A study on structure and tribological properties of the electroerosion coating Mo-Ni-Cu, formed by the mixed method on copper

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Abstract. Multi-layered coating from immiscible components based on the system Mo-Ni-Cu was formed by the combined method of electro-explosive sputtering and subsequent irradiation by high-intensity pulse electron beam of submillisecond duration of influence on the surface of electrical copper contact (M00 grade of copper). The structure and phase composition studies of the applied coating as well as its mechanical and tribological properties are carried out.

1. Introduction

About a quarter of the world’s silver production is consumed by electrical technologies industry for manufacture of interrupting electrical contacts of low-voltage equipment. Because of the relatively high cost of such contacts, the developments of non-silver interrupting contacts, which can provide reliable operation of the commutation devices at low prices, are carried out. Copper, as a substitute of silver in the electrical contacts, has properties set which allow alloys, based on copper, with increased resistance to arc wear and welding, to be created. Thus, composite alloys from cooper are widely applied in the electrical technology as a contact material for low and high-voltage circuit breakers, inserts of plasmatrons, electrodes of welding machines, etc. [2]. Refractory metals, carbides, oxides and nitrides are applied as strengthening phases in such materials. Composites are obtained by methods of powder metallurgy [2, 3] and advanced technique of electro-explosive sputtering (EES) [4-6].

The aim of this work is to research into the structure, elemental and phase composition, mechanical and tribological properties of the coating based on Mo-Ni-Cu, formed by combined method on the copper substrate.

2. Materials and methods

The coating based on Mo-Ni-Cu, formed by the combined method of electro-explosive sputtering and electron-beam treatment on the copper substrate (electrical copper of grade M00), served as a material for examination [2-5]. EES was carried out on the electro-explosive unit EVU 60/10M [7].

It includes capacitive energy storage and pulsed plasma accelerator, consisting of coaxially-butt system of electrodes with a conductor placed on them, flash chamber localizing explosion products
and passing into the nozzle, through which it flows into the evacuated process chamber with residual pressure 100 Pa. The electro-explosion takes place due to the high-density current passing through the conductor during the capacitor discharge.

Coatings were deposited on the samples of annealed copper grade M00 with sizes 15×15×5 mm. The mode of thermal and power influence on the irradiated surface was set by charge voltages election of capacitive energy storage, according to which the absorbed power density was calculated [7]. The electro-explosive sputtering was conducted with the use of a composite electro-explosive conductor [8] for deposition of coatings. The conductor consisted of a copper double layer foil with a powder sample of molybdenum and nickel. Their weights were: molybdenum – 0.217 g, nickel – 0.120 g and copper – 0.277 g. The power density, absorbed by the irradiated surface during sputtering, was 4.1 GW/m², copper nozzle diameter of the flash chamber of the plasma accelerator – 20 mm, the distance of the sample from the nozzle section was 20 mm.

The subsequent treatment by high-intensity pulse electron beam was carried out on the unit SOLO (Institute of High Current Electronics Siberian Brunch of the Russian Academy of Sciences) [9] at the following parameters of the electron beam: 18 keV, 55 J/cm², 100 µs, 0/3s⁻¹, 10 pul.

The studies of the phase composition and defect substructure of the coating were carried out by the methods of scanning and transmission electronic diffraction microscopy.

The wear resistance tests were carried out at a dry friction according to the scheme disc-ball on a high-temperature tribometer TNT-S-AH0000, CSEM, Switzerland. The indenter (counterbody) was a ball with a diameter 3 mm from hard alloy VK8. Tests were carried out at room temperature and relative humidity of 50% under the following conditions: normal load on the indenter 8 H, sliding velocity 3.5 cm/s, the track diameter 4 mm, the number of revolutions (cycles) 5000. The wear rate of surface layer was evaluated after profilometry of the formed track with the help of the laser optical profilometer Micro Measure 3D Station (Stil, France). Deterioration parameter was calculated by the formula:

\[ V = \frac{2 \pi R A}{FL} \text{[mm}^3\text{/N·m]}, \]

where \( R \) – the track radius [mm], \( A \) – cross-sectional area of the wear groove [mm²], \( F \) – the value of the applied load [H], \( L \) – the distance covered by the ball [m].

3. Results and discussion

The coatings formed by the method of electric explosion of the conductive material, is typically characterized by a highly developed relief (lappings, drops, micropores) [7]. The subsequent irradiation of such coatings by high-intensity pulsed electron beam at a mode of surface layer melting under the influence of surface tension forces leads to smoothing of the irradiated surface (Figure 1 a, d).

At the optimal mode of irradiation the surface layer is formed with an island structure (Figure 1, b, d); in the islands volume the submicro- crystalline structure is found, the characteristic image of which is given in Figure 1 c, f. It should be noted that the optimization of the irradiation mode was performed by carrying out thermal calculations that the thermal field in the surface layer of the materials to be modeled.
Figure 1. Structure of the coating surface Mo-Ni-Cu, formed on the copper sample and irradiated by high intense pulse electron beam.

The formed coating is multi-layered (Figure 2). Analyzing the results presented in this figure the surface layer can be distinguished (Figure 2 b, c, layer 1), firmed in the result of coatings melting by high intensity electron beam; transitional layer characterized by a large amount of micropores (Figure 2 b, layer 2), and coating layer adjoining to the substrate (Figure 2, b layer 3).

At the same time, in the near-surface volume of the substrate, adjoining to the coating, the structure with a submicron size of crystallites is identified (Figure 2 b, layers 4 and 5). The copper substrate is a polycrystalline aggregate, the grain sizes of which are units-tens of micrometers (Figure 2 a, layer 6).

Figure 2. Structure of the transversal section of the coating Mo-Ni-Cu, formed on the copper sample and irradiated by high intensity pulse electron beam.

The performed investigations show that the identified layers differ not only in their structure but in the elemental composition, which is proved by the results of micro X-ray spectral analysis of the coating elemental composition given in Figure 3 and 4 in Table 1.

Table 1. Elemental composition of the modified layer presented in Figure 3a.

| Zone No. | Element, at. % |
|----------|----------------|
Analyzing the results in Figure 3 and in Table 1, it can be noted that the elements of the sputtered coating along the thickness of the modified layer are distributed unevenly. And namely, the concentration of the alloying elements Mo and Ni increases as the distance from the coating surface rises. Additionally to the sputtered elements in the coating the atoms of carbon and oxygen are found. The presence of oxygen and carbon atoms indicates the possibility of carbides and metal oxides formation in the coating.

The phase composition and the defect substructure of coatings were analyzed by the methods of transmitting electron diffraction microscopy of thin foils. The coating layer located at a depth of \( \approx 15 \) \( \mu \text{m} \) was examined.

**Figure 3.** Structure of the transversal section of the coating Mo-Ni-Cu, irradiated by high intensity pulse electron beam (a); b – energy spectra obtained from the zone 3 (a). Scanning electron microscopy.

|       | Mo | Ni | Cu   | C   | O  |
|-------|----|----|------|-----|----|
| 1     | 2.3| 6.2| 16.4 | 67.6| 7.1|
| 2     | 27.0| 14.3| 11.6 | 36.6| 10 |
| 3     | 49.5| 17.3| 15.1 | 0.0 |16.8|

**Figure 4.** Structure of the transversal coating section of the system Mo-Ni-Cu, formed on the copper sample and irradiated by high intensity pulse electron beam, revealed during mapping of the elemental composition of the material [13]; a – image, obtained by imposition of the X-Ray radiation of the basic elements in the material; b – image obtained in the X-Ray radiation of copper atoms; c – nickel atoms; d – molybdenum atoms.
Electron-microscopic image of the defect coating substructure is presented in Figure 5. The analysis of micro electron-diffraction patterns obtained from such zones of the material makes it possible to conclude that the copper has this substructure. Thus, in the copper matrix the reticular (Figure 5 a), cellular-reticular, band and fragmented dislocation substructures are identified.

![Figure 5](image1.png)

**Figure 5.** Electron microscopic image of defective coating substructure of Mo-Ni-Cu composition, formed on the copper; a, b, c, e – bright fields; d, f – micro electron-diffraction patterns for (c) and (e).

Alongside with a single-phase there are two-phase zones of the foil, and namely, the zones, containing copper and molybdenum. The typical images of such structures are presented in Figure 6. It can be clearly seen that in the process of high speed crystallization the two-phase structure of lamellar (Figure 6 a-c) or cellar type (Figure 6, d) is formed. In the first case molybdenum in the form laminas is located in the copper matrix (Figure 6 a-c); in the second – molybdenum in the form of interlayer contours the copper cellars (Figure 6 d-e).

![Figure 6](image2.png)

**Figure 6.** Electron-microscopic image of the coating structure of Mo-Ni-Cu composition, formed on the copper; a, d – bright fields; b, e – micro electron-diffraction patterns for (a) and (d); c – dark field obtained in the reflections [111]Cu + [110]Mo; the arrows in (a) and (d) indicate the molybdenum particles; in (b) – reflections, in which a dark field was obtained (c); in (e) – reflections of type [002]Mo and [220]Mo.
The strength characteristics of the coating were analyzed to determine the hardness value by the methods of nano-hardness measurement. Alongside with the nano-hardness the value of Young modulus was determined. The results are given in Figure 7.

![Figure 7](image)

**Figure 7.** Dependence of hardness value (curve 1) and Young modulus (curve 2) of the coating with composition Mo-Ni-Cu, treated by electron beam from the load on indentor.

Analyzing the presented in Figure 7 dependencies, it can be noted that at low loads on indentor (5-25 mN) the hardness and Young modulus achieve rather significant values, that points on the strong influence of the oxide film formed on the material surface. At load on the indentor not higher 30-40 mN, hardness and Young modulus of the examined coating practically do not change, and consequently, correspond to the hardness of material coating.

From the reference data it follows that microhardness of copper is 0.6 GPa [3], microhardness of system coating Mo-Ni-Cu is \( \approx 1.0 \) GPa. Thus, coating hardness exceeds the hardness of copper substrate in \( \approx 1.7 \) times. Young modulus of commercially pure copper changes within range (110-120) GPa [7], which is close to coating Young modulus of the system Mo-Ni-Cu.

One of the important characteristics of the electrical contacts is their durability. Results of durability tests for the coating with composition Mo-Ni-Cu are shown in Table. 2. Analysis of the presented in Table 2 measurement results of specific wear volume (V) and the average value of the friction coefficient (f) shows the coating system based on the system Mo-Ni-Cu formed on the surface of copper is characterized by high values of wear resistance and close values of the friction coefficient (f).

### Table 2. Tribological test results of coating with composition Mo-Ni-Cu formed on copper.

| Mode       | V, \( 10^{-6} \) mm\(^3\)/N·m | V(initial) | V(coating) | \( <f> \) | f(min) | f(max) |
|------------|-------------------------------|------------|------------|-----------|--------|--------|
| Cu initial | 76.7                          | 0.332      | 0.116      | 0.412     |
| Mo-Ni-Cu   | 33.4                          | 2.3        | 0.408      | 0.2       | 0.442  |

### 4. Conclusions

- By the electron plasma combined method including electro-explosive spattering and subsequent irradiation by high-intensity pulse electron beam on the surface of copper a multi-phase multi-layer coating on the basis of the system Mo-Ni-Cu was formed, characterized by high values of hardness and wear resistance.
- The specific wear volume of the coating of the system Mo-Ni-Cu exceeds the similar parameter of electrical copper by more than 2.3 times.
- The coefficient of friction values of the coating system Mo-Ni-Cu and electrical copper have similar values.
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