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PRODUCTION TECHNOLOGY, PHYSICAL, MECHANICAL AND PERFORMANCE CHARACTERISTICS OF Cu-Zr-Y-Mo FINELY-DISPERSED MICROLAYER COMPOSITE MATERIALS

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The production of Cu-Zr-Y-Mo Finely-Dispersed (FD) microlayer composite materials for electrical contacts by the method of electron-beam evaporation and layer-by-layer condensation from the vapor phase is described and the chemical composition, structure, density, electrical conductivity, hardness, and main mechanical characteristics of the materials in the temperature range from 290 to 1070 K are studied.

Key words: *microlayer composite material, electric contacts, characteristics, high-temperature strength and hardness*

Tehnologija proizvodnje, fizikalna, mehanička i karakteristike malo disperznih mikroslojeva kompozitnih materijala sustava Cu-Zr-Y-Mo. Opisana je tehnologija proizvodnje i istraživanja kemijskog sastava, strukture, gustoće, elektroprovodljivost, tvrdoće i temeljna mehanička svojstva malo disperznih mikroslojnih kompozitnih materijala (MDK) sustava Ci-Zr-Y-Mo u dijapazonu temperatutre 290 - 1070 K, koji se rabi za električne kontakte, a dobiveni su metodom elektro-lučnog isparavanja i slojevite kondenzacije iz parne faze.

Ključne riječi: *mikroslojni kompozitni materijal, električni kontakti, svojstva, visokotemperaturna čvrstoća i tvrdoća*

INTRODUCTION

Developed at the E.O. Paton Electric Welding Institute, National Academy of Sciences of Ukraine, the method of obtaining thick films by means of electron-beam evaporation and the subsequent condensation of metallic and nonmetallic materials in vacuum provided the basis for industrial production technologies of advanced structural and functionally-gradient materials and coatings. Production of microlayer composite materials for electrical contacts is one of the most promising applications for the electron-beam method [1 - 3].

Based on the fundamental concepts of solid-state physics, the Gekont Research and Production Company, Vinnitsa, created and patented a one-of-a-kind industrial technology of electron-beam production of new-generation composites for electrical contacts consisting of copper, molybdenum, and rare earth metals. The FD materials developed and electrical contacts produced on their basis exhibit unique physical, mechanical, chemical, and performance characteristics, which make them stand out from the known materials of this class. They have been certified and are mass-produced in Ukraine.

MATERIAL, TREATMENT AND TESTING

We obtained condensed composite materials of Cu - (0,08 … 0,2) wt. % Zr - (0,08 … 0,2) wt. % Y - (6 … 14) wt. % Mo using an industrial electron-beam facility UE-189 (Figures 1., 2.). The facility comprises work chamber 1 made in the form of a 1100 × 1200-mm rectangle. In the lower part of the work chamber there are four mechanisms 2, 3, 4, and 5 with water-cooled copper crucibles 6, 7, 8, and 9 of diameter 70 and 100 mm to lift ingots being evaporated. The length of rods 10 and 11 of these mechanisms allows for ingots as long as 500 mm to be put in the crucibles. The side wall of the work chamber has gun chamber 12 attached to it, which contains two electron-beam heaters 13 and 14 with a power of 20 kW each to heat the substrate. On the upper lid of the work chamber there is a unit with 100 kW electron-beam heaters 15, 16, 17, and 18 meant directly for evaporation of feed materials.

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The production of Cu-Zr-Y-Mo composite material was carried out as follows. We fixed Substrate 19 made in the form of a disk 1000 mm in diameter and 20 mm in width to the upper rod 20. The substrate surface which was presented to the crucibles and on which the condensation occurred was polished to achieve N8-N9 surface finishes. For an easy separation of condensed material from the substrate, the latter was precipitated with a thin (10-15 μm) separating layer of calcium fluoride. Copper ingots 21 and 22 of diameter 98,5 ± 0,1 mm and length up to 500 mm were placed into two of the four water-cooled copper crucibles 100 mm in diameter and molybdenum ingots 23 and 24 of diameter 68,5 ± 0,1 mm and length 300-320 mm long were placed into the other two.

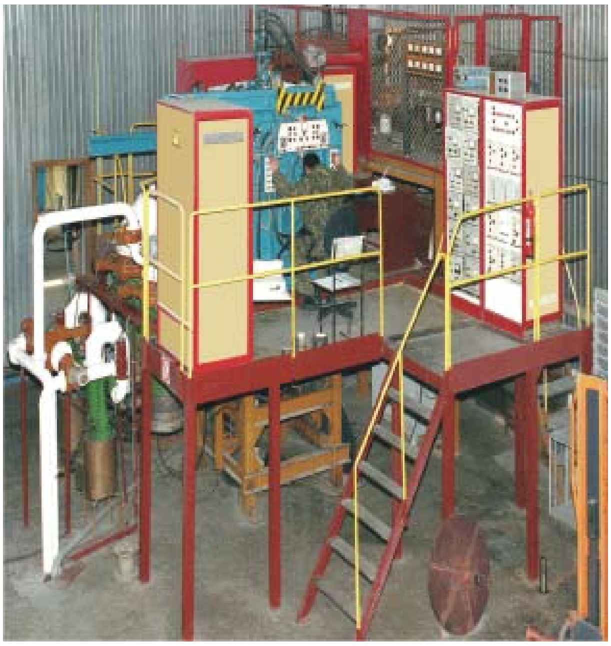

Figure 1. **Surface appearance of industrial electron-beam facility UE-189**
Slika 1. **Izgled industrijskog elektro-lučnog uređaja UE-189**

The copper matrix was alloyed with yttrium and zirconium as follows. Two batches of these components, 135 g each, were put on the surface of the copper ingots. On reaching a vacuum of (1,3 - 4)×10^{-2} Pa in the chamber, we performed the electron-beam heating of the substrate, on which vapors were to be condensed, up to the temperature 950 ± 15 K. Simultaneously, we heated the surface of the copper ingots, making the constituents (zirconium, yttrium, copper) lying on it melt. The melt pool became homogeneous after 15 - 20 minutes of heating. At the production stage the evaporation of the copper ingots was performed at a beam current of 2,6 … 2,8 A. The acceleration voltage was 20 kV.

Molybdenum was evaporated from the two other crucibles. By varying the beam current in the range from 1,7 to 2,4 A, one can readily regulate the evaporation rate of molybdenum and its concentration in the composite in the range from 4 to 14 wt. %.

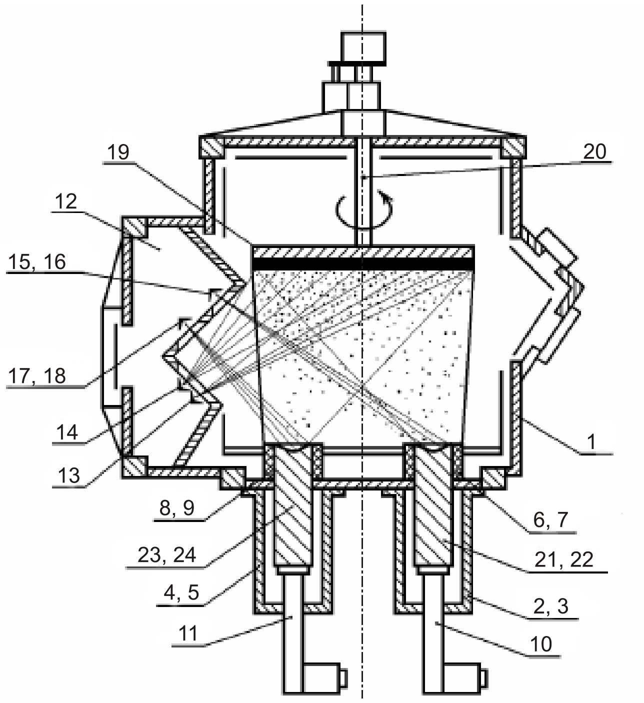

Figure 2. **Scheme of industrial electron-beam facility UE-189 for producing materials for electrical contacts**
Slika 2. **Principijalna shema elektro-lučnog uređaja UE-189 za proizvodnju materijala za električne kontakte**

On completing the production process, the composite material condensed was separated from the substrate and annealed in a vacuum furnace at 1170 K for 3 h.

FD composite materials are produced in three modifications: MDK-1, MDK-2, and MDK-3 with the molybdenum content of 2,5 - 5, 5,1 - 8, and 8,1 - 12 wt. %, respectively. The total content of zirconium, yttrium, and their oxides in all cases is no more than 0,8 wt. %.

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-P 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, which corresponded to a relative strain rate of ~ 2,2 10^{-3} s^{-1}. During the tests deformation diagrams were recorded to determine the proof strength $R_{p0,2}$, the ultimate strength R_m, the percentage elongation after fracture A, and the percentage reduction of cross-sectional area Z.

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 $\alpha = 0,05$.

RESULTS AND DISCUSSION

By applying the layer-by-layer condensation of low-alloy copper and molybdenum and moving the substrate out of the zone of the vapor flow while it is rotating, it is possible to perform tempering from vapor and obtain materials with the structural elements typical of nanomaterials [8]. Cu-Zr-Y-Mo composites are characterized by a specific microlayer structure with the alternating layers of Cu-Zr-Y low alloy and molybdenum from 0.1 to 0,4 μm thick (Figure 3.). The grain size of copper in the composite is 0,1 - 0,3 μm and that of molybdenum is from 0,01 - 0,02 μm.

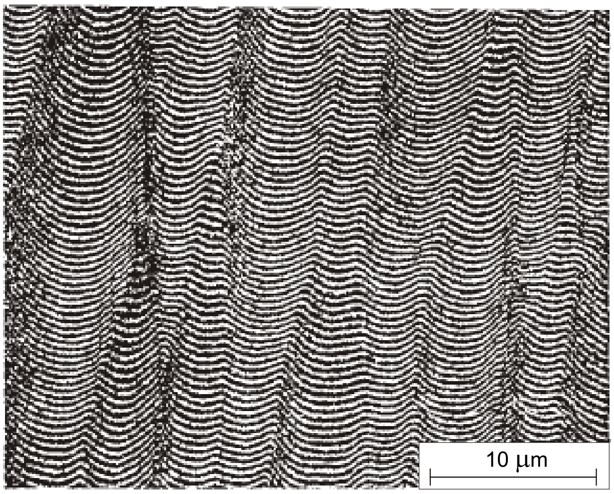

Figure 3. **Microstructure of Cu-Zr-Y-Mo composite material (SEM)**
Slika 3. **Mikrostruktura kompozitnog materijala Cu-Zr-Y-Mo (SEM)**

Numerous properties requirements which a material for electrical contacts should meet are highly inconsistent and are mainly dictated by their operating conditions. To meet these requirements, the contacts should be made from a material possessing a certain complex of physical, structural, mechanical, chemical, and electrical contact properties. In particular, these properties include high electrical and thermal conductivity, melting temperature, high critical current strengths and voltages, strength characteristics, low contact resistance, high electrical erosion and corrosion resistance, volatility of its oxides, ease of processing, relatively low prime cost and environmental compatibility. At present, none of the known electrical contact materials possess the full set of the above properties.

Standard values of physical and mechanical characteristics of FD microlayer composite materials and rated currents for contacts produced on their basis are given in Table 1.

Table 1. **Standard values of physical, mechanical and performance characteristics of MDK materials**
Tablica 1. **Normativne vrijednosti fizikalnih, mehaničkih i svojstvenih karakteristika MDK materijala**

Material type	Molybdenum content /wt %	Density g/cm^3	Vickers hardness / MPa	Electrical resistivity Ohm mm^2/m	Rated current of contacts / A
MDK - 1	2,5 – 5,0	8,98 – 9,00	1000 – 1500	0,021 – 0,022	up to 10
MDK - 2	5,1 – 8,0	9,00 – 9,05	1500 – 1650	0,022 – 0,024	up to 100
MDK - 3	8,1 – 12,0	9,05 – 9,10	1650 – 1750	0,024 – 0,028	above 100

Table 2. lists the mechanical characteristics of the most promising material MDK-3 in the temperature range from 290 to 1070 K.

Table 2. **Hardness, strength, and plasticity of MDK-3 composite material in the temperature range from 290 to 1070 K**
Tablica 2. **Tvrdoća, čvrstoća i plastičnost MDK-3 kompozitnog materijala u temperaturnom intervalu od 290 do 1070**

T / K	HV / MPa	R_m / MPa	$P_{0,2}$ / MPa	A / %	Z / %
290	1802	645	596	8,7	37,6
370	1349	568	533	8,8	18,3
470	1066	475	438	12,4	33,1
570	776	348	330	1,8	7,0
670	577	287	266	7,9	13,5
770	414	205	185	8,8	12,8
870	303	140	130	13,1	9,1
970	213	82	73	17,1	16,6
1070	151	45	39	21,7	33,7

The electrical conductivity of Cu-Zr-Y-Mo microlayer composite materials ranges from 65 to 75 % of that of copper, which is almost twice as much as that of all known Mo-Cu powder compositions. Their maximum magnitude of transferred current (up to 4000 A) is 2,5 times higher than that of silver.

FD composites significantly surpass all existing electrical engineering materials in radiation resistance, thermal stability, and wear resistance. They exhibit a high thermal conductivity, do not maintain the arc, and are more corrosion-resistant and durable than silver [3].

Cu-Zr-Y-Mo composite materials exhibit a unique complex of mechanical characteristics combining high hardness and strength with a satisfactory plasticity in the whole temperature range studied. The strength of these composite materials is 2 or 4 times higher than that of Cu-Al_2O_3 and Cu-BeO powder composites and cast copper superalloys [9].

Additional alloying of the copper matrix with yttrium and zirconium allowed us to modify greatly the composition of the oxide film appearing in operation when the condensed material is in an oxidizing medium. Unlike Mo-Cu powder composites where the oxide films consist of $CuO \times MoO_3$ and $3CuO \times 2MoO_3$ compounds, the films of condensed materials are formed on the basis of complex spinels, such as $CuMoY_2O_7$ and $CuMoZrY_2O_9$. In such oxide films no polymorphic transformations occur and they are distinguished by a high electrical conductivity and adhesion to the base material.

Electrical contacts made of Cu-Zr-Y-Mo microlayer composite materials exhibit high thermal and electrical corrosion resistance. They are unweldable and meet all increasing demands for the reliability and service life of switchgear.

CONCLUSION

Finely-Dispersed microlayer composite materials of Cu-Zr-Y-Mo system for electrical contacts exhibit unique physical, mechanical, chemical, and performance characteristics, which make them stand out from the known materials of this class.

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