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Research article
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Influence of thermomechanical treatment on the formation of the structure in dispersed-reinforced aluminum alloy-based metal composite materials

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Abstract. The study explored various facets of the structure of dispersed-reinforced aluminum alloy-based metal composite material (MCM) under different modes of thermomechanical treatment. Replacing traditional structural materials with MCM provides manufacturers with an opportunity to achieve higher levels of engineering superiority. The ability to choose composition, modify primary component ratios, and employ a range of MCM manufacturing techniques allows for precise tuning of the material's strength, rigidity, temperature range, and other physical and mechanical properties. Two prevalent technologies for crafting dispersed-reinforced aluminum alloy-based MCM exist: liquid-phase and powder technologies. Liquid-phase methodology entails merging the reinforcing component into the binder alloy's melt, followed by crystallization. This process guarantees the dispersion and fixation of reinforcing particles within the binder volume. In contrast, powder technology involves simultaneous processing of primary component powders in high-energy mills, with subsequent amalgamation of the resultant composite granules via pressure molding. The chief aim of thermomechanical treatment lies in yielding blanks that closely mimic the final product's geometry and reshaping the deformable material's structure to heighten its strength properties. Powder technology was employed to fabricate monolithic composite material samples. Their structures were analyzed, accompanied by tests to ascertain density and strength parameters of the MCM at room temperature. Consequently, dispersed-reinforced aluminum alloy-based MCM possessing a uniform structure, density exceeding 99.0 % of the theoretical value, and elevated mechanical attributes: σ_u = 300÷305 MPa and E = 87÷95 GPa, were successfully produced.

Keywords: metal composite material (MCM), aluminum alloy, thermomechanical treatment, pressing, structure, strength properties

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Влияние деформационно-термической обработки на формирование структуры дисперсно-армированного металлического композиционного материала на основе алюминиевого сплава

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Аннотация. Исследованы аспекты формирования структуры дисперсно-армированного металлического композиционного материала (МКМ) на основе алюминиевого сплава в зависимости от различных режимов деформационно-термической обработки. Замена традиционных конструкционных материалов на МКМ позволит производителям перейти на качественно более высокий технический уровень. Подбор состава, изменение соотношения исходных компонентов и применение различных методов изготовления МКМ позволяют направленно регулировать прочность, жесткость, диапазон рабочих температур и другие физико-механические характеристики материала. Существуют две наиболее распространенные технологии получения дисперсно-армированных МКМ на основе алюминиевых сплавов – жидкофазная и порошковая. Первая предполагает размешивание армирующего компонента в расплаве матричного сплава с последующей кристаллизацией, которая обеспечивает распределение и фиксацию армирующих частиц в объеме матрицы, а вторая представляет собой совместную обработку порошков исходных компонентов в высокоэнергетических мельницах с последующим объединением полученных композиционных гранул методами обработки давлением. Основной целью деформационно-термической обработки является получение заготовок с формой, максимально приближенной к геометрии конечных изделий, а также изменение структуры деформируемого материала, приводящее к повышению уровня прочностных свойств. В работе с использованием порошковой технологии были изготовлены образцы монолитного композиционного материала, исследована их структура и проведены испытания с целью определения плотности и прочностных характеристик МКМ при комнатной температуре. В результате получены дисперсно-армированные МКМ на основе алюминиевого сплава с однородной структурой, плотностью более 99,0 % от теоретической и повышенными механическими свойствами: $\sigma_в$ = 300÷305 МПа и E = 87÷95 ГПа.

Ключевые слова: металлический композиционный материал (МКМ), алюминиевый сплав, деформационно-термическая обработка, прессование, структура, прочностные характеристики

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Introduction

Currently, the creation of promising products in aviation and rocket-space engineering demands materials with low density and enhanced strength properties for primary structures. Such materials, owing to their distinct properties, can also find utility in ultralight, high-load structures across various industries [1; 2].

Moreover, a critical concern for contemporary material developers revolves around devising energy-efficient production technologies that lead to reduced product costs, heightened material utilization coefficients in end products, and enhanced product competitiveness [3–5].

A prospective avenue for addressing the aforementioned challenges lies in the utilization of metal composite materials (MCM) based on dispersed-reinforced aluminum alloys, coupled with the refinement of techniques for manufacturing components from these materials to ensure the requisite levels of physical, mechanical, and operational parameters in the resultant products [5–10].

Typically, metal composite materials comprise a plastic metal alloy fortified with solid ceramic reinforcement materials in the form of particles characterized by varied sizes and shapes [11–13].

The production of MCM through powder technology entails the concurrent processing of primary component powders within high-energy mills, followed by the consolidation of the resultant composite granules through pressure molding. The fundamental goal of thermomechanical treatment is to yield blanks that closely approximate the final product's geometry, while also inducing structural modifications in the deformable material to enhance its strength properties. The thermomechanical treatment procedure hinges upon the inherent capacity of plastic materials to undergo irreversible shape changes when subjected to external forces, all without succumbing to destruction [14].

The structure of dispersed-reinforced MCM comprises a binder metal wherein finely dispersed particles of the reinforcing phase are uniformly distributed. The binder metal within the MCM imparts plasticity, while the ceramic phase enhances strength, rigidity, thermal resistance and wear resistance. The mechanism underpinning MCM reinforcement is preconditioned by the formation by the strengthening phase particles of barriers for dislocation movement, similar to the mechanism in alloys with dispersion hardening. Opting for aluminum alloys as a binder metal in MCM is favored due to their superiority over alternative alloys, encompassing excellent workability, performance, and cost-effectiveness [15; 16].

The objective of this study was to investigate the impact of thermomechanical treatment on the structure of MCM based on an aluminum alloy from the Al–Mg–Si system, reinforced with 20 vol. % SiC and produced via powder technology.

Research methodology

The primary material used for manufacturing dispersed-reinforced aluminum alloy-based MCM consisted of composite granules obtained through mechanical alloying in a laboratory planetary ball mill model PM 100 (SM Retsch, England).

AD31 aluminum alloy was employed as the binder, while the reinforcing phase consisted of 63C (F800) silicon carbide particles.

The composite granules were compressed within a blind die to produce blanks in the shape of cylindrical briquettes. Subsequently, these briquettes were heated to the hot deformation temperature and then pressed using a k03.032 hydraulic press (Russia).

The necessary pressing force for MCM through a cone die via direct pressing was determined using the following formula:

$$P = \sigma_{0.2}\left[\left(\frac{1}{2\sin\alpha}\right)+\left(\frac{2}{1+\cos\alpha}\right)\ln\frac{F}{f}+\frac{2L}{D}+\frac{2l}{d}\right]F,$$

where $\sigma_{0.2}$ is the yield strength of MCM at the pressing temperature, MPa; α is the angle of inclination of the die generatix, deg; F and f are the projection areas of the briquette and the pressed bar on the plane perpendicular to the direction of the male's die movement, respectively, mm^2; L is the height of the briquette, mm; l is the height of the die bearing, mm.

The structure of the pressed MCM samples was examined using an optical electron microscope Olympus BX51 (Olympus, Japan).

The density of the MCM samples was determined through hydrostatic weighing.

The porosity of the material was calculated using the following formula:

$$n = \left(1 - \frac{\rho_{fact}}{\rho_{calc}}\right)\cdot 100\ \%,$$

where ρ_{fact} and ρ_{calc} are the measured and calculated values of MCM density, respectively, g/cm^3.

The strength characteristics of the MCM were assessed through uniaxial tension conducted in accordance with GOST 1497-84 using a Zwick Roell testing machine (Zwick Roell Group, Germany).

Results of the study and their discussion

The morphology of the initial material, which consists of mechanically alloyed composite granules, is presented in Figure 1. The majority of these granules exhibit a spherical shape with a textured surface. The particle size distribution of the granules predominantly falls within the range of 600 to 1000 μm.

Cylindrical briquettes were manufactured from the composite granules using a blind die pressing technique on a hydraulic press, with the intention of subsequently undergoing hot direct pressing via a cone die.

The compaction of granules through blind die pressing unfolds in multiple stages. During the initial phase, the pressing tool induces mutual shifts among the granules, consequently reducing the available interstitial space. This, in turn, leads to the deceleration of their mobility due to mounting friction emerging at the points of contact between the granules. The ensuing stage is marked by the escalation of contact stresses and the commencement of deformation processes. Once the stress level matches the yield strength of the composite material, plastic deformation pervades the entirety of the briquette's volume. Consequently, an intensive alteration in the shape and condition of the granule contact surfaces transpires. This culminates in the formation of a compacted structure within the composite material, characterized by a porosity ranging from 5 to 10 %.

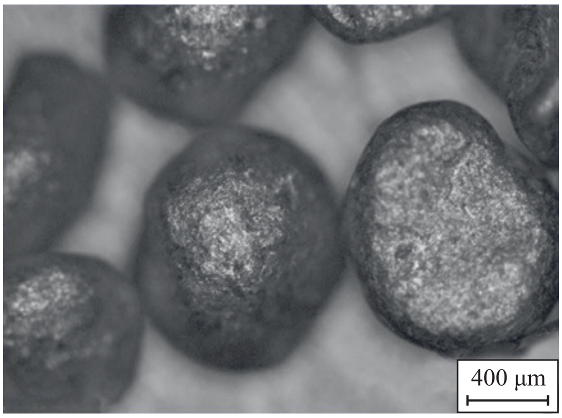

Fig. 1. Structure of mechanically alloyed aluminum alloy-based MCM granules

Рис. 1. Структура механически легированных гранул МКМ на основе алюминиевого сплава

In [17–19], investigations were conducted into the impact of specific pressing pressures on the density of briquettes crafted from powdered materials. It was demonstrated that upon reaching a density threshold of 90–95 % of the theoretical density, the compaction process slows down, leading to no further density augmentation despite increased pressing force.

The graph illustrating the correlation between density and pressing force, as observed in the experiments carried out in the context of this study, is depicted in Figure 2. In this diagram, zone *1* corresponds to the initial phase of the blind die pressing process, while zone *2* pertains to the subsequent stage.

The deceleration of material compaction can be elucidated through the specific nature of deformation processing within the confined space of the blind die. This is attributed to both the restricted ability for pressed MCM volume redistribution within the confined dimensions of the blind die and the limited extent of deformation experienced by the material under the comprehensive compressive force.

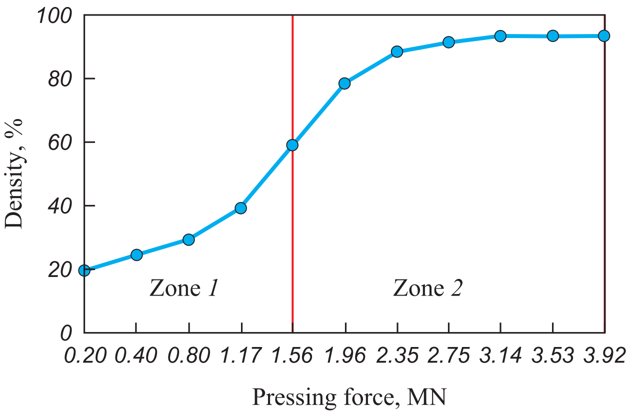

Fig. 2. Dependence of MCM density on the pressing force

Рис. 2. Зависимость плотности МКМ от усилия прессования

The distribution of accumulated deformation fields, acquired from modeling the pressing procedure within a blind die, is illustrated in Figure 3. Notably, the central region of the briquette displays the most pronounced structural refinement. Conversely, the upper and lower portions of the briquette, which were in contact with the male die and the bottom of the blind die, exhibit a comparatively lower level of accumulated deformation, ranging from 0.1 to 0.3. The emergence of frictional forces at the contact surface between the male die and the blind die's base curtails the motion of the compressed material within the confined space of the blind die. Consequently, this uneven distribution of deformation elaboration within the resulting briquette volume is engendered [20–22].

In the images depicting the structure of the MCM after being pressed in a blind die, the outlines of the initial granules are discernible (Figure 4). Simultaneously, the resultant structure captures alterations that transpired within the material during the deformation process. Notably, the periphery of the briquette exhibits higher levels of porosity when contrasted with the central region.

The presence of porosity within the pressed material exerts a detrimental influence the strength properties of the MCM, thereby limiting its suitability as a structural material for part fabrication. In order to achieve heightened performance, the enhancement and refinement of the material's structure can be achieved through subsequent thermomechanical treatment involving increased degrees of deformation.

Within this study, we undertook the process of hot direct pressing through a cone die and scrutinized the impact of the elongation ratio on the structure and properties of the resultant composite material.

Hot direct pressing denotes deformation of a briquette, wherein heated pressed material flows continuously into the deformation center. This process yields alterations not only in the material's shape but also in

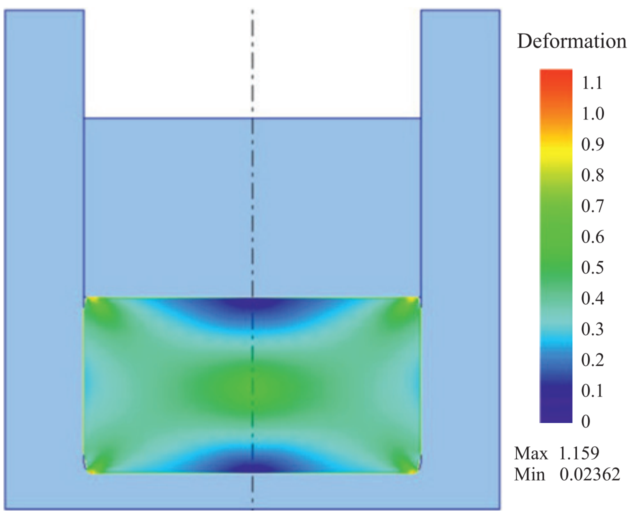

Fig. 3. Results of modeling the MCM sample pressing process in a blind die

Рис. 3. Результаты моделирования процесса прессования образца МКМ в глухой матрице

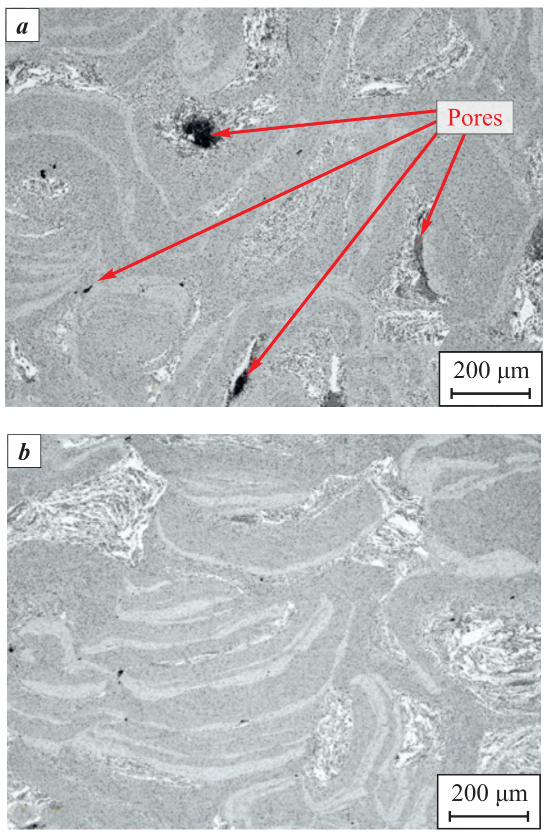

Fig. 4. Structure of the MCM sample pressed in a closed blind die
a and ***b*** – peripheral and central parts of the briquette, respectively

Рис. 4. Структура прессованного в закрытой обойме образца МКМ
а и ***б*** – периферийная и центральная части брикета соответственно

its inherent properties. The external forces exerted upon the MCM during direct pressing encompass the male die pressure, normal pressures on the container's side surfaces, the die, and the drawing cylinder, alongside friction forces arising on the contact surfaces between the MCM and the tools. This constellation of forces culminates in material restructuring, correlating with augmented density and heightened strength properties of MCM.

The process parameters that exert considerable influence on the resulting material's structure during pressing have been identified. These parameters comprise the deformation rate (characterizing the rate of movement of the press's male die), the material's outflow speed from the die, and the elongation ratio. The deformation rate, denoting the linear velocity of the press's working piece movement in the primary deformation direction, remains consistent and was set at 10 mm/s in this study. The material's outflow speed from the die and the elongation ratio share an interdependent relationship: the latter determines the extent of deformation within the pressed material, and its elevation leads to a proportional rise in the outflow speed.

It is acknowledged that the presence of a reinforcing element in the form of finely dispersed ceramic particles classifies disperse-reinforced MCM as intricate deformable materials, endowed with notable resistance to deformation. Consequently, to ensure the uniform flow of MCM during deformation and to diminish the requisite pressing force, a conical die shape was selected.

Throughout this study, direct hot pressing processes with elongation ratios (μ) ranging from 10 to 30 were investigated.

The findings revealed that the highest density (more than 99.0 % of the theoretical one) was attained for MCM samples with $\mu \geq 20$. Notably, surface indentations (score lines) emerged on their surfaces in proximity to the discarded area. This particular form of defect is attributed to the gradual thinning of the lubricant layer applied onto the tool during hot direct pressing, coupled with the escalation of contact friction forces within this region. Consequently, the peripheral layers of the pressed bar start to lag behind the central layers. This phenomenon can be mitigated through the utilization of multi-component lubricants or by applying an exceedingly hard coating to the tool's functional surface. Employing the Qform 3D software package for modeling the hot direct pressing process corroborates the outcomes obtained from the experimental work. Cumulative deformation within the peripheral layers of the bar surpasses that within the central region by a factor of 1.25 (Figure 5).

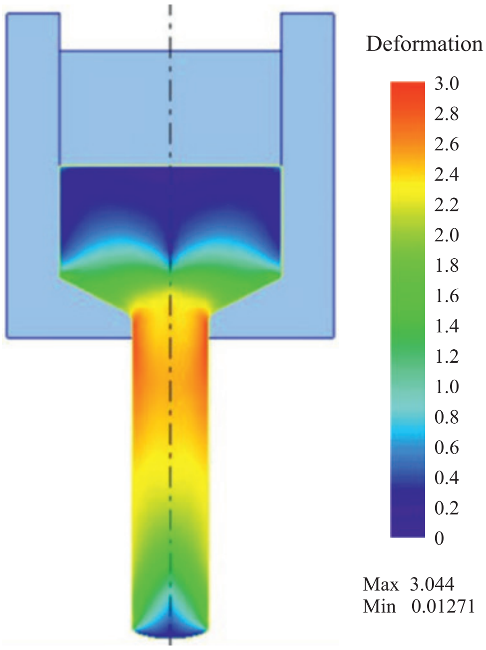

Fig. 5. Results of modeling the process of MCM direct pressing in a cone die

Рис. 5. Результаты моделирования процесса прямого прессования МКМ в конической матрице

The structure of the MCM in the pressing direction exhibits a banded pattern, linked to the material's stress distribution during deformation. Specifically, this is influenced by the presence of tensile stresses aligned along the deformation axis. The boundaries of the granules, which were initially set within the briquette's structure, undergo extension along the axis of compression, thereby shaping the structure depicted in Figure 6. Furthermore, for elongation ratio of $\mu \geq 10$, the structure of the pressed MCM appears non-uniform (see Figure 6, *a*), attributed to inadequate compressive stresses originating within the deformation center. In contrast, at $\mu \geq 20$ and ≥ 30 (Figure 6, *b*, *c*), the structure demonstrates higher uniformity.

Samples were manufactured from the resultant bars for the purpose of conducting tensile tests. The visual representation of these samples is presented in Figure 7.

The mechanical properties of the pressed dispersed-reinforced MCM samples were examined at a temperature of 20 °C. The tabulated data showcases the acquired outcomes for strength (σ_u), yield strength ($\sigma_{0.2}$) and elastic modulus (E).

MCM samples produced with an elongation ratio of ≥ 20, which exhibit a uniform structure, demonstrated superior strength characteristics compared to the samples with $\mu \geq 10$, marked by non-uniform structure. Meanwhile, elevating $\mu \geq 30$ did not result in a significant performance improvement, similar to the density findings detailed earlier.

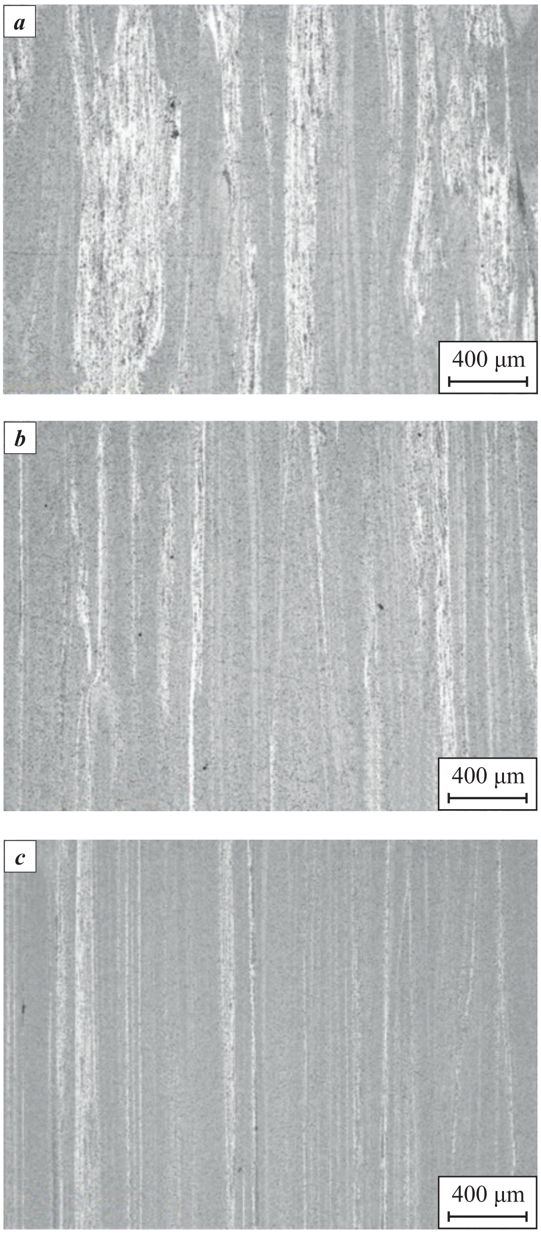

Fig. 6. Structure of MCM bars after direct pressing with elongation ratios of ≥10 (***a***), ≥20 (***b***) and ≥30 (***c***)

Рис. 6. Структура прутков МКМ после прямого прессования с коэффициентами вытяжки ≥10 (***a***), ≥20 (***b***) и ≥30 (***c***)

Values of mechanical parameters of dispersed-reinforced MCM samples in comparison with aluminum alloy of AD31 grade

Значения механических характеристик образцов дисперсно-армированного МКМ в сравнении с алюминиевым сплавом марки АД31

Sample	μ	σ_u, MPa	$\sigma_{0.2}$, MPa	*E*, GPa
MCM	≥10	290–300	235–240	87–93
	≥20	300–305	240–245	88–94
	≥30	300–305	240–245	87–95
AD31	–	240–250	200–205	71–73

Fig. 7. Samples of dispersed-reinforced MCM for tensile testing

Рис. 7. Образцы из дисперсно-армированного МКМ для испытаний на растяжение

Conclusions

1. Thermomechanical treatment of dispersed-reinforced aluminum alloy-based MCM through blind die pressing enables the production of material with porosity ranging from 5 to 10 %.

2. Once the density reaches a threshold of 90–95 % of the theoretical value, is compaction of dispersed-reinforced MCM decelerates, and further augmentation of the pressing force does not lead to increased density.

3. Subsequent thermomechanical treatment, characterized by intensified material deformation, enhances the structure and attributes of the aluminum alloy-based MCM obtained.

4. Hot direct pressing with the elongation ratio greater than 20 yields dispersed-reinforced aluminum alloy-based MCM featuring a uniform structure, density surpassing 99.0 % of the theoretical value and heightened mechanical properties: σ_u = 300÷305 MPa and *E* = 87÷95 HPa.

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A. N. Nyafkin – conceptualized the main ideas, defined the study's objectives, formulated the research questions, devised experimental protocols, determined modes of thermomechanical treatment, and authored the paper's content.
D. V. Kosolapov – prepared mixtures, conducted thermomechanical treatments, analyzed experimental outcomes, assessed sample properties, performed calculations, and contributed to data interpretation.
E. I. Kurbatkina – provided scientific supervision, reviewed and revised the manuscript, refined conclusions, and ensured textual accuracy.

Вклад авторов

А. Н. Няфкин – формирование основной концепции, постановка цели и задачи исследования, подготовка экспериментов, подбор режимов деформационно-термической обработки, написание текста статьи.
Д. В. Косолапов – приготовление смеси и проведение деформационно-термической обработки, анализ полученных результатов экспериментов и исследований свойств образцов, выполнение расчетов.
Е. И. Курбаткина – научное руководство, корректировка текста, корректировка выводов.

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