Structure and properties of the electromagnetic starter’s contacts with the electro-explosive CuO-Ag coating

D A Romanov¹, S V Moskovskii¹, V E Gromov¹, Yu F Ivanov², A D Filjakov¹

¹ Siberian State Industrial University, 42 Kirov st., 654007 Novokuznetsk, Russia

¹ Institute of High Current Electronics SB RAS, 2/3 Akademichesky av., 634055 Tomsk, Russia

E-mail: romanov_da@physics.sibsiu.ru

Abstract. Phases and elemental composition of CJ20 electromagnetic starter’s contacts subjected to electro-explosive spraying of the CuO-Ag coating were studied by using transmission and scanning electron microscopy methods. Electro-explosive spraying CuO-Ag coating were carried out in mode providing contact’s premelting condition. Such mode managed to minimize energy cost. Produced coating has a homogeneous structure containing silver matrix and CuO inclusions located in the matrix. After electro-explosive spraying the structure of coating elements’ surface and their scale vary in a very wide range from thousands µm to tens of hundreds µm. The high-speed cellular crystallization’s structure is formed in the electro-explosive CuO-Ag coating regardless of distance to modifying surface. The cell’s size is ranged from 150 nm to 300 nm. The cells are separated by the second phase’s layers which thickness varies from 10 nm to 70 nm. The cell is volume formed by copper atoms; silver atoms are located in interlayers along the cell boundaries. Sprayed coatings were tested for wear resistance, friction coefficient, nanohardness and Young’s modulus. The formed coating shows an increase in 2.0 times nanohardness, in 3.3 times wear-resistance and in 1.4 times friction coefficient and decrease to 5.3 times Young’s modulus in comparison with the original copper electrical contact.

1. Introduction

When the electric current passes through the electrical contacts they heat while the highest temperature is observed on the contact surface because of the presence of the transient resistance [1, 2]. As a result of heating of the contact the specific resistance of the contact material increases and the transient resistance, respectively [3, 4]. In addition, the increase in the temperature of the contact favors the formation of the oxides on its surface that increases in the transient resistance to a far greater degree [5, 6]. Though the material of the contact may somewhat soften when the temperature increases that is connected with the increase in the contact surface, on the whole, this process may lead to the failure of the contacts or their welding [7, 8]. The latter, for example, for the opening contacts is rather dangerous, because, as a result, the electrical apparatus with these contacts will not be able to switch off the circuit [9, 10]. Therefore, for different types of the contacts the definite permissible temperature at the electric current flowing continuously through them is prescribed [11, 12]. To decrease the heating the mass of the contact material and the surface being cooled may be increased that will intensify the heat removal. In order to decrease in the transient resistance, it is necessary to increase in the contact pressure, choose the corresponding material and the type of the contacts [13,
14]. For example, it is recommended to manufacture the opening contacts, intended for the operation in open air, from the materials poorly amenable to oxidation or to cover their surface by the anticorrosion layer [15]. To these materials belongs silver, in particular, by which the contact surfaces may be covered. The other alternative method is the formation of the electroerosion resistant coatings of different systems on the surface of the electrical contact [16-18]. Such coatings, possessing the nanocrystalline structure, demonstrate the excellent service properties. The aim of this work is to detect the way elements and phases are formed defective substructure’s condition of the CJ20 contact’s surface layer, subjected to electro-explosive spraying of the CuO-Ag coating, and study nanohardness, Yung’s modulus, wear-resistant and friction coefficient.

2. Materials and methods
The object of the study was the CJ20 electromagnetic starter’s copper contacts. The Surface modification was realized by electro-explosive spraying. 250 mg of silver foil which was used as an electrical current conducting material, on the surface of which the charge of 120 mg of the CuO powder was placed in the explosion area. The time of plasma impact on the sample surface was ~100 µs, the absorbed power density on the jet axis was ~5.5 GW/m, the pressure in the shocked layer near the irradiated surface was ~12.5 MPa, the residual gas pressure in the working chamber was ~100 Pa; the plasma temperature on the nozzle cut was ~10^4 K, the thickness of the thermal affected zone was ~50 μm.

Elemental and phase composition, morphology and defect structure of the coating were analyzed by means of scanning electron microscopy (Carl Zeiss EVO50 device equipped with microanalyzer EDAX) and transmission diffraction electron microscopy (JEOL JEM-2100F device). Material properties were characterized by hardness (Nano Indentation Tester DUH-211S, indentation load is 30 mN). Terminological studies (determination of wear resistance and friction coefficient) were carried out on Pin on Disc and Oscillating TRIBOtester tribometer. The parameters were as follows: the ball was made with VK6 hard alloy, ball's diameter is 6 mm, radius track is 3 mm, indentation load is 3 N; track length depends on material's wear-resistance properties.

3. Results and discussion
Wear test shows that wear-resistance of the modified layer increase in ~1.4 times with electro-explosive spraying on the copper electrical contact (figure 1). Mechanical condition of the modified layer was characterized by nanohardness. Nanohardness and Yung’s module were determined by Agilent U9820A Nano Indenter G200 system on transitive section. Denting was carried out at the distance of ~15 μm from the working surface.

Figure 1. Dependence of nanohardness (curve 1) and Young's modulus (curve 2) of the modified layer on the indenter’s position on a line located at a depth of ~15 μm from the surface of the copper electrical contact processing.
The study of the surface layer’s structure of copper electrical contact subjected to electro-explosive spraying were carried out by means of cross-section analysis. Supplied results (figure 2) attest to the fact that electro-explosive spraying forms multilayered structure. The surface layer thickness (figure 2a, b, layer 1), having a submicro crystal structure, ranges from 30 to 35 μm. The surface layer is separated by transitive layer. The transitive layer thickness is 6-8 μm (figure 2a, b, layer 2). It is also worth noting that there are many micropores in transitive layer.

Figure 2. Cross section’s structure of the electrical copper contact’s subjected to electro-explosive spraying (Ag + CuO): a — surface layer; b — transition layer; c — electron microscope image of the structure of surface layer.

The study of the elemental phase compositions’ modified layer was analyzed by means of X-ray microanalysis. The results shown on figure 3 attest to the fact that silver atoms are located only in surface layer. Such kind of atoms aren’t detected in transition layer and copper volume. Consequently, transition layer was formed as a result of thermal influence, initiated by electro-explosive spraying.

Figure 3. Ag (graph 1) and Cu (graph 2) atom distribution in surface layer of the electrical copper contact subjected to electro-explosive spraying.

Phases and elemental composition, defective substructure condition of copper sample modified by electro-explosion was analyzed by means of transmission electron microscopy of thin foil. Completed studies show that high speed cellular crystallization structure is formed in the surface layer ~30 μm thick. Typical electron microscope images are shown in figure 4a-c. Cells scale ranges from 150 to 300 nm. The cells are separated by layers, which thickness ranges from 10 to 70 nm. Randomly distributed dislocations structure was identified in cell volume (figure 5a). Dislocation scalar density is ~1·10^{10} cm^-2. A dislocation substructure is detected in the cell volume. A typical image is shown in figure 4d.
Figure 4. Structure of electrical contact subjected to electro-explosive spraying: $a$ — surface layer; $b$ — layer located at a distance of 10 μm from the surface; $c$ — layer located at a distance of 20 μm from the surface; $d$ — layer located at the distance of 35 μm from the surface.

The thermal influence layer is located at a distance of more than 40 μm from the surface. This layer is copper’s solid solution and has polycrystalline structure. There is cellular mesh dislocation substructure in the copper grain’s volume. Typical image is shown in figure 5, 6. Cell size ranged from 350 to 700 nm. Scalar density is $0.9 \times 10^{10}$ cm$^{-2}$.

Figure 5. Electron microscope image of copper electro-explosive coating, subjected to electro-explosive spraying CuO-Ag coating: $a$ — surface layer structure; $b$ — structure of layer located at a distance of ~60 μm from the surface.
Figure 6. Electron-microscopic STEM-image (a) of the surface layer structure of copper electrical contact subjected to electroexplosion deposition; b — image of the structure of the area (a) obtained in the characteristic X-rays of silver atoms.

Silver atoms distribution results are shown in figure 6 and 7. Analyzing the results shown in figure 6 it can be concluded that in the high speed cellular crystallization structure formed in the surface layer, the cell volume is formed by copper atoms, silver atoms are mainly located on the cell borders forming extended layers (figure 6b).

Figure 7. Electron-microscopic STEM-image (a) of the copper electrical contact structure subjected to electroexplosion deposition; b — the image of the structure of the area (a) obtained in the characteristic X-rays of silver atoms. The analyzed layer is located at a depth of ~30 µm.

The results obtained in this work suggest that increasing strength (nanohardness) and tribological properties (wear resistance) of copper electrical contact, subjected to electro-explosive spraying, is caused by the formation of a multi-elemental multi-phase coating of a nanocrystalline structure in surface layer.

4. Conclusion
It was shown, that surface modification by means of electro-explosion of silver foil with CuO powder are accompanied by an increase of the modified layer wear resistance in ~3.3 times and friction
coefficient in ~1.4 times. Formed coating’s nanohardness is more than 2 times the copper electrical contact nanohardness. The electro-explosive coating form multilayered structure, which thickness was ranged to 40 μm. The High-speed cellular crystallization structure is formed regardless of the distance to the surface modifying in 30 μm surface layer. The cell’s size ranged from 150 to 300 nm. The cells are separated by layers of the second phase, which thickness varies from 10 to 70 nm. It has been discovered by means of the X-ray microanalysis, that cell’s volume is formed by copper atoms and silver atoms are located in the second phase layers on the cell’s borders. It is suggested that increasing strength (nanohardness) and tribological (wear-resistance) properties of cooper electrical contact, subjected to electroexplosive coating is caused by the formation in surface layer multiphase submicro-nanoscale structure.

Acknowledgments
The present work was performed within Russian Science Foundation project No. 18-79-00013.

References
[1] Baek S J, Kim M S, An W J and Choi J H 2019 Compos. Struct. 220 179
[2] Tayebani B and Mostofinejad D 2019 Construction and Building Mater. 208 75
[3] Roh H D, Lee S Y, Jo E, Kim H, Ji W and Park Y B 2019 Compos. Struct. 216 142
[4] Zhang Y, Hang T, Dong M, Wu Y, Ling H, Hu A and Li M 2019 Thin Solid Films 677 39
[5] Zhu Y, Xu Y, Li K, Wang X, Liu G and Huang Y 2019 Meas. J. Int. Meas. Confederation 138 8
[6] Kim Y I, An S, Kim M W, Jo H S, Kim T G, Swihart M T, Yarin A L and Yoon S S 2019 J. Alloys Compd. 790 1127
[7] Das A, Ashwin T R and Barai A 2019 J. Energy Storage 22 239
[8] Mohammed A G, Ozgur G and Sevkat E 2019 Cold Regions Sci. Technol. 160 128
[9] Astacio R, Gallardo J M, Cintas J, Montes J M, Cuevas F G, Prakash L and Torres Y 2019 Int. J. Refract. Met. Hard Mater. 80 259
[10] Zhang D, Yi P, Peng L, Lai X, Pu J 2019 Carbon 145 333
[11] Mombrú D, Romero M, Faccio R and Mombrú A W 2019 J. Mater. Sci. Mater. Electron. 30 5959
[12] Kazemzadeh A, Ein-Mozaffari F and Lohi A 2019 Chem. Eng. Res. Des. 143 226
[13] Zhao T, Iso Y, Ikeda R, Okawa K and Takei M 2019 Flow Meas. Instrum. 65 90
[14] Tokarska M and Orpel M 2019 Textile Res. J. 89 1073
[15] Singh B K, Jain E and Buwa V.V 2019 Chem. Eng. J. 358 564
[16] Romanov D A, Goncharova E N, Budovskikh E A, Gromov V E, Ivanov Y F and Teresov A D 2015 Inorg. Mater. Appl. Res. 6 536
[17] Romanov D A, Gromov V E, Glezer A M, Panin S V and Semin A P 2017 Mater. Lett. 188 25
[18] Romanov D A, Moskovskii S V, Sosnin K V, Gromov V E and Bataev V A 2019 Mater. Res. Express 6 055042