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Current state and prospects for application of a high power electron beam technology to produce metallic and nonmetalic components for electric contacts and electrodes

N. I. Grechanyuk, R. V. Minakova*, I. N. Grechanyuk,
B. Miedzinski**, L. J. Xu***

Scientific and Producing Company "ELECHMASH", Vinnitsa, Ukraine
*Institute of Material Science UAN, Kiev, Ukraine
**Wroclaw University of Technology, Wroclaw, Poland
***Beijing University of Posts and Telecommunications, Beijing, China

In the paper current state and prospects of applicability of a high power electron beam technology for manufacturing both metallic and nonmetallic composite materials mostly for electric contacts and electrodes are presented and discussed.

Keywords: *composite materials, technology, power electron beam, installation, height annual rate, electrical contacts and electrodes.*

Introduction

Evaporation and following condensation of materials in vacuum comprises relatively young, alternative trend in material technology [1]. It uses physical-technological properties of the electron beam resulting in the highest efficiency of material treatment with compare to another technologies that employ concentrated energy fluxes (i.e. laser, plasma). The electron beam is distinguished by considerable high concentration of energy (its effective power value can be over 1MW). Therefore, the required temperature value (melting, evaporation etc) of a heated material is attained at optionally selected very short time. The high speed of material evaporation with following condensation in vacuum constitutes specific quality of the technological process used on a large scale for deposition of both thin films (<5 u. m) in radio engineering, micro-electronics etc [2] and thick (>5 u. m) layers employed for anticorrosion and other environmental protection technique [3, 4].

Expectations if about metal-composition technology indicates increased contribution of vapor deposition technique in fabrication of new materials [5]. Therefore, development and manufacturing of different multicomponent coatings for electrical contacts to increase their resistance to electric corrosion seems to be promising. Recent scientific achievements confirmed by investigated results in industry for the developed coatings are presented the most exhaustively in monograph [6]. Particular attention was there paid on copper based alloys with tin, chromium, aluminum, nickel and titanium elements as additions respectively. High mechanical resistance of layers made of Cu (0,5%) Al_2O_3 what suggest their use for electrical contact protection is mentioned in [7]. It should be noted that the coating deposited in vacuum indicates superior properties if about temperature stability as well as mechanical wear level with compare to the electroplated. However, not necessarily it can be economically justified since, effective coefficient of utilization of the vapor volume usually does not exceed 20%. One has to face also another specific problems,(under evaporation), when essential material e.g. copper or silver must be dopped with the high melting component like tungsten, molybdenum, niobium, zirconium etc of any composition. It is due to difference in vapor bulk elasticity of the particular alloy forming elements. It is a well known fact that at present powder metallurgy is commonly used for fabrication of materials for electric contacts. Physical properties of fine powder sinters, their operating characteristics and areas of application are presented and discussed in details, among others, in [8—11]. However, when pass detailed as technical as well as technological difficulties over the problem of achievement of a right material for electrical contacts still is topical. It results both from contradictory operational requirements concerning electrical contacts properties, type of switch and load as well as variation of the contact properties under its life. Nowadays, market price of raw materials forces producers to exploration new materials and to develop the new switch structures as well. In general one can say that only particularly selected metal compositions of a "proper" structure and demonstrating combination of suitable properties both electrical, chemical, mechanical etc can be recommended as the contact materials. It was found that the material structure "wields" selective influence on the operating characteristics of the electrical contact. For example, increase of resistance to electric corrosion in powder-metal contacts of both Ag-metal and Ag-metal oxide compositions results in the decrease of plasma vapor intensity under electrical discharge (if increase the material dispersion) [12].

Evaporation and following condensation in vacuum enable control of the material structure already at the atomic-molecular level. Therefore, use of the high power electron beam technology to produce compositions, among others, for electric contacts is both technically and economically justified. It is also interested with scientific point of view. However, first samples of micro layers and dispersion hardening structure materials of about l—2 mm of thickness were already developed in 70-es of the last century in numerous research labs (among others in Institute of Material Science in Kiev [13] and in Royal Aviation institute of British Ministry of Defense [14]), but, so far the problem of mass production remains unsolved. Before to set about working on application of the power electron beam technology to obtain composite materials for electrical contacts one has to consider all problems both with practical as well as scientific point of view. One of them is economy, Therefore, price of new materials for electrical contacts and electrodes should be competitive to these made by means of so far used powder-metal technology. It can be reduced significantly if decrease amount of expensive noble metallic components. However, the most important is that these new products were able to meet all requirements for successful application in switching equipment. Therefore, one had to face various problems like selection of proper composition and structure of the material, proper investigation of its electrical and mechanical properties and to develop the high power electron beam technology to mass production.

Very useful was here experience on performance of the powder-metal (P-M) compositions without or with the reduced amount of noble materials (e.g. silver) when use in switchgear under NTP conditions. They are usually composed of (20—80)% in mass of a high melting metal, (0,5—12)% of alloy additions (like: nickel, cobalt, silver) and the rest of so called "functional" component-mainly copper. The (P-M) composite materials of about 50% and/or 70% content of tungsten or molybdenum are widely used in industry [15]. When use the W—Cu composition the main oxidation products on the contact surface arc found to be tungsten oxide (WO3} and cupric (Cu_2O) oxide [16]. Their specific resistance can be changed in wide range {10^2—10^{14}) Ohm/m for WO_3 and (10^5—10^{12}) Ohm/m for Cu_2O respectively. For Mo—Cu compositions, when switching the electrical arc in air, the oxidation process is similar. However, both Mo and Cu are limited — soluble [17] and as well as their oxides interacts and produce stable compounds ($CuMoO_4$, $Cu_3Mo_2O_3$ etc) [18, 19] that in temperature over 700 °C form a fusible eutectic (in MoO_3—Cu_2O system). It reduces, as a result, electromechanical corrosion under operational temperature over 800 °C. Besides, the oxide film being constituted as pseudo eutectic as well as eutectic, in MoO_3—Cu_2O bounding, easily spreads over the contact surface and fills up its roughness [18, 19]. It is next (after crystallization) exfoliated from the surface due to weak adhesion force and produces so called **"self-cleaning"** effect. This effect is revealed as the decrease in the contact resistance value [15]. Metals and powder-metal compositions assigned to operation in corroded medium are usually protected against oxidation by deposited films or by use selected improvers. We have found that for products on the copper base and for the molybdenum and copper compositions the operational characteristics of the electrical contacts are improved when use zirconium or yttrium elements as additives. As a result, when use the electron beam technology various contact materials were able to be developed like Cu—Zr—V—Mo for breaking and sliding contacts, Cu—Zr—Y—Cr, Cu—Zr—Y—W for arcing contacts and Cu—Zr—Y—Al_2O_3 for electrodes of electric — arc welding.

Developed equipment for high power beam technology

To make full use of the electron beam technology to obtain both metallic and/or nonmetallic components in commercial scale of production a suitable fabrication facility has been developed in Scientific and Production Company "ELTECHMASH" in Vinnitsa, Ukraine. Its general view is presented in fig. l, while the schematic diagram can be seen in fig. 2.

The installation presents pretty complex equipment composed of working chamber, chamber of electron guns, power supply system and other necessary equipment for mechanical, electronic and vacuum level control. At the bottom of the working chamber arc located the adjustment mechanisms for maneuver of four water-cooled crucibles made of copper. Two of them are of 1 m in diameter and another two of 0,7 m

Fig. 1. General view of the production facility (L-5) using high power electron beam technology for manufacturing of materials and components.

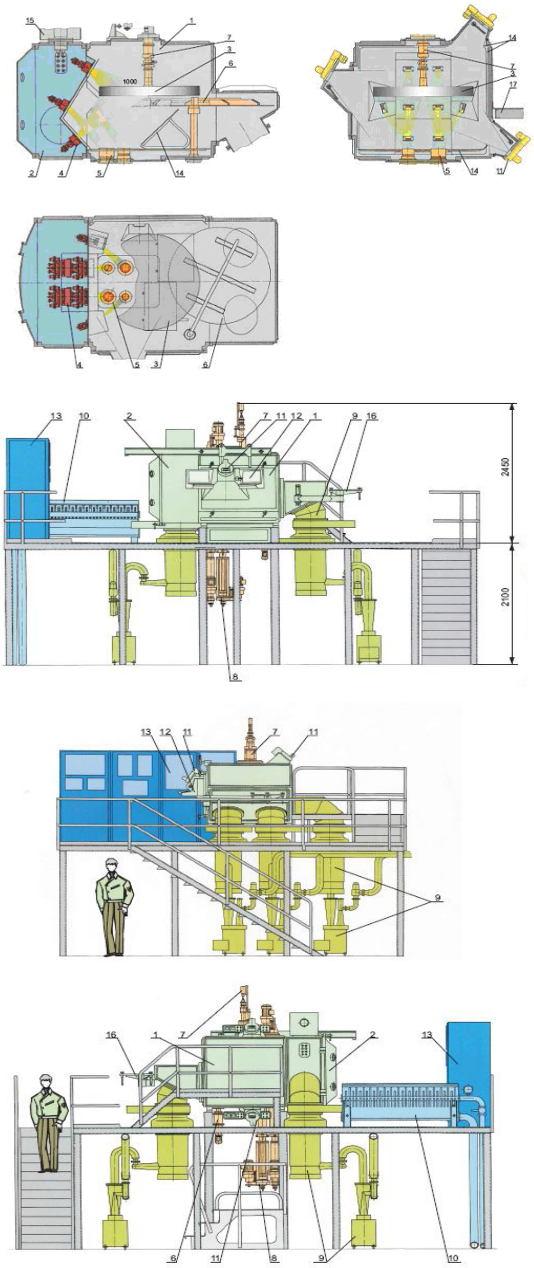


Fig. 2. Schematic diagram of the L-5 equipment: 1 — working chamber; 2 — electron gun chamber; 3 — product (base); 4 — electron guns; 5 — melting crucible block; 6 — curtain; 7 — lifting and rotation mechanism of the product; 8 — feeder of ingots; 9 — vacuum system; 10 — cooling system; 11 — visual inspection windows; 12 — control desk; 13 — control box; 14 — shielding; 15 — high voltage input; 16 — manipulator; 17 — plane of routine maintenance.

respectively. The crucibles can change location with respect to the others and their sequence of operation is also controlled optionally. Basic technical data of the industrial installation (1—5 type) are set up in table 1.

Dimensions of mandrels of the bottom mechanisms enable location of heavy bars of overall length up to about 8m of selected materials inside the crucibles. The four electron guns situated at the top and bottom of the guns chamber (fig. 2) heat directly the wear being subjected to vacuum sublimation. While, the remaining four accomplished the evaporation of the selected output materials. To begin work on fabrication of a new material first the base (3 in fig. 2) in disk form of about lm in diameter, must be located in lifting and rotation mechanism of the product (7 in fig. 2).The base surface, which is subjected to sublimation, must be appropriately prepared according to 9—10 class of purity. Next, to provide easy separation of the condensed material from the base, this last one has to be covered with tiny dividing layer (10—15u.m) made of calcium fluoride (CaF). To obtain composite materials by evaporation and following condensation in vacuum the following output materials (in form of ingots) were used: copper of 0,985 m in diameter and 5 m in length, molybdenum and tungsten of 0,685 m and 5 m and chromium of 0,685 and 3 m respectively. (Chromium was properly prepared by respective melting-in fractional crystallizer-of electrolytic material in purifying argon environment). Yttrium was selected of ITM1 and/or ITM2 class of quality. Zirconium was prepared according to TU 5-20-069-85 technical standard. While, the ingots of aluminum oxide of 0,685 m in diameter and 0,5 m in length were manufactured from a high quality powder (chemically pure) by cold molding and following sintering in air at 1500 °C. It is necessary to stress that purity of all applied materials was not below 99,9% (mass) [20].

Table l. Data of the (L-5 type) high power electron beam installation

Parameter	Value/Unit
Installed rated power	480 kW
Rated voltage of 3-phase system, 50 Hz	380 V
Accelerating voltage of electron guns	20 kV
Number and rated power of electron guns	8x60 kW
Diameter of a ware being sublimated in vacuum	≤ 1 m
Thickness of a condensate	$(0,1—5)\cdot 10^{-3}$ m
Condensation rate: for metals	up to 50 μm/min
for ceramics	up to 5 μm/min
Number of crucibles of 0,1 m in diameter	2
of 0,07 m in diameter	2
Length of evaporating ingots	0,5 m
Speed of ingot feeding	$(0,28 —280)\cdot 10^{-3}$ m/min
Maximum two weight to hold the good in position and to rotate it by mechanism	100 kg
Level of technical vacuum	$6\cdot(10^{-3}—10^{-2})$ Pa
Pressure of cooling water	$(3—4)\cdot 10^{5}$ Pa
Consumption of cooling water	12 m^3/h
Total weight	~20 t
Usable equipment area	80 m^2

Selected compositions and their properties

The most interested for industrial applications turned out the compositions prepared on copper-molybdenum base. They are particular convenient for breaking as well as sliding electrical contacts operating in environmental conditions. To make such the multilayer composite material two crucibles must be loaded with ingots made of copper based alloy with Zr—Y alloy additions up to 0,2% (mass). While, the two others — with metal selected depending on application. Therefore, it is molybdenum ingot to obtain compositions of Cu—Zr—Y—Mo type for breaking and sliding contacts; tungsten (Cu—Zr—Y—W) or chromium (Cu—Zr—Y—Cr) for contacts with electric arc or ceramic ingot made of aluminum oxide Cu—Zr—Y—AI_2O_3 for electrodes of electrical welding equipment respectively. After actuation of the installation and when the vacuum level reaches around $(1{,}3—4)\cdot10^{-2}$ Pa the electron guns are set in motion to heat the base (subjected to deposition) up to about 700 ± 20 °C. Simultaneously there is heated also surface of ingots of the out-put evaporated materials up to melting and evaporating points. Duration of the technological process to obtain a semi-finished product (perform) in form of sheet of lm in diameter and $(2—4)\cdot10^{'3}$ m lasts about 3—5 hours depending on requirements. The composite sheet is next separated from the base and is ready for further processing (forming of contact samples and their following oven soldering to contact bases). The composite materials of Cu—Zr—Y—Mo structure have been certified and are produced according to Ukrainian technical requirements. Their technology as well as preparation procedure are protected by Ukrainian patents [21, 22]. Basic physical-mechanical properties of the condensation compositions Cu—Zr—Y—Mo type are listed in table 2. As one can see from table 2 the developed composite materials are characterized by pretty high hardness, high strength and resistivity and sufficient plasticity. To explain the

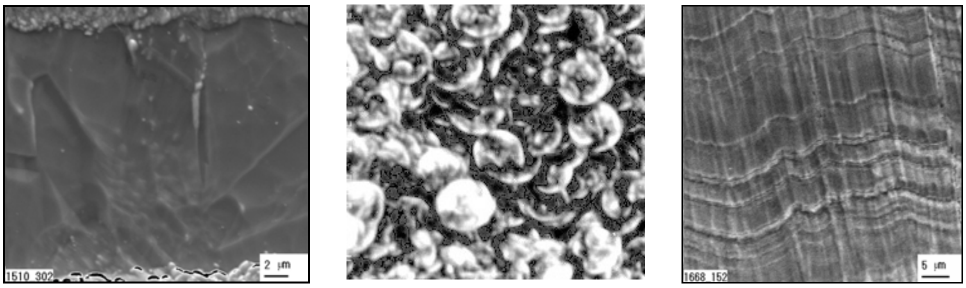
Table 2. Physical-mechanical properties of compositions Cu—Zr—Y—Mo

Type	Chemical composition % (mass)	Density, kg/m^3	Resistivity, μΩm	Microhardness *HV*, MPa
MDK-1	Cu—Zr—Y; 3—5% Mo	8980—9000	0,021—0,022	1000—1500
MDK-2	Cu—Zr—Y; 5,1—8% Mo	9000—9050	0,022—0,024	1500—1650
MDK-3	Cu—Zr—Y; 8,1—12% Mo	9050—9100	0,024—0,028	1650—1800

Type	Mechanical properties					
	Before tempering			After tempering 1 h, 300 °C		
	$\sigma_{0,2}$, MPa	σ_w, MPa	σ, %	$\sigma_{0,2}$, MPa	σ_w, MPa	σ, %
MDK-1	210—370	300—430	10,3—7,3	200—360	295—420	17,6—9,5
MDK-2	380—530	440—630	7,25—3,4	365—510	425—600	9,45—4,9
MDK-3	550—750	635—785	3,25—1,8	520—695	605—730	4,85—3,9

influence of physical properties of the composite material on its switching performance the respective investigations of the material structure variation under operation were carried out. Therefore, the microstructure of the contact surface as well as the sample volume was inspected. It was investigated both along parallel and perpendicular direction of the vapor stream flow respectively. It was found that the surface roughness of a substrate influences significantly as the composite surface morphology as well as properties of its structure along the cross section. For the copper-molybdenum condensates typical is banded-structure of micro- and macro hierarchy with submicro layers and/or numerous layers of different structure. However, for the layers enriched with copper an isotropic structure made of depredated multi polar grains (fig. 3, *a*) or of modular molecules situated inside copper based matrix (fig. 3, *b*) is dominated. While, for the molybdenum enriched layers an anisotropic (columnar) structure is typical (fig. 3, *c*). Chemical microetching along the cross section of the condensate (perpendicular to the surface) revealed, that for smaller amount of molybdenum (material MDK-1, see table 2) the high melting metal occurs in form of both separate grains of a medium diameter less than 1μm and of their mixture inside the copper based matrix. As a matter of fact the change of the structure and chemical compositions results in respective variation of physical properties of the material as one can see from table 2.

Therefore, the increase of the molybdenum content (in mass) related to increase of the columnar like structure results in the increase of strength and hardness of the material however decreases its plasticity. The investigations of the switching performance have indicated that for such the gradient type condensates the variation of chemical composition of the layers can successfully restrict a thermal zone of the electrical discharge. As a result the



a *b* *c*

Fig. 3. Typical structure of the composite Cu—Zr—Y—Mo condensate material.

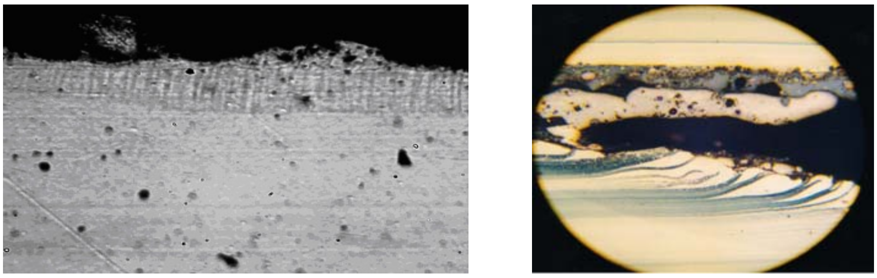

a *b*

Fig. 4. Typical structure of external layer of the composite material (MDK-3 type) after switching test.

volume of a secondary structure decreases (fig. 4) what is equivalent to the increase of electrical durability with compare to the contacts made by means of powder-metal technology [23].

On the basis of the investigated results one can conclude that the condensate compositions on the copper-molybdenum basis (Cu—Zr—Y—Mo) are characterized by following advantages:

they are fabricated during only one technological cycle therefore, they are cheaper by about 1,5—1,7 times compare with equivalent material made by means of the powder-metal processing and by about 4 times, when apply silver as the basic component;

electrical durability of the contacts made of the (Cu—Zr—Y—Mo) condensation compositions is not lower than for these made of silver base. Their maximum switching current value was checked up to about 1200 A;

the copper -molybdenum based components produced by means of the high power electron beam technology are found to be easy for mechanical processing (cutting, pressing, grinding and turning). They do not create any problem under soldering when use both brazing and silver content solders.

Area of application of the composite materials made by means of the high power electron beam technology is gradually increased and includes currently among others:

municipal transport (electric contact in underground railway, trams, trolley-busses, etc.);

elevator equipment (e.g. passenger- and cargo lifts);

cargo and towing winches;

all types electrical vehicles, mining equipment;

industrial and household electric appliances;

long-distance electrical transportation etc.

The Scientific and Producing Company "ELTECHMASH" has already produced over 15tons of the condensation composite material of the Cu—Zr—Y—Mo type. As a result more than 1,5 mln pieces of electric contacts of various (around 376 types) dimensions have been fabricated and involved in practice successfully. Some of them are presented as an example in fig. 5, 6.

Since, fine powder sinters on the copper-tungsten base are widely used as the contact materials in circuit interrupters (both in oil-poor, SF_6 and recently in vacuum circuit breakers) therefore, the condensation compositions have been considered as a choice. First, the influence of the tungsten content (ranged from 5 to 60% (mass)) on the composition structure was inspected. The structure

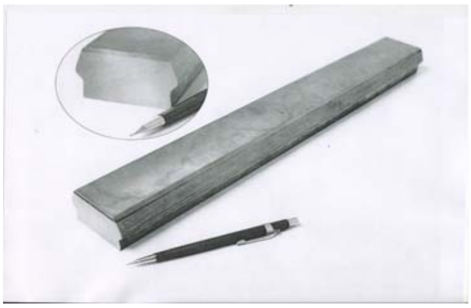


Fig. 5. General view of the sliding contact made of composition Cu—Zr—Y—Mo.

Fig. 6. Appearance of selected contact elements made from the condensate composite material Cu—Zr—Y—Mo.

displays gradient, laminar character of a different hierarchy and variety of the layers. For the respectively high amount of tungsten (40—60% (mass)) the column type of structure is dominated. It is common frequently not only for different hierarchical levels but, also passes through total cross section of the composite material as it can be seen from fig. 7.

The columns, of the diameter less then 100 um, are also metal-matrix composites however, with the tungsten grains below 1 p.m. Therefore, the vapor condensed compositions on the copper-tungsten basis are characterized by the gradient, laminar structure with visible effect of the dispersion hardening. Variation of the tensile stress and plasticity of the copper-tungsten compositions before and after tempering is presented in fig. 8.

As one can see the best mechanical properties are obtained for tungsten concentration ranged from 40 to 60% (mass). However, annealing processing results in some decrease of the tensile strength value but, increase plasticity, in turn. For the electrical contacts the copper-chromium compositions (35—50% of Cr) are found interest also. The condensation composites made by means of the high power electron beam technology of a similar content of chromium display the laminar structure as well however, with respective dimensions hierarchy of the particular layers. One can see here both macro-, micro- and submicrolayers.

These last two levels are interconnected by anisotropy of a normal size what, favor creation of pillars within area of a few layers of the condensate (fig. 9).

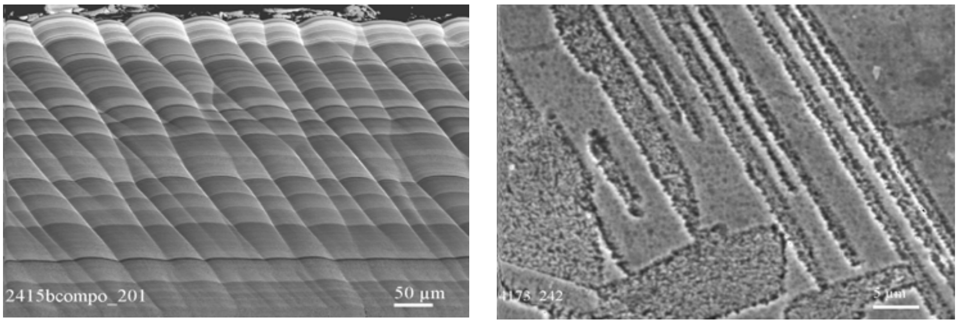
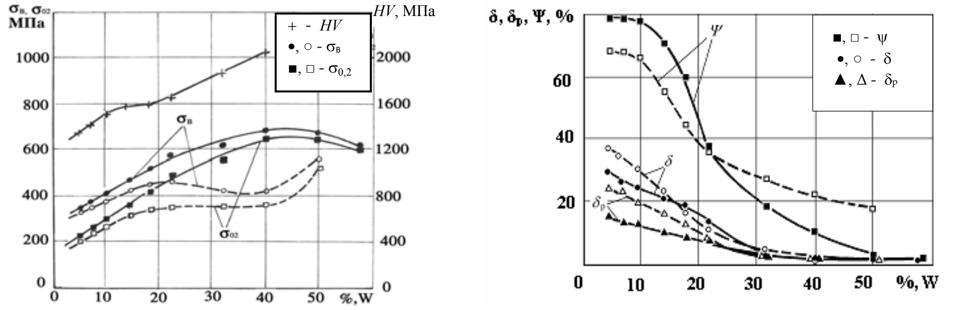
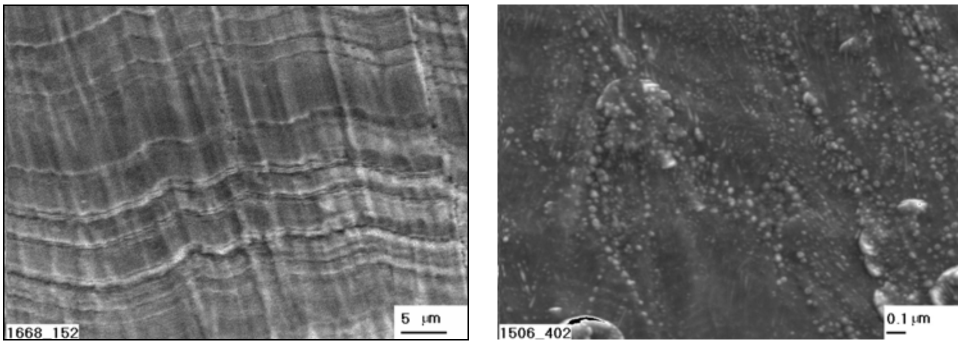


Fig. 7. Typical structure of the condensate component of Cu—Zr—Y—W type with the increased content of tungsten (from 40 up to 60% (mass)).



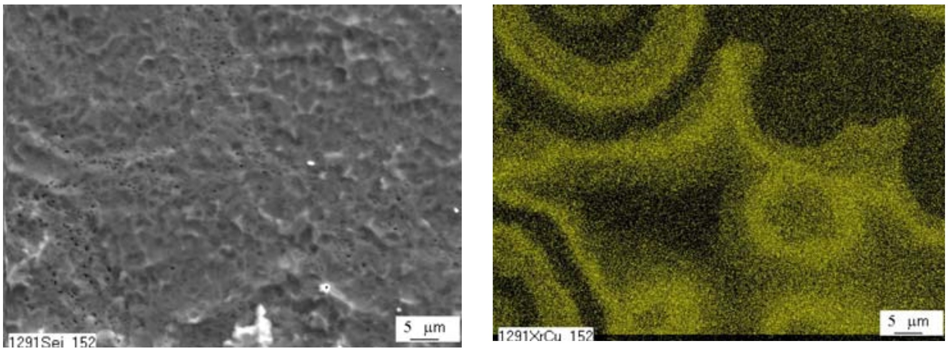
a *b*

Fig. 8. Influence of tungsten content on tensile strength (*a*) and plasticity (*b*) of the composition Cu—W (investigated in room temperature) (solid lines and dark dots-initial state, dashed lines and light dots-after tempering in 900 °C and in 1 hour).



a *b*

Fig. 9. Typical structure of the condensation composition Cu—Zr—Y—Cr for chromium content of 35—50% (mass): layering (*a*), structure of layer (*b*).



a *b*

Fig. 10. Different appearance of the Cu—Zr—Y—Cr composite structure with different content of chromium 35—50% (mass), granular, polygonal-initial structure (*a*) and decomposition of supersaturated solid solution (*b*).

Widely concentrated area of the pillar structure indicates uniform character of a mass transfer and highly unbalanced feature of the material. It is confirmed by creating under evaporation-condensation the granular, polygonal structure (fig. 10, *a*) in cross section perpendicular to the pillar-indicating and by structure features under formina of decomposition of the supersaturated solid solution (fig. 10, *b*).

Vickers hardness measurements revealed it nonlinearity with the chromium content ranged from 0 up to 70% in mass (e.g. for 35—50% of Cr the hardness is within 2069—2503 MPa). The tensile strength is also increased and indicates its maximum (about 550 MPa) for 40% of chromium. However, at this content the plasticity is decreased in turn. Under the tensile strength test the structural damage was controlled. The intercrystalline failure was found to be dominated. It is increased with the amount of chromium and depends on another, as external as well as inherent sources of weakness (like cracks at the sample surface, defects at interface due to impurities etc). The both Cu—Zr—Y—W and Cu—Zr—Y—Cr condensation composites are being also tested as contact materials in vacuum chambers of low and medium voltage contactors and interrupters. The results of preliminary investigations carried out independently in “ELTECHMASH” Company in Kyiv, Ukraine and Wroclaw University of Technology, Wroclaw, Poland are found to be interesting and promising [24]. General view of selected contacts for chambers of vacuum contactors are

Fig. 11. General view of electrical contacts for vacuum chambers of LV (1200 V) contactors.

Fig. 12. Perspective view of electrodes made by means of the high power electron beam technology.

presented for example in fig. 11 [25]. The good results were also obtained for electrodes made of the composition Cu—Zr—Y—Al_2O_3 used in electric welding equipments. Their view can be seen from fig. 12 [26].

Conclusions

Presented investigated results confirm that the high power electron beam technology can be successfully used as an alternative method to the powder-metal one for manufacturing, among others, of electric contacts as well as electrodes material. No doubt that this technology is much more cheaper compare to the powder-metal. The finished product is obtained already during only one manufacturing cycle and all the alloy-forming components are cheaper. Of course the efficiency can be tremendously increased when replace all expensive (particularly noble) metals and apply the preforms of a technical purity. The high power electron beam technology is save and environmental friendly. None harmful both organic and nonorganic matter is emitted to surroundings under manufacturing. Besides, all products are recyclable. The developed modern high power electron beam installation is characterized by high annual rate of production up to about 15 tons of the condensation composite preforms. It makes manufacturing of about 800 000 pieces of various electrical contacts and electrodes possible in practice.

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Современное состояние и перспективы применения электронно-лучевой технологии высокой мощности для производства металлических и неметаллических компонентов для электрических контактов и электродов

Н. И. Гречанюк, Р. В. Минакова, И. Н. Гречанюк, В. Медзинский,
Л. Дж. Хи

Представлены и обсуждаются текущее состояние и перспективы применимости электронно-лучевой технологии высокой мощности для изготовления как металлических, так и неметаллических композиционных материалов, главным образом для контактов и электродов.

Ключевые слова: *композиционные материалы, технология, мощный электронный луч, оборудование, высокая производительность, электрические контакты и электроды.*

Сучасний стан та перспективи застосування електронно-променевої технології високої потужності для виробництва металевих і неметалевих компонентів для електричних контактів і електродів

М. І. Гречанюк, Р. В. Мінакова, І. М. Гречанюк, В. Медзинськiй, Л. Дж. Хі

Представлено і обговорюються поточний стан та перспективи застосовності електронно-променевої технології високої потужності для виготовлення як металевих, так і неметалевих композиційних матеріалів, головним чином для контактів і електродів.

Ключові слова: *композиційні матеріали, технологія, потужний електронний промінь, обладнання, висока продуктивність, електричні контакти та електроди.*