductivity of a contact device in real constructions under numerous contact conditions is provided by single contacts of the following three types: metal/metal, metal/carbon phase, and carbon phase/carbon phase. Since these single contacts conduct a current in parallel, according to the well-known rule for parallel connection of conductors, the resulting electrical resistance is lower than the lowest resistance of its components. The fact that the minimum electrical contact resistance of the CM is higher than that of gold only by a factor of 2.6 demonstrates that it is a promising electrical contact material with allowance for its high mechanical and contact characteristics.

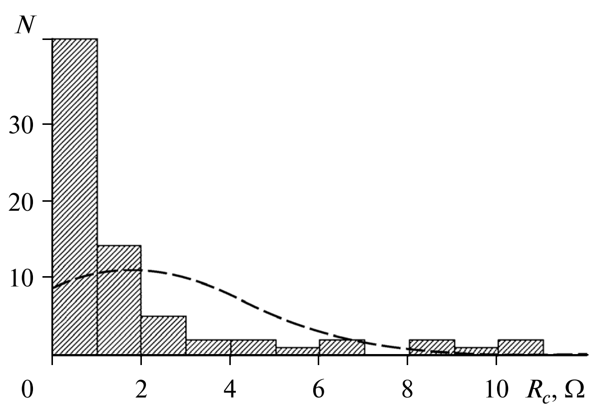

Fig. 4. Electrical contact resistance histogram of CMs. (dashed line) Normal distribution. N is the number of observations.

Electric-Erosion Wear Resistance of Cu + 10% C CM

Electric-erosion wear is one of the most important processes that determine the resource of electrical contact devices. This wear is caused by the complex thermophysical and gasdynamic processes that occur in the interelectrode gap and on the working surfaces of contacting parts. Although electric-erosion mechanisms are diverse, their common feature is that this process is induced by the action of energy released in a contact during switching.

Figure 5 shows the traces of action of a pulsed discharge, namely, craters on CM samples after a test cycle in a pair with a tungsten probe. The products of erosion and the traces of ejection of molten metal are also visible.

The characteristics of electric-erosion wear resistance of a number of materials are given in Table 2 (I is the average linear wear (or the crater depth), I_c is the average linear wear per switching cycle, I_q is the average linear wear per unit charge having passed through a contact during switching). Apart from the data of CMs, we also present the electric-erosion wear resistances of experimental copper-based CMs with dispersed diamonds (their content is given in wt %) for comparison [4].

It is seen that the wear resistances of all test materials are substantially higher than the wear resistance of chromium bronze. The wear resistance of the copper-

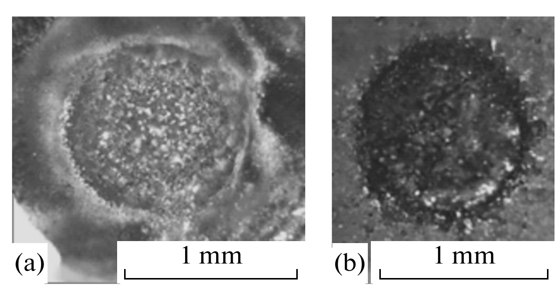

Fig. 5. Craters formed upon electric-erosion wear (products of erosion are visible).

Table 2. Electric-erosion wear resistance characteristics of copper-based CM and chrome bronze

Material	I, mm	I_c, μm/cycle	I_q, μm/C
Chrome bronze	0.353	3.53	53.5
CM Cu + 10% C	0.110	1.10	16.6
Diamond-containing CMs [4]:			
Cu + 5% C	–	1.30	19.7
Cu + 10% C	–	1.00	15.2

based materials containing superelastic hard carbon is very close to the wear resistance of the copper-based CMs with dispersed diamonds.

CONCLUSIONS

(1) Copper-based CMs were reinforced by superelastic hard carbon particles, which are characterized by a high ratio of the microhardness to the elastic modulus HV_{50}/E. Such CMs were used to prepare electrical contacts that should have high contact characteristics and a high carrying ability.

(2) The minimum electrical contact resistance of the CMs is comparable with that of a reference sample made of gold of 99.99% purity, which demonstrates that these CMs are promising electrical contact materials with allowance for their high contact characteristics.

(3) The electric-erosion wear resistance of the CMs is more than threefold that of chrome bronze, which is a widely used as an electrical-contact material for high-current contacts.

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