Dispersed and layered volumetric nanocrystalline materials based on copper and molybdenum condensed from the vapor phase

Nikolai Hrechaniuk, Vera Hrechaniuk, Elena Khomenko, Dmytro Kovalchuk

The paper presents features of structure formation and phase composition on copper and molybdenum based composite materials, condensed from the vapor phase. Three types of condensed composite materials with thicknesses from 0.8 to 5 mm, obtained at deposition temperatures of 700 and 900 °C, are considered. Namely dispersed-hardened, microlayer with thickness of alternating copper and molybdenum layers from 1 to 10 μm, and bulk nanocrystalline with thickness alternating layers less than 0.5 μm are studied.

Keywords: High-speed evaporation-condensation of copper and molybdenum in vacuum, composite dispersed-hardened and laminar materials based on copper and molybdenum

Introduction

Electron-beam high-speed evaporation of metals and non-metals in vacuum (deposition rates of atomic or molecular vapor streams on the substrate reach 150 μm/min) is a relatively new direction in materials science. The application of the processes of high-rate vacuum evaporation-condensation of materials for manufacturing began in the early seventies of the last century, and these technologies are constantly being improved [1]. At present, these processes for the application of protective coatings to products of various technical purposes are widely used [2 - 8]. New materials by the condensation of vapor streams on the substrate prepared to a certain temperature, which can be heated, can be referred to dispersed-hardened, layered or porous materials, depending on the structure. Advances in the development of such materials, their structure, properties and application fields are generalized [9 - 12]. The evaporation-condensation processes for the nanocrystalline thin films production are widely used. Thin films to nanosize, nanophase, nanostructured materials, if their topological dimensions, lie in the nanometer range in at least one direction (for example, thickness) [13 - 15]. Modern thin metal films that are used in industry are classified on [15]:

- materials with a multilayer structure, in which the chemical composition varies abruptly at the boundary of the layers;
- quasi-multilayer structures in which each of the components is distributed very heterogeneously in thickness and there is no discernable boundary between the quasi-layers;
- materials with phase or concentration heterogeneity in terms of volume, including within a single grain;
- island, granular films, etc.

Condensation from the vapor phase a wider range of states makes possible to obtain, in comparison with the original massive systems, which can be predicted by the equilibrium phase diagrams of the state. In thin metallic films of complex composition, for example, phases corresponding to the phase equilibrium diagram may not be absent, and phases that are not predicted by the equilibrium state diagram for a given source material or even for actual compositions of condensed layers may be present, for example, formation of supersaturated solid solutions was confirmed in thin films Al-Cu [15] and Cu-W [16]. Thin films and thin-film compositions on them based are widely used in modern manufacturing [15]. At the same time, the production of thick (10 - 100 μm or more) thick nanostructures with a large number of layers, the form of massive macroscopically homogeneous bodies with an internal nanostructure, produced by deposition on a high temperatures substrate (300 °C or more), insurmountable difficulties until recently. These difficulties are due to decay of the nanolayers structure, by grain growth during high temperatures condensation and there are due to the fact that the transformation of nanostructured compositions into typical polycrystalline materials results.

As is known [17], an acceptable complex of physico-mechanical properties in massive condensed systems can be obtained under the condition that the temperature of the substrate to be condensed for,
equals or exceeds 0.3 of the temperature of the most fusible component. Now multicomponent, multilayered, gradient, doped, dispersed and disperse hardening there is the arsenal of methods of directed formation of massive thermodynamically nonequilibrium but kinetic stable at high temperatures nanostructured materials.

When choosing the object of research, we proceeded from an assessment of the thermodynamic and kinetic compatibility of composite materials components (CM). According to [18], the thermodynamic compatibility of the matrix and the reinforcing elements is determined by the possibility of being in a state of thermodynamic equilibrium for an unlimited time at the temperatures of manufacturing and exploitation. Kinetic compatibility is the ability of the composite components to be in a state of metastable equilibrium, which is controlled by factors such as adsorption, diffusion rate, chemical reaction rate, and so on. In addition to chemical compatibility, the mechanical compatibility of CM components is important to ensure, namely elastic constants, thermal linear expansion coefficients, plasticity indices, which allow achieving a strong bond necessary for efficient stress transfer across the interface.

Thermodynamic and kinetic compatibility have a limited amount of composites (for example, Cu-Mo, Cu-W). The features of high-rate evaporation-condensation (manufacturability) of the initial components (copper, molybdenum, tungsten) and the composition of oxide films in similar powder compositions, as well as possible applications of condensed composite materials, were also taken into account in the analysis.

Complex analysis of the literature [19, 20, 21], as well as previous studies of thick vacuum condensates of metallic and nonmetallic materials [22] made it possible to select the copper-molybdenum system as a composition for studying condensed composite materials.

The initial materials for the preparation of the condensates

The grades of the initial materials for the production of CMC are given in Table 1. Copper ingots with a diameter of 98.5 mm and molybdenum with a diameter of 68.5 mm and a length of up to 450 mm were used after vacuum-arc remelting as initial (evaporated) blanks. Their purity by the main component was not less than 99.5 % by weight.

### Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Grade</th>
<th>GOST, TY</th>
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<tbody>
<tr>
<td>Copper (Cu)</td>
<td>Mo, MI</td>
<td>GOST 859-78</td>
</tr>
<tr>
<td>Molybdenium (Mo)</td>
<td>MCVP</td>
<td>TY 48-19-247-87</td>
</tr>
<tr>
<td>Zirconium (Zr)</td>
<td></td>
<td>TY 95.46-82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TY 95.166-83</td>
</tr>
<tr>
<td>Yttrium (Y)</td>
<td>It M-I</td>
<td>TY 48-4-208-72</td>
</tr>
<tr>
<td>Calcium Fluoride (CaF)</td>
<td></td>
<td>GOST 7167-77</td>
</tr>
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</table>

**Technique of the experiment for preparation of the condensates**

The condensed composites were prepared according to the technological schemes:

1. The condensed composites were prepared according to three technological schemes: On a stationary substrate with dimensions of 700 × 400 × 15 mm. The scheme of the technological experiment is shown in Fig. 1.

2. On a substrate rotating at a speed of 36 rpm with a diameter of 800 mm and a thickness of 25 – 30 mm (Fig. 2).

3. On a rotating substrate by evaporation of copper and molybdenum from two independent sources with separation of vapor streams (Fig. 3). The preparation of composites according to the first variant was carried out at the substrate temperatures of 700 ± 30 °C and 900 ± 30 °C. The concentration of the refractory component at 700 °C varied from 0.1 to 6% by weight, at 900 °C from 0.4 to 46.7% by weight. These concentration ranges are due to the peculiarities of the evaporation-condensation process on this type of electron beam equipment at selected substrate temperatures.

Before the formation of condensates on a substrate preheated to 700 ± 30 °C, a separating layer of zirconia stabilized with yttrium oxide or calcium fluoride (CaF₂) are precipitated [22, 25]. More expedient is the use of CaF₂, given its low cost and the possibility of removing the film from the substrate or condensate by dissolving in hot water [26]. Evaporation of copper was carried out through an intermediary bath [27]. This technological method allowed to increase the evaporation rate of copper approximately 2 – 3 times and to reduce the amount of microdroplet phase in the steam flow. The rate of copper deposition on a stationary substrate (variant 1) was varied from 8 to 60 μm/min and molybdenum
from 3 to 10 μm/min; on a rotating substrate (variant 2, 3) from 3 to 20 μm/min and from 1 to 3.5 μm/min, respectively. The total content of zirconium and yttrium in condensed Cu-Mo materials did not exceed 0.1% by weight. CMC for research consisted of sheet billets of rectangular 700 × 400 mm and cylindrical 500 and 800 mm types with thickness from 0.8 to 5 mm. Determination of the chemical and phase composition, the study of physicomechanical and corrosion characteristics of CMC was carried out according to the methods described in [23].

**Phase composition**

X-ray phase analysis showed that in all types of investigated compositions, in addition to the main components of copper and molybdenum, an insignificant amount (up to 3% by weight of the total content of the strengthening phase) of dispersed inclusions of CuO and MoO₃ is present. This fact indicates that at a working vacuum of 3 × 10⁻² .... 5 × 10⁻³ Pa, partial oxidation of the main components of the composites occurs with residual gases present in the working space where the evaporation-condensation process takes place.

**Structure. Gradient condensed composite materials**

The main feature of the evaporation of technically pure metals and multicomponent alloys from a single source is fractionation, due to the difference in the rates of evaporation of impurities in metals and the components forming the alloy. The condensate formed on the substrate has an inhomogeneous composition,
since the initial layers enriched in an easily volatile component, and in the subsequent layers a substance with low vapor pressure predominates. As the metal (alloy) enters the evaporation zone, the amount of impurities (components) in the liquid bath constantly changes. Therefore, the heterogeneity (banding) of the structure along the thickness of the condensate has a different character (color, thickness of the zones, etc.). The formation of an inhomogeneity is also affected by the technological parameters of deposition (substrate temperature, deposition rate, depth and dynamics of changes in vacuum, slope of the steam flow, etc.). A detailed theoretical analysis of the evaporation of binary alloys from a single source was carried out by Zinsmeister [28]. The production of condensed composite materials by separate evaporation of components with simultaneous condensation of their vapors on a substrate promotes the formation of a strong structural inhomogeneity. Of particular note is the temperature change on the surface of the liquid baths of the evaporated components. Even with a temperature fluctuation within 10 – 20 °C, the evaporation rate can be changed by half, which is extremely unfavorable, since it leads to a shift in the composition of the condensate [2].

During the deposition of such gradient materials on the substrate, both known vapor-liquid → crystal (PLC) and vapor → crystal (PC) condensation mechanisms can be simultaneously realized. At a certain critical temperature close to 2/3 of melting temperature T for a given condensable substance, one condensation mechanism can be replaced by another [15, 25, 29]. In this case, amorphous and glassy states arise due to supercooling of the liquid phases, when condensation occurs in the PC mechanism. Metastable modifications, strongly supersaturated solid solutions (not only with respect to normal solubility at room temperature, but also to the maximum in the solid phase according to the phase diagram) are formed by the PLC mechanism from sharply supercooled liquid solutions. Such a mechanism is easily realized in cases of binary or multicomponent systems, when a limited solubility is observed in the solid state. Composites Cu-Mo are a prime example of such systems [30]. Due to high deposition rates and temperature fluctuations on the surface of the liquid bath, resulting in a change in the velocities, the substrate temperature is increased by vapor condensing (phase transformations) and heat radiation from the evaporator (evaporators). Energy is absorbed in a thin surface layer. This gave reason to believe that for a short time the surface temperature rises to such an extent that it exceeds the average temperature of condensation by several hundred degrees [31]. Experimental confirmation of this phenomenon was provided by the authors during the formation of copper condensed composite materials at a copper deposition rate of 40 – 60 µm/min. On the surface of a condensate 0.8 – 1 mm thick, a film of liquid copper was formed, the melting point of which, as is known [26], is 1083 °C. In view of the foregoing, it can be expected that the structural, substructural concentration and phase nonequilibrium can be so high that the transformations develop even with the condensation of the substance and with its natural aging. A detailed study of the structure and physicomechanical properties of CMC Cu-Mo with the content of the refractory phase up to 6% by mass deposited at a substrate temperature of 700 – 900 °C is given in [32 – 39]. Macrostructural studies subjected the surface and cross sections of the samples in parallel and perpendicular to the steam flow (before and after etching), as well as kinks. The entire surface is characterized by the presence of crystallized microdroplets of metal ejected from the baths and tubercles (Fig. 4). The number of the latter from batch to batch changes and can reach 1 • 10 – 2 cm² at maximum deposition rates. The formation of tubercles is associated with the ejection and transfer to the substrate of droplets of liquid and solid phases at different stages of the evaporation-condensation process.

For Cu-Mo compositions with a refractory phase content of up to 3% by weight a structure typical of dispersed hardened materials with poorly expressed layering is inherent [10]. Condensates have a characteristic columnar structure (Fig. 5a). Crystallites are elongated in the direction of the vapor flow almost perpendicular to the condensation surface. The grain size decreases as the concentration of the strengthening phase increases. The most intensive

Fig. 4. Characteristic morphology of the surface of a condensed composite.

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grinding of the matrix grain occurs at low concentrations of the second phase (up to 1% of the mass, Fig. 6). The grinding of grain intensifies at low deposition temperatures.

Thus, in condensates obtained at substrate temperatures 500 ± 30 °C, 700 ± 30 °C and 900 ± 30 °C with a hardening phase content of ≈ 2% by mass, the average grain size and dispersed particles are respectively 1.45; 2.0; 7.0 μm; 12, 27 and 53 nm [32, 34, 40]. The particles of the strengthening phase have a shape close to spherical (Fig. 5b). In such condensates, the structure of the material is represented by two main phases behind the X-ray phase analysis results: FCC on the basis of copper and VCC on the basis of molybdenum. In this case, there is a tendency to a strong erosion of the molybdenum lines and their shift toward large angles, characteristic for materials with nanoparticles.

![Fig. 5. Microstructure of condensed dispersed-hardened Cu materials - 1.2% Mo; (a) - x 600; (b) - x 6500.](image)

![Fig. 6. Dependence of the average grain size D on the content of the second phase in dispersed-hardened Cu-Mo materials: 1 - T_{mel} = 700 ± 30 °C, 2 - T_{mel} = 900 ± 30 °C.](image)

Micro-X-ray spectral analysis showed that condensed composite composition is characterized by a micro-inhomogeneity of the distribution of components along the thickness.

For the one shown in Fig. 8 of the composite, the average chemical composition of molybdenum is 7.62% by mass in the thickness of the condensate, whereas in some of its layers the concentration ranges from 2.83 to 11% by weight.

![Fig. 7. Typical structure of a condensed composite with Mo content from 6 to 12 ± 15% by mass. region of a material with continuous lamination (dark field); – area of material with intermittent stratification (light field) (x6000).](image)

![Fig. 8. Distribution of components in the condensate Cu-7.62 Mo % by mass. (averaged thickness value).](image)
This is due to the influence of a number of technological factors (temperature oscillations on the surface of a liquid bath, the presence of oxide films, changes in the chemical composition of the bath, dynamics by a change in vacuum, etc.). The thickness of the layers, their contrast, the inhomogeneity of the location in the volume of the material, the inhomogeneity of the distribution of the strengthened phase in individual layers increases with increasing molybdenum content (Fig. 9).

Fig. 9. Structure of composite materials with different content of components: (a) - Cu - 7.62% by mass. Mo; (b) - Cu - 46.7% by mass. Mo.

Fig. 10. The structure of the condensed composite (Ni - 20.1% by mass, Cr - 2.2% by mass, Al - 2.8% by mass Ti - 22.5% by mass) - Al₂O₃ (x900).

Qualitatively, such structural changes are characteristic for condensed composites of the gradient type Cu-Cr, Cu-W [23, 43, 44]. It should be noted that the oriented distribution of the strengthening phase is characteristic not only for metal systems with a minimum solubility of components, but also for metal-ceramic compositions where such solubility is absent altogether. In Fig. 10, as an example, the microstructure of the condensed NiCrAlTi-Al₂O₃ materials obtained at a substrate temperature of 1000 °C is given. One can see the characteristic linear structuring of the ceramic (light field) and metallic (dark field) phases in the condensate volume. At deposition at temperatures below 1000 °C, no such structuring is observed. Temperature fluctuations on the surface of the liquid bath, which lead to a change in the evaporation rates of the components, various mechanisms of condensation of PC and VLC, various precipitation of supersaturated solid solutions with different concentrations of copper and molybdenum cause the heterogeneity of the structure (Fig. 7) and chemical composition 8) over the thickness of the condensate. As a result, in different balls of the CMC, depending on the ratio of the fusible and refractory components, the substrate temperature, a different type of structure is formed (Fig. 11): domed (a), polygonal (b), columnar (c).

Fig. 11. The structure of the layers in the condensed Cu-Mo: domed (a), polygonal (b), columnar (c).

Microlayer condensed composites obtained by sequential deposition of copper and molybdenum layers

Variants of the investigated samples of condensed composites are presented in Table 2. Condensed composites were prepared at a substrate temperature of 700 ± 30 °C. The total thickness of the composites is 0.8 ÷ 1.2 mm. The maximum content of the strengthening phase was limited by the formation of cracks and brittleness of the composites.

In [11, 41, 42], significant dependences of the structure and physico-mechanical properties of microlayer condensed composites Fe-Cr and Cr-Cu on the thickness of alternating layers are shown. In microlayer of this type condensed materials, by selecting the appropriate components and the thickness of the layers, highly stable structures have
been obtained. There are have a low creep rate at high temperatures as compared to the creep rate of the constituents composing the material and there are the strength and ductility can be controlled within wide limits. It was noted that it was possible to achieve a high level of strength characteristics with a thickness of a single layer from 1.0 to 1.5 μm. At smaller layer thicknesses, they are unstable and decay. With a layer thickness of $10 \div 15 $ μm, these materials are close to the properties of matrix materials in terms of strength values. In connection with this, several series of compositions were investigated (Table 2), in which the thickness of the layers varied within the following limits: a carrier high-modulus Mo layer from 1.0 to 4 μm; the matrix Cu layer is from 1.3 to 10 μm.

<table>
<thead>
<tr>
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<td>The compositions of the condensed composite</td>
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<table>
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<tr>
<th>Mo, % vol.</th>
<th>16</th>
<th>16</th>
<th>19</th>
<th>33</th>
<th>38</th>
<th>40</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness of Mo layers, μm</td>
<td>1.7</td>
<td>1.3</td>
<td>1.0-1.3</td>
<td>2.5</td>
<td>3.0</td>
<td>4.0</td>
<td>1.0-1.3</td>
</tr>
<tr>
<td>thickness of Cu layers, μm</td>
<td>10.0</td>
<td>7.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>6.0</td>
<td>1.3</td>
</tr>
<tr>
<td>total number of layers, units</td>
<td>108</td>
<td>102</td>
<td>288</td>
<td>192</td>
<td>274</td>
<td>116</td>
<td>390</td>
</tr>
</tbody>
</table>

Metallographic studies have established that in all microlayer condensates the supporting layers of molybdenum have a columnar structure. The height of the columnar crystallites Mo is commensurable with the thickness of the layer. Matrix layers of Cu consist of almost equiaxed grains with a large number of twins. Certain differences in the crystal structure of copper and molybdenum microlayers are due to the condensation features for the supporting (Mo) and matrix (Cu) layers. The deposition temperature of 700 ± 30 °C corresponds to the first structural zone for Mo and the third for Cu [17].

Volumetric Nanocrystalline Condensed Composites

We have shown above the essential dependence of the structure of condensed composites on the concentration of the strengthening phase, deposition temperature, and other technological parameters. The introduction of the second phase in a certain amount makes it possible to obtain polycrystalline or layered (microlayer) materials based on copper and molybdenum with a grain size of ~1 μm. Further dispersion of the structure at substrate temperatures of 700 – 900 °C is not possible because of the heterogeneity of the graded condensed composites and the breakdown of microlayers with a thickness of less than 1 μm. Obtaining bulk nanocrystalline materials based on Cu and Mo at elevated condensation temperatures with an acceptable complex of physicochemical and mechanical properties is possible when certain (mandatory) conditions for stabilizing the nanostructure are fulfilled [23, 44, 45]. These include: a) ensuring homogeneity of the chemical composition of the components in the condensate volume; b) hardening nanoparticles with nanoparticles to increase their thermodynamic stability; c) the creation of nanoparrier layers at the interphase boundaries, which slow down the coalescence of nano-springs. The concentration gradient that is not desirable in materials is eliminated by using rotating substrates. The method of rotating substrates with separate evaporation of components for the production of binary and multicomponent alloys of a given composition is characterized by a high coefficient of vapor utilization, and also, to a large extent, eliminates the columnar structure, which sometimes leads to cracking and increased porosity. The columnar structure is not formed, since the angle of incidence of the vapor on the substrate is continuously changing. By changing the geometric arrangement of the crucibles, the rotation speed of the substrate, the evaporation rate of the components, it is possible to create different types of structures.

Of the known types of composite materials obtained by the evaporation-condensation method, dispersed-hardened, microporous and microlayer [9 – 12], microlayer compositions are the most promising for creating nanostructured systems. Formation of an internal nanostructure in layers of Cuand Mo at condensation temperatures of 700 °C can be expected if the layer thicknesses are less than 0.5 ± 0.6 μm and they will not be disintegrated. The main technological factors affecting the formation of a layered structure are the substrate rotation speed and the deposition rate of the components, and the structure stability is affected by the thickness of the alternating layers and the condensation temperature. In obtaining such composites, the geometric arrangement of the crucibles and the substrate relative to the crucibles is also of great importance. Technical literature [20] describes in some detail the distribution of atoms (molecules) upon evaporation from a point source (a conical distribution law). The expected distribution is valid if the vapor pressure is insignificant and when the evaporation process is not hindered (for example, by oxide films that can form on the surface of the
evaporated bath). In the real conditions of obtaining a condensates, there are significant deviations from this law In the papers [44, 45]. The main boundary conditions are determined under which formation of a layered structure with a single layer thickness of less than 0.5 μm is possible with simultaneous evaporation and condensation of copper and molybdenum onto a rotating substrate.

In Fig. 12 is a diagram of the distribution of steam flows of Cu and Mo on a substrate. It can be seen that for a certain geometrical arrangement of the crucibles adopted in calculations for point sources of evaporation and a substrate that rotates, there are regions of distribution of practically pure evaporated Cu and Mo.

![Fig. 12. Scheme of distribution of the vapor flow during the evaporation of Cu and Mo from two independent sources: (a) – front view; (b) – view from below.](image_url)

The density of distribution of the condensed Cu and Mo atoms decreases monotonically with increasing diameter of the substrate. As a result, in a certain region of the substrate, steam flows are mixed to form a transition layer between the components forming the condensate. Rotation of the substrate provides a transition from component A (Cu) to component B (Mo) and vice versa. According to Fig. 12 it can also be concluded that on the substrate there are zones with a minimum density of distribution of steam streams of copper and molybdenum. In these zones, the formation of oxides and carbides is most likely due to the interaction of the evaporated materials with the vapor of the vacuum pump oil (carbon) and the residual atmosphere of the working chamber (oxygen, nitrogen). Complex chemical and X-ray phase analysis of gradient materials Cu-Mo with a thickness of 20 – 30 μm obtained on a stationary substrate showed that Mo (0.07 – 0.09% by mass) is present in the condensates from the Cu evaporation side, and the side of evaporation of Mo is Cu (0.28 – 0.45% by mass). Zr and Y films were also found in the films, the total content of which did not exceed 0.07% by mass, and the oxides of copper (CuO) and molybdenum (MoO3). Their concentration was about 3% by mass. It follows that alternating copper-based layers consist of a low-alloy copper-based alloy (Cu-Zr-Y) hardened with dispersed Mo, MoO3, and CuO particles, and molybdenum-based layers contain dispersed Cu, CuO, and Mo particles. Strengthening by dispersed particles contributes to grinding the structure and increasing the thermal stability of the layers, and a smooth transition from component A to component B neutralizes the disintegration of layers at elevated condensation temperatures and reduces the level of stresses caused by different Cu and Mo coefficient of thermal linear expansions. Based on the results of X-ray phase analysis, the structure of the condensates is represented by two main phases: FCC on the basis of Cu and VCC on the basis of Mo by crystal lattices. In this case, strong erosion of Mo lines and less pronounced Cu lines and their displacement toward large angles are observed. Usually this characterizes the materials with nano-sized particles and grains. Rotation of the substrate contributes to a significant decrease in the layering and dispersion of the distribution of components along the thickness of the materials, which is characteristic of gradient composites. Figure 13 shows a typical distribution of Cu and Mo in condensed composite Cu - (8 – 12% by mass.) Mo. For condensed composite materials with a Mo content of more than 5% mass, the hierarchy of the layered structure on the micro- (Fig. 14a) and submicron levels is characteristic (Fig. 14b). The formation of a layered structure at the microlevel is due to the evaporation of the technically pure components of the investigated composite materials, in which impurities are present. In a liquid (evaporated) bath, impurities are accumulated. Therefore, evaporation of low alloyed copper and molybdenum alloys with different impurity concentrations is observed at various stages of the technological process.

![Fig. 13. The laminated structure of composite materials (Cu – 0.1% by mass. Zr, Y) – 8 – 12% by mass. Mo (a) and the distribution of molybdenum in composite materials (b).](image_url)
The formation of stratification is also significantly affected by variations in the evaporation rate of the initial components due to temperature changes on the surface of the liquid baths and by the presence of oxide films, etc. When etching the sections, a characteristic decoration of the structure of the composites is manifested, due to the influence of the above factors. The formation of the structure at the submicron level (Fig. 14b) is effected by the complex influence of the substrate rotation, which ensures the formation of layers with a thickness of less than 0.5 μm and the decay of supersaturated solid solutions based on copper and molybdenum. Electron-microscopic studies on the luminescence of layered CM Cu- (8 – 12) % mass. Mo showed that the average grain size of copper ranges from 58 to 96 nm, molybdenum from 46 to 62 nm. In the volume of grains, dispersed particles of the strengthening phases are evenly distributed. Their size ranges from 10 to 18 nm and depends on the nature of the strengthening phases (oxides, metals). A typical electron microscopic image of the structure is given in Fig. 15 a, b. The micro-electron diffraction pattern of the composite (Fig. 15c) has a characteristic annular shape inherent in nanocrystalline structures. The microelectronogram of the composite (Fig. 15c) has a characteristic annular shape inherent in nanocrystalline structures.

**Conclusions**

The structure of copper and molybdenum based condensed composites complex way depends on the technological conditions for their production (the chemical composition of the evaporated ingots, the rate of their deposition, the deposition conditions (stationary or rotating substrate), the substrate temperature, the vacuum depth, the geometric arrangement of the crucibles with evaporated materials relative to the substrate and other parameters). Typical strengthening on Cu and Mo based materials condensed from the vapor phase at substrate temperatures of 700 – 900 °C can be obtained in a relatively narrow concentration range of the strengthening phase 0.1 ... 3% mass. Mo. With a molybdenum content of 3 – 5% by mass. there is a change in the shape of the strengthening phase with a rounded to needle with its oriented arrangement in the material in the form of intermittent chains perpendicular to the fall of the vapor stream. In the concentration range of the second phase, more than 5% by mass. condensed materials is characterized by a layered structure of continuous layers of copper and molybdenum. The stability of the continuity of the layers depends on the conditions of deposition.

A layered structure can also be obtained in other types of condensed composites (Cu-W, Cu-Cr, NiCrAlTi-Al2O3) at a certain chemical composition of the composites and the technological conditions for their deposition. It has been experimentally confirmed that layered condensates based on low-alloy copper and molybdenum alloys up to 6 mm thick obtained on a rotating substrate heated to a temperature of 700 ± 30 °C refer to bulk nanocrystalline materials in which the grain size does not exceed 96 nm, and the size of dispersed inclusions strengthening phase 18 nm.
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