 ISSN 2071-1077(print)
ISSN 2663-2411(online)

doi: 10.32620/oikit.2026.108.11

UDK 620.378.325

O. Popova, V. Ostapchuk

Influence of structural parameters on the properties of nanocomposites

National Aerospace University "Kharkiv Aviation Institute"

The processes of formation of the structure of dispersion-strengthened composite materials, which determines their physical and mechanical properties and therefore is of scientific and practical interest, have been studied. Experimental studies of the mechanism of inclusions crystallization during condensation of a vapors mixture of two metals that do not have solubility in equilibrium conditions have been carried out using the example of the Cu-Mo composite. The structure of the Cu-Mo composite has been studied, as well as the dependence of the size of molybdenum particles on its concentration and temperature of substrate. The influence of the production conditions on properties of dispersion-strengthened composite materials has been studied.

Studies have shown that Cu-Mo composites obtained at t_S = 150 – 450 °C are double-phase: dispersed molybdenum particles are uniformly distributed in the matrix, which is a substitutional solid solution of molybdenum in copper. The particles of the strengthening phase are uniformly distributed throughout the matrix grains. The molybdenum particles are nearly spherical in shape and apparently form during the formation of the Cu-Mo composite at the crystallization front as a result of surface diffusion of molybdenum atoms.

With increasing substrate temperature, the size of the strengthening molybdenum particles and the distance between them increase, resulting in a decrease in microhardness of dispersion-hardened composite. Thus, at a substrate temperature of t_S = 150 °C and a molybdenum content of 0.6% to 5.4%, the average particle size is from 98 Å to 120 Å; at a substrate temperature of t_S = 450 °C and a molybdenum content of 2.0% to 4.0%, the average particle size is from 500 Å to 700 Å; at substrate temperatures of t_S = 150 – 450 °C, the microhardness is H_μ = 850 – 350 MPa, respectively.

***Keywords**:* dispersion-strengthened composite materials; dispersed particles; particle sizes; substrate temperature; diffusion; microhardness.

Introduction

The rapid development of aviation technology places ever-higher demands on materials. Metal composite materials can be divided into several groups based on their strengthening mechanism: fibrous composites, layered composites, and dispersion-strengthened composites.

Strengthening of materials in the first group is achieved by reinforcing a metal matrix with high-strength continuous or discrete fibers. Laminated composites are created by using layers of materials with different mechanical properties. For fibrous and laminated composites, the strength level depends primarily on the properties of the reinforcing materials. The role of the matrix is primarily to redistribute stress between the reinforcing elements [1].

In dispersion-strengthened composites, the matrix is the primary load-bearing element, while the dispersed particles can act as obstacles, inhibiting dislocation movement.

Changing the morphology, dispersion, and distribution of the strengthening phase particles allows for a combination of properties that is impossible to achieve in other materials. Using refractory elements or chemical compounds that do not actively interact with the matrix as strengthening particles makes it possible to maintain the structure and properties at elevated temperatures [2].

 ISSN 2071-1077(print)
ISSN 2663-2411(online)

Creating a structure in composites with uniformly distributed dispersed particles that do not interact with the matrix is quite complex and is only possible through the use of specific materials production techniques.

A promising method for producing dispersion-strengthened composites is the simultaneous condensation of the matrix and reinforcing phase vapors in a vacuum [3]. Vapor-phase crystallization offers unlimited flexibility in selecting the constituent components and enables the production of materials with a uniform distribution of second-phase particles throughout the volume, opening up significant prospects for solving the problem of dispersion of reinforcing particles.

The effectiveness of strengthening by dispersed particles of the second phase is determined by the geometric parameters of the structure: the size of the reinforcing particles, the distance between them, and the uniformity of their distribution.

The processes of structure formation in dispersion-strengthened composite materials determine their physical and mechanical properties and are therefore of scientific and practical interest.

Purpose and task statement

The purpose of the work is to experimentally examine the mechanism of inclusion crystallization during the condensation of a mixture of vapors of two metals that are insoluble under equilibrium conditions. In order to ensure the achievement of this goal, the following tasks were solved: electron microscopic studies were conducted to obtain data on grain size and particle morphology; properties of nanocomposites were determined by measuring microhardness.

Analysis of research results

To research the formation mechanism of dispersed particles of the strengthening phase, Cu-Mo composites obtained by vacuum vapor condensation were studied. Condensation of the component vapors was carried out simultaneously at substrate temperatures of 150 – 450 °C. The molybdenum concentration was varied by adjusting the molybdenum deposition rate.

Efficient strengthening is achieved with a strengthening phase content of no more than 5 – 10%. Therefore, vacuum condensates of Cu-Mo with a molybdenum content of 0.5 – 5% and a thickness of 20 μm separated from the substrate were studied.

Since structural factors play a leading role in the strengthening of dispersion-hardened materials, electron microscopic studies were conducted to obtain data on grain size and particle morphology. The researches were performed using an EM-200 electron microscope.

The electron diffraction patterns of the studied samples show both copper and molybdenum reflections. The electron microscopic images reveal a characteristic point contrast, which is interpreted as an image of molybdenum particles in a copper matrix in the Cu-Mo composite (Fig. 1).

The presence of overlapping molybdenum particles adjacent to each other indicates their volumetric distribution. The molybdenum particles are nearly spherical in shape. The particles are uniformly distributed throughout the matrix grains. No preferential segregation along grain boundaries is observed.

ISSN 2071-1077(print)
ISSN 2663-2411(online)

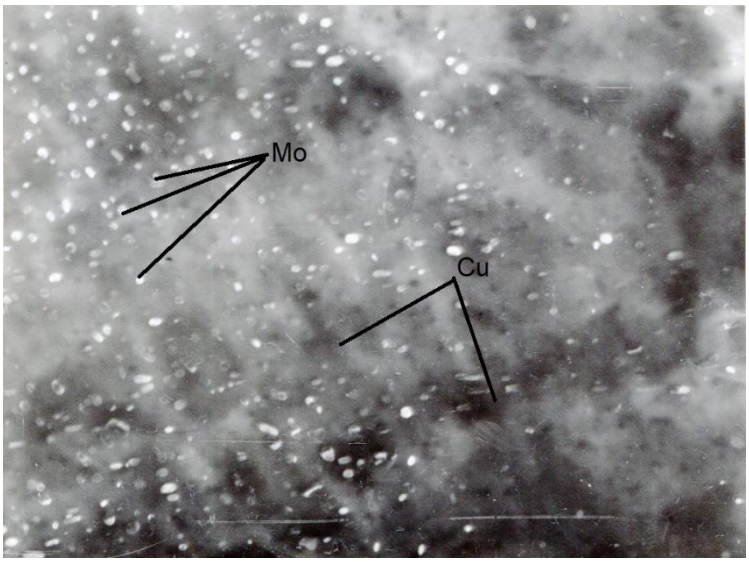

Fig. 1. Electron microscopic image of the Cu-Mo composite, x42000

The dependence of average particle size on molybdenum concentration at various substrate temperatures is shown in Table 1 and Table 2.

Table 1

Dependence of the molybdenum average particle size (d) on it concentration at a substrate temperature of 150°C

Mo, %	0.6	1.0	2.8	4.0	5.4
d, (Å)	98	100	110	115	120

Table 2

Dependence of the molybdenum average particle size (d) on it concentration at a substrate temperature of 450°C

Mo, %	2.0	2.5	3.2	4.0
d, (Å)	500	580	680	700

As Table 1 and Table 2 show, with increasing molybdenum concentration and substrate temperature, the average particle size increases.

To determine the potential dissolution of molybdenum in the copper matrix, precision measurements of the copper lattice constant were performed in composites with a 3 % of molybdenum concentration, depending on the substrate temperature (Table 3).

Table 3

Dependence of the matrix lattice period (a) on the substrate temperature (t_S) in composite with the molybdenum content of 3%

t_S , °C	100	230	320	450
a, Å	3.6178	3.6173	3.6163	3.6150

At $t_S \geq 450$°C Cu-Mo composites with a lattice constant corresponding to homogeneous copper form. As the substrate temperature decreases, the lattice constant increases, indicating the formation of a substitution solid solution of molybdenum in copper.

 ISSN 2071-1077(print)
ISSN 2663-2411(online)

Table 4

Dependence of molybdenum particle size (d) on substrate temperature (t_S) in compositions with the molybdenum content of 3%

t_S, °C	100	230	320	450
d, Å	95	100	190	650

As Table 4 shows, with increasing substrate temperature, the size of the reinforcing particles increases, which affects the properties of the Cu-Mo composite.

To study the effect of production conditions on the properties of dispersion-hardened materials, samples were tested for microhardness using a ПМТ-3 instrument at a load of 20 g.

Table 5

Dependence of microhardness (H_μ) on substrate temperature (t_S)

t_S, °C	150	200	220	450
H_μ, MPa	850	820	710	350

As Table 5 shows, the microhardness of the Cu-Mo composite decreases with increasing substrate temperature.

Structural methods have shown that Cu-Mo composites obtained at t_S = 150 - 450°C are double-phase: dispersed molybdenum particles are uniformly distributed in the matrix, which is a substitutional solid solution of molybdenum in copper.

During the study, the mechanism of formation of particles of the strengthening phase was considered. Two mechanisms for the formation of second-phase particles are possible: particles can form and grow as a result of the decomposition of a supersaturated solid solution of molybdenum in copper (the controlling process in this case is the bulk diffusion of molybdenum atoms in the copper matrix), or this process occurs at the crystallization front, in which case surface diffusion is the controlling process. In both cases, particle growth is diffusion-based. Therefore, it can be assumed that particle size will be proportional to the surface or bulk diffusion coefficient:

$$d = kD, \quad (1)$$

where d – is the particle size; k – is the proportionality coefficient;

D – is the diffusion coefficient.

The temperature dependence of the diffusion coefficient is described by the relationship

$$D = D_0 \exp(-Q/RT), \quad (2)$$

where D_0 – is a constant for a given substance; Q – is the diffusion activation energy;

R – is the universal gas constant; T – is the temperature.

In this case, the activation energy for diffusion is equal to the activation energy for particle growth, since it is diffusive in nature. Therefore,

$$d = D_0 \exp(-Q/RT), \quad (3)$$

$$\ln(d) = \ln kD_0 - Q/RT. \quad (4)$$

Therefore, there should be a linear relationship between ln(d) and 1/T, which is confirmed experimentally. From this relationship, the activation energy for diffusion, Q, can be estimated. In this case, Q = 30 kJ/mol.

This value corresponds to the activation energy for surface diffusion, suggesting that molybdenum particles are formed during the formation of Cu-Mo composite at the crystallization front as a result of the surface diffusion of molybdenum atoms.

Conclusions

Research has shown that Cu-Mo composites obtained at t_S = 150 – 450 °C are double-phase: dispersed molybdenum particles are uniformly distributed in the matrix, which is a substitutional solid solution of molybdenum in copper.

The particles of the strengthening phase are uniformly distributed throughout the matrix grains. No preferential precipitation along grain boundaries is observed. The molybdenum particles are nearly spherical in shape and apparently form during the formation of the Cu-Mo composite at the crystallization front as a result of surface diffusion of molybdenum atoms.

With increasing substrate temperature, the size of the strengthening molybdenum particles and the distance between them increase, resulting in a decrease in the microhardness of the dispersion-hardened composite. Thus, at a substrate temperature of t_S = 150°C and a molybdenum content of 0.6% to 5.4 %, the average particle size is from 98 Å to 120 Å; at a substrate temperature of t_S = 450°C and a molybdenum content of 2.0 % to 4.0 %, the average particle size is from 500 Å to 700 Å; at substrate temperatures of t_S = 150 – 450°C, the microhardness is Hμ = 850 – 350 MPa, respectively.

Список літератури

1. Власенко, А. М. Матеріалознавство та технологія металів : підручник / А. М. Власенко. – Київ : Літера ЛТД, 2019. – 224 с.

2. Композиционные материалы : справочник / под. ред. Д. М. Карпиноса. – Киев : Наукова думка, 1985. – 592 с.

3. Шпак, А. П. Кластерні та наноструктурні матеріали : Т.1 / А. П. Шпак, Ю. А. Куницький, В. Л. Карбівский. – Київ : ІМФ НАНУ, 2001. – 588 с.

References

1. Vlasenko, A. M. Materialoznavstvo ta tekhnolohiia metaliv : pidruchnyk / A. M. Vlasenko. – Kyiv : Litera LTD, 2019. – 224 s.

2. Kompozytsyonnыe materyalы : spravochnyk / pod. red. D. M. Karpynosa. – Kyiv : Naukova dumka, 1985. – 592 s.

3. Shpak, A. P. Klasterni ta nanostrukturni materialy : T.1 / A. P. Shpak, Yu. A. Kunytskyi, V. L. Karbivskyi. – Kyiv : IMF NANU, 2001. – 588 s.

Надійшла до редакції 30.03.2026; розглянута на редколегії 16.04.2026

Вплив параметрів структури нанокомпозитів на їх властивості

Вивчено процеси формування структури дисперсно-зміцнених композиційних матеріалів, що визначає їхні фізико-механічні властивості і тому становить науковий і практичний інтерес. Виконано експериментальні дослідження механізму кристалізації включень при конденсації суміші парів двох

ISSN 2071-1077(print)
ISSN 2663-2411(online)

металів, що не мають розчинності в рівноважних умовах на прикладі композиту Cu-Mo. Досліджено структуру композиту Cu-Mo, а також залежність розміру частинок молібдену від його концентрації і температури підкладки. Вивчено вплив умов одержання на властивості дисперсно-зміцнених композиційних матеріалів.

Дослідженнями встановлено, що композити Cu-Mo, отримані при $t_П$ = 150 – 450 °С, є двофазними: дисперсні частинки молібдену рівномірно розподілені в матриці, яка є твердим розчином заміщення молібдену в міді. Частинки зміцнюючої фази рівномірно розподілені в об'ємі зерен матриці. Переважного виділення на межах зерен не спостерігається. Форма частинок молібдену близька до сферичної і вони утворюються у процесі одержання композиту Cu-Mo на фронті кристалізації в результаті поверхневої дифузії атомів молібдену.

При збільшенні температури підкладки розмір зміцнюючих частинок молібдену та відстань між ними збільшується, що призводить до зниження мікротвердості дисперсно-зміцненого композиту. Так, при температурі підкладки $t_П$ = 150 °С та вмісту молібдену від 0,6 % до 5,4 % середній розмір частинок становить від 98 Å до 120 Å; при температурі підкладки $t_П$ = 450 °С та вміст молібдену від 2,0 % до 4,0 % середній розмір часток становить від 500 Å до 700 Å; при температурах підкладки $t_П$ = 150 – 450 ° С мікротвердість склала $H_μ$ = 850 – 350 МПа відповідно.

Ключові слова: дисперсно-зміцнені композиційні матеріали; дисперсні частинки; розміри частинок; температура підкладки; дифузія; мікротвердість.

Відомості про авторів:

Попова Олена Георгіївна – кандидат технічних наук, доцент, доцент кафедри композиційних конструкцій і авіаційного матеріалознавства (403), Національний аерокосмічний університет «Харківський авіаційний інститут», м. Харків, Україна, e-mail: o.popova@khai.edu, (+38) 067-570-12-17, ORCID: 0009-0003-3599-2273.

Остапчук Валентина Віталіївна – старший викладач кафедри композиційних конструкцій і авіаційного матеріалознавства (403), Національний аерокосмічний університет «Харківський авіаційний інститут», м. Харків, Україна, e-mail: v.ostapchuk@khai.edu, (+38) 093-574-99-67, ORCID: 0000-0002-1584-6960.

About the Autors

Olena POPOVA – PhD, Associate Professor, Department of Composite Structures and Aviation Materials, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, e-mail: o.popova@khai.edu, (+38) 067-570-12-17, ORCID: 0009-0003-3599-2273.

Valentyna OSTAPCHUK – Senior Lecturer, Department of Composite Structures and Aviation Materials, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, e-mail: v.ostapchuk@khai.edu, (+38) 093-574-99-67, ORCID: 0000-0002-1584-6960.