06

Composite Materials with Nanostructured Carbon Inclusions for Sliding Electrical Contacts

© I.N. Lukina,[1] E.A. Ekimov,[2] E.I. Drozdova,[1] O.P. Chernogorova,[1] N.A. Dormidontov[1]

[1]Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences,
119334 Moscow, Russia
[2]Institute for High Pressure Physics, Russian Academy of Sciences,
142190 Troitsk, Moscow, Russia
e-mail: lukina.i.n@yandex.ru

Received October 15, 2024
Revised October 15, 2024
Accepted October 15, 2024

Composite materials (CM) for miniature sliding bearings and current leads have been synthesized from regular brass or copper 3D conducting frameworks with holes filled with C_{60} fullerites. The CM samples were also obtained by thermobaric treatment of L80 brass wire networks with 0.3 and 0.5 mm slots filled with C_{60} fullerites. The processing parameters ensure the consolidation of the workpiece and the transformation of fullerites in the cells into monolithic inclusions of a superelastic hard carbon with a nanocluster graphene structure. The hardness and indentation modulus of the carbon phase in the cells of 0.3 mm in a side size ($H_{\text{IT}} = 24$ GPa, $E_{\text{IT}} = 139$ GPa) are higher than in the cells of 0.5 mm in a side size ($H_{\text{IT}} = 18$ GPa, $E_{\text{IT}} = 105$ GPa) at an elastic recovery of 84%. The carbon inclusions provide good tribological properties of the CM: their friction coefficient CM ($\mu = 0.09-0.13$) is lower than that of brass ($\mu = 0.3$). Due to the presence of continuous conductors in the form of a brass grid, the experimental CM crystals have a sufficiently high electrical conductivity (36 MS/m), which is slightly lower than that of the copper standard (42 MS/m), but substantially higher than that of the CM obtained from mixtures of metal and fullerite powders (10 MS/m).

Keywords: fullerenes, high pressure, structure, hardness, tribological properties, electrical conductivity.

DOI: 10.61011/TP.2025.02.60830.289-24

Introduction

Contact electrical resistance and friction coefficient are the key performance specifications of sliding contacts, besides high stability of electrical and tribological properties shall be simultaneously ensured throughout the service life. Utilization of composite materials (CM) is virtually the only way to provide the desired combination of performance properties in a single electrocontact material [1,2]. Such electrocontact CMs generally consist of a high-conductive matrix that provides low contact resistance and good heat removal from the contact zone, and functional fillers. Depending on the intended use of an electrocontact material, a functional filler for sliding contacts shall offer a low friction coefficient, high mechanical and electroerosion wear resistance, physical strength, low weldability, etc. Hyperelastic bulk solid carbon materials made on the basis of fullerites at high pressure [3–5] may be used as reinforcing particles for tribotechnical metal-matrix CM [6]. Solid and elastic materials with high hardness-to-modulus of elasticity ratio (H/E) are currently recognized to be the best materials in terms of wear resistance and tribological properties. Increase in H/E facilitates surface deformation accommodation and impact load absorption without fracture [7]. New CM with a metal matrix reinforced with hyperelastic carbon solid particles made from fullerenes at high pressure feature high wear resistance and low friction coefficient [6]. Abrasive wear resistance of copper-based and brass-based CM is more than 40 times as high as that of brass, therefore potential utilization of such CM as electrocontact materials was evaluated and electrofrictional properties were examined [8]. However, the large number of carbon-containing interfaces in CM made using the powder technique increases CM's electrical resistance significantly. To solve this problem, high-conductive metal elements shall be provided throughout the height of the sample with superhard hyperelastic carbon particles retained on the contact surface.

1. Experimental procedure

Composite material samples 5 mm in diameter and $3-4$ mm in height were synthesized from brass (L80) — C_{60} fullerites and copper — C_{60} fullerites composition in a toroid type high-pressure chamber. C_{60}fullerite powder with purity $\geq 99.5\%$ and crystal grain size $\sim 40\,\mu$m was used. Samples were synthesized at 8 GPa and $820-840^\circ$C. Mesh pressure for calibration dependence was determined from phase transitions in bismuth and tin. Pressure measurement accuracy was ~ 0.5 kbar. Samples were heated through a graphite tube and graphite covers. Temperature was meaured using a chromel-alumel thermocouple with the

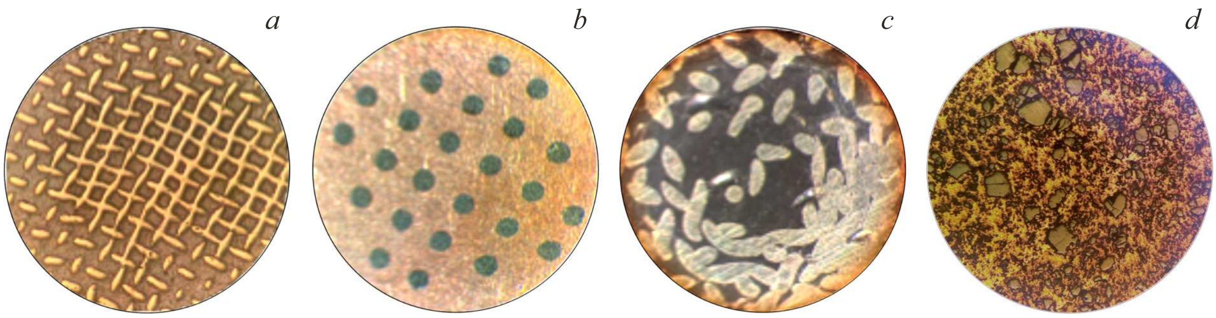

Figure 1. Structure of CM based on the L80 brass grid (CM I) (*a*), copper cylinder with holes (CM II) (*b*), L80 grid roll (CM III) (*c*), as well as copper and C_{60} powder mixture CM (*d*).

junction placed in center of the heater. The temperature measurement accuracy for the synthesis was $\pm 10^\circ$C K.

L80 brass grids made of 0.16 mm and 0.25 mm wires with mesh sizes 0.3 mm and 0.5 mm, respectively, placed horizontally on a copper cylinder or braided from 0.25 mm wires and placed vertically were filled with C_{60} fullerites. Copper-based CM samples are made of copper cylinders with 0.3 mm and 0.5 mm drilled holes 1 mm in depth that were filled with C_{60} fullerites using ultrasound. Carbon phase structure was studied by the RSS spectroscopy method using the inViaReflex „Renishaw" spectrometer (50x lens, 405 nm Nd:YAG DPSS laser, power lower than 0.3 mW, spot diameter about 2 μm). For each sample, 10 RSS spectra were recorded.

Mechanical properties (indentation hardness H_{IT}, indentation modulus E_{IT} and elastic recovery η_{IT} expressed as a ratio between the elastic and general indentation work components) of carbon coatings were measured using the DUH-211S (Shimadzu) ultramicrohardness tester in accordance with GOST R 8.748-2011 using the Vickers indenter at a load of 500 mN in „loading–unloading" mode at a loading rate of 70 mN/s. The results were averaged over $>$ 10 measurement data with a spread of $\pm 10\%$.

Tribological tests of CM were performed using the CETR UMT-3MO multifunctional system with a circular motion scheme at a rate of 300 mm/s during 2 h on a steel counter body with hardness 62 HRC under a load of 10 N and 50 N. Friction coefficient measurement error was 5%.

Conductivity was measured using the „Konstanta K6" instrument with error $\sim 2\%$.

2. Results and discussion

To increase electric conductivity of CM, this study uses a sample design that provides continuous electrocontact on the matrix metal body without carbon-containing interface surfaces. Three different types of samples were fabricated and examined: CM I — L80 brass wire grids with different mesh sizes (0.3 mm and 0.5 mm) embedded into copper cylinders (Figure 1, *a*), CM II — copper cylinders with 0.3 mm and 0.5 mm (Figure 1, *b*) and CM III — vertical braided 0.5 mm L80 wires (Figure 1, *c*). CM

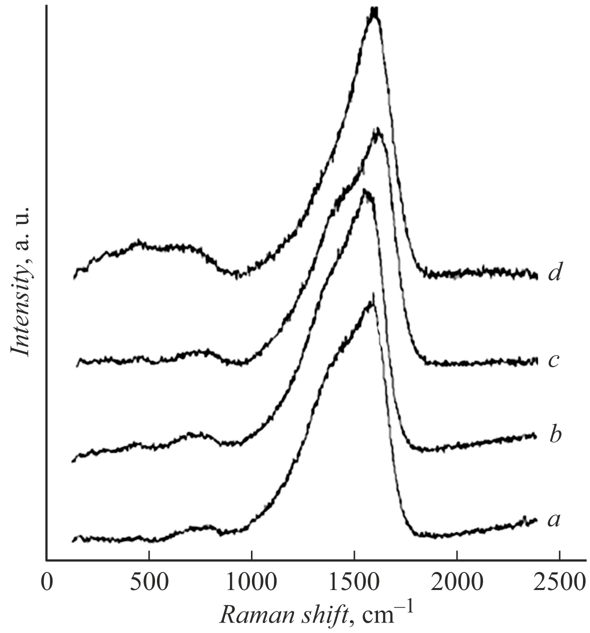

Figure 2. RSS spectra of carbon phase in: *a* — copper and C_{60}powder mixture CM, *b* — CM I with mesh 0.3, *c* — CM I with mesh 0.5 mm, *d* — in CM II.

structure [8] fabricated from a copper and C_{60} fullerite mixture (Figure 1, *d*) is shown for comparison.

During pressure heating in CM consolidation, C_{60} fullerites were converted into inclusions or hard hyperelastic carbon arrays.

Examination of the carbon phase surfaces of various CMs showed that their RSS spectra are a wide nonseparated band in the wavenumber range of 1000–1800 cm^{-1} (Figure 2). According to [9], such band consists of two peaks known as D- and G-components. For structures obtained from fullerene molecules under pressure, RSS spectra with a peak at 1580 cm^{-1} are typical. Dominating D- and G-peaks are assigned to amorphous or nanocrystalline phases with sp^2-hybridization [9]. For all RSS spectra obtained from carbon phases in CM on the basis of a brass grid with various mech sizes (Figure 2, *b, c*) and in standard CM on the basis of copper powder (Figure 2, *a*), quite close

Table 1. Mechanical properties of the carbon phase in CM

CM	H_{IT}, GPa	E_{IT}, GPa	η_{IT}, %
CM of Cu and C_{60} powders	12	65	91
CM I from C_{60}+L80 with mesh 0.3 mm	24.3	139	83
CM I from C_{60}+L80 with mesh 0.5 mm	17.9	105	84
CM II from C_{60}+copper with 0.3 mm holes	21.5	121	81
CM II from C_{60}+copper with 0.5 mm holes	14.2	79	84

Note. Indentation hardness H_{IT}, indentation modulus E_{IT} and elastic recovery $\eta_{IT} = W_{elast}/W_{total}$, where W_{elast} and W_{total} are elastic and total indentation work, respectively.

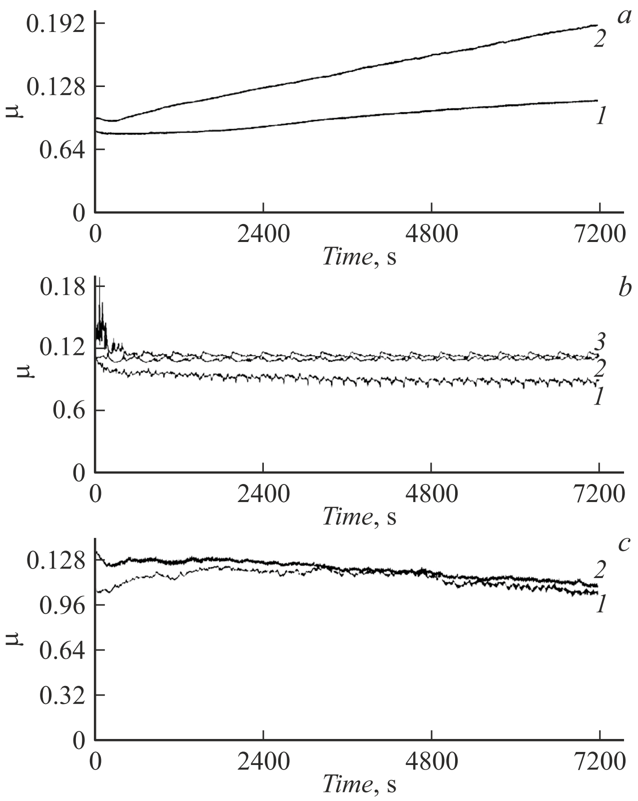

Figure 3. Kinetic curves of friction under load: *1* — 5 N, *2* — 10 N; *3* — 50 N: CM I (*a*), CM II (*b*), CM III (*c*).

profiles typical of carbon phases with nanocrystal sizes of $L_a = 1-2$ nm were observed [10]. The spectrum obtained for carbon phases in copper-based CM with drilled holes (Figure 2, *d*) features an apparently prevailing peak G, which is probably associated with finer graphite nanocrystals ($L_a < 1$ nm).

In the CM I samples, H_{IT} and E_{IT} of a carbon phase in meshes with side 0.3 mm ($H_{IT} = 24$ GPa, $E_{IT} = 140$ GPa) are higher than in grid meshes with side 0.5 mm ($H_{IT} = 18$ GPa, $E_{IT} = 105$ GPa) in 84% elastic recovery (Table 1). Carbon phase hardness also increases as the hole size and, accordingly, the carbon phase inclusion size in CM II decrease.

Carbon inclusions provide good tribotechnical properties of CM (Figure 3): friction coefficient of CM samples $\mu = 0.09-0.13$, excluding CM I (Figure. 3, *a*) where the brass grid mesh causes formation of an acute-angled phase that scratches the counterbody resulting in the increase in the friction coefficient during testing. For CM II and CM III, μ doesn't depend on the test load: when load increases from 10 to 50 N, μ remains at 0.12 (Figure 3, *b, c*), which is much lower than that of L80 ($\mu = 0.3$).

The lowest conductivity (4 MS/m) is observed in CM III consisting of twisted brass grids filled with hyperelastic carbon particles due to bad design of such CM. Due to the presence of continuous conductors in the form of brass grid or copper cylinder in the structure, CM I and CM II samples have quite high conductivity (36 MS/m) that is a little lower than that of the copper sample made in the same conditions (46 MS/m), but much higher than that of CM made from the metal and fullerite powder mixture (10 MS/m) (Table 2).

Table 2. Friction coefficient μ and conductivity σ of the standard and CM

Samples	μ	σ, MS/m
Standard copper alloy	0.30	42
CM of Cu and C_{60} powders	0.18	10
CM I from C_{60}+L80 with mesh 0.3 mm	0.11	12
CM I from C_{60}+L80 with mesh 0.5 mm	0.13	36
CM II from C_{60}+copper with 0.3 mm holes	0.11	34
CM II from C_{60}+copper with 0.5 mm holes	0.20	34
CM III from C_{60}+twisted brass grid with mesh 0.5 mm	0.11	4

Conclusion

CM samples were made by pressure and temperature treatment of L80 brass wire grids with mesh 0.3 mm and 0.5 mm and copper cylinders with drilled 0.3 mm and 0.5 mm holes filled with C_{60} fullerites. Treatment parameters ensure workpiece consolidation and conversion of fullerites in the grid meshes into solid inclusions consisting of hyperelastic hard carbon with nanocluster graphene structure. Carbon inclusions ensure good tribotechnical properties of CM: μ of CM sample ($\mu = 0.09-0.13$) is much lower than that of brass ($\mu = 0.30$). Due to the presence of continuous conductors in the structure, CM samples have quite high conductivity (36 MS/m) that is a little lower than that of the standard copper alloy (42 MS/m), but much higher than that of CM made from the metal and fullerite powder mixture (10 MS/m).

Funding

This study was performed under state assignment 075-00320-24-00.

Conflict of interest

The authors declare no conflict of interest.

References

[1] N.K. Myshkin, V.V. Konchits, M. Braunovich. *Elektricheskie kontakty* (Izdat. dom „Intellekt“, Dolgoprudny 2008) (in Russian)
[2] M. Balasubramanian. *Composite materials and processing* (Boca Raton e.a.: CRC Press, 2014)
[3] V.D. Blank, S.G. Buga, G.A. Dubitsky, N.R. Serebryanaya, M.Yu. Popov, B. Sundqvist. Carbon, **36** (4), 319 (1998). DOI: 10.1016/S0008-6223(97)00234-0
[4] V.V. Brazhkin, A.G. Lyapin. J. Superhard Mater., **34** (6), 400 (2012). DOI: 10.3103/S1063457612060135
[5] M. Alvarez-Murga, J.L. Hodeau. Carbon, **82** (C), 381 (2015). DOI: 10.1016/j.carbon.2014.10.083
[6] O. Chernogorova, E. Drozdova, I. Ovchinnikova, A. Soldatov, E. Ekimov. J. Appl. Phys., **111**, 112601 (2012). DOI: 10.1063/1.4726155
[7] A. Leyland, A. Matthews. Surf. Coat. Technol., **177–178**, 317 (2004). DOI: 10.1016/j.surfcoat.2003.09.011
[8] V.V. Izmailov, I.N. Ushakova, E.I. Drozdova, O.P. Tchernogorova, E.A. Ekimov, D.A. Gusev. Trenie i iznos, **37** (3), 328 (2016) (in Russian). DOI: 10.3103/S1068366616030089
[9] A.C. Ferrari. Mat. Res. Soc. Symp. Proc., **675**, 1151 (2001). DOI: 10.1557/PROC-675-W11.5.1
[10] A.C. Ferrari, J. Robertson. Phys. Rev. B: Condens. Matter., **61** (20), 14095 (2000). DOI: 10.1103/PhysRevB.61.14095

Translated by E.Ilinskaya