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Research article
Научная статья

Selection of heat treatment and its impact on the structure and properties of AK10M2N–10%TiC composite material obtained via SHS method in the melt

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Abstract: The composite materials based on the Al–Si system alloys, strengthened with a highly dispersed titanium carbide phase, possess improved characteristics and belong to the group of promising structural materials. Currently, self-propagating high-temperature synthesis (SHS) based on the exothermic interaction, wherein titanium and carbon precursors directly involve in the melt, is the most accessible and effective method to obtain them. This paper proves the feasibility and demonstrates the successful synthesis of a 10 wt.% titanium carbide phase in the melt of the AK10M2N alloy, resulting in the AK10M2H-10% TiC composite material. Samples of the matrix alloy and the composite material were subjected to heat treatment according to the T6 mode, with various temperature-time parameters for hardening and aging operations. Based on the results, optimal heat treatment modes were selected to ensure maximum hardness. We studied the macro- and microstructure of the obtained samples and performed micro *X*-ray spectral and *X*-ray diffraction phase analyses. Different groups of properties underwent comparative tests. It was established that the density of AK10M2N–10%TiC samples before and after heat treatment, according to optimal modes, is close to the calculated value. We showed that the combination of reinforcement and heat treatment significantly increases hardness, microhardness, and compressive strength, with a slight decrease in ductility. Additionally, it maintains the values of the coefficient of thermal linear expansion, high-temperature strength, and resistance to carbon dioxide and hydrogen sulfide corrosion at the level of the original alloy. The greatest effect was observed during the investigation of tribological characteristics: heat treatment of the composite material according to the recommended mode significantly reduces the wear rate and friction coefficient, eliminates seizure and tearing, and prevents temperature rise due to friction heating.

Keywords: composite material, aluminum, melt, titanium carbide, self-propagating high-temperature synthesis (SHS), heat treatment.

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Выбор термической обработки и исследование ее влияния на структуру и свойства композиционного материала АК10М2Н–10%TiC, полученного методом СВС в расплаве

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Аннотация: Композиционные материалы на основе сплавов системы Al–Si, упрочненные высокодисперсной фазой карбида титана, характеризуются улучшенными свойствами и относятся к группе перспективных конструкционных материалов. В настоящее время наиболее доступным и эффективным способом их получения является самораспространяющийся высокотемпературный синтез (СВС), основанный на экзотермическом взаимодействии прекурсоров титана и углерода непосредственно в расплаве. В работе обоснована целесообразность и показан успешный опыт синтеза 10 мас.% фазы карбида титана в расплаве сплава АК10М2Н и получения композиционного материала АК10М2Н–10%TiC. На образцах матричного сплава и полученного на его основе композиционного материала реализована термическая обработка по режиму Т6 с различными температурно-временными параметрами операций закалки и старения, по результатам которых выбраны оптимальные условия термообработки, обеспечивающие получение максимальной твердости. Исследована макро- и микроструктура, проведены микрорентгеноспектральный и рентгенофазовый анализы полученных образцов. Выполнен комплекс сравнительных испытаний разных групп свойств. Установлено, что образцы АК10М2Н–10%TiC до и после проведения термической обработки по оптимальным режимам имеют плотность, близкую к расчетному значению. Показано, что совместное проведение армирования и термообработки способствует существенному повышению показателей твердости, микротвердости и прочности на сжатие при незначительном уменьшении пластичности, а также позволяет сохранить значения коэффициента термического линейного расширения, жаропрочности и стойкости к углекислотной и сероводородной коррозии на уровне исходного сплава. Наибольший эффект отмечен при исследовании трибологических характеристик: проведение термической обработки композиционного материала по рекомендованному режиму способствует существенному снижению скорости изнашивания и коэффициента трения, позволяет исключить схватывание и появление задиров, а также не допустить повышения температуры вследствие разогрева при трении.

Ключевые слова: композиционный материал, алюминий, расплав, карбид титана, самораспространяющийся высокотемпературный синтез (СВС), термическая обработка.

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Introduction

The Al—Si system alloys, commongly known as silumins, are among the most common cast aluminum alloys. They are characterized by high casting properties, satisfactory weldability, and corrosion resistance, making them suitable for manufacturing medium and large critical duty cast parts such as compressor housings, crankcases, cylinder heads, pistons, and more.

Special alloys, which contain additional alloying components besides silicon, such as Cu, Mg, Mn, Ti, and less frequently Ni, Zr, Cr, etc., are the most common. The introduction of such additives enhances the strength characteristics of silumins, and the presence of copper and magnesium allows for heat treatment according to the T6 mode, which includes hardening followed by artificial aging to achieve additional strengthening. However, it remains important to find ways to further enhance the mechanical properties of silumins, as even after alloying and heat treatment, their properties remain lower than those of duralumins [1].

One of the most promising approaches is creating casting composite materials based on silumins by combining a matrix alloy with a dispersed phase constituted of particles of silicon or titanium carbides [2; 3]. Silicon carbide is produced in large volumes and is more affordable. However, it can react with the SiC filler and the matrix, forming the hexagonal lamellar Al4C3 phase, which leads to instability in physical and mechanical properties and a decrease in corrosion resistance [4]. Titanium carbide reinforcement is less common but is a better choice: firstly, unlike the SiC hexagonal lattice, titanium carbide has a FCC lattice close in size to the lattice of matrix aluminum, so dispersed particles of this compound can effectively act as crystallization centers. Secondly, titanium carbide is characterized by higher physical and mechanical properties, such as a melting point of T_{melt} = 3433 K (compared to 2873—2970 K for SiC); Young's modulus $E = 440 \cdot 10^9$ N/m^2 ($\geq 3350 \cdot 10^9$ N/m^2); hardness $HV = 32 \cdot 10^9$ N/m^2 ($24 \div 28 \cdot 10^9$ N/m^2); strength σ_{ucs} = $= 1.2 \div 1.54 \cdot 10^9$ N/m^2 ($0.4 \div 1{,}7 \cdot 10^9$ N/m^2) [5].

The final characteristics of composite material reinforced with dispersed carbide phases are largely determined by its production method [6; 7]. In terms of technological availability and cost-effectiveness, liquid-phase methods are preferable. These methods are subdivided into *ex situ*, where reinforcing particles are prepared in advance outside the matrix and later introduced into the melt, and *in situ*, where reinforcing particles are synthesized by chemical reactions directly in the matrix alloy during composite fabrication [8]. The most common method from the first group is mechanical mixing, which often leads to contamination with oxides and impurity elements and excludes the possibility of obtaining a highly dispersed reinforcing phase, as the particles tend to agglomerate [9]. The more promising method from the second group, self-propagating high-temperature synthesis (SHS), does not have these disadvantages. It can be implemented on standard foundry equipment, is characterized by low energy consumption due to the short duration of the process, and most importantly, it enables the synthesis of the titanium carbide phase from initial powders of carbon and titanium (or their compounds) with particle sizes from 100 nm in a wide range of concentrations [10].

A number of studies on liquid-phase reinforcement of silumins with carbide phases have been conducted in Russia. The study in [11] shows that mechanically mixing SiC particles into AK12, AK9, and AL25 alloys contributes to a deterioration of the castings' dendritic parameter and an increase in the modulus of elasticity, hardness, and bearing capacity. In [5; 12], researchers compared antifriction compositions based on the AK12 and AK12M2MgN alloys reinforced with dispersed SiC or TiC particles in amounts of 5 or 10 wt.%, with and without intermetallic phases (Al_3Me type compounds). It was found that the optimal filler is a titanium carbide phase in the amount of 10 wt.%, as this increased wear resistance up to 10 times and reduced the coefficient of friction by 60 %.

There are also several publications on heat treatment of silumin-based composites [13—16]. The paper [14] showed that the AK12M2MgN alloy, reinforced with endogenous (formed in the melt) AlTi, Al_3Ti, Al_3Ni, etc. phases and exogenous (introduced from outside) SiC and Al_2O3 nano- and microparticles in the amount of 0.1 wt.%, exhibits a hardness increase of 50 MPa at t = 20 °C and 30 MPa at 300 °C. After heat treatment (holding at 515 °C, quenching in water, and aging at 210 °C), the hardness increased by 110—160 MPa and 60—80 MPa, respectively. Similar results were obtained in [15; 16], where mechanical stirring of SiC dispersed phase up to 15 wt.% into the AK9h, AK12MMrN, and A359 alloys with subsequent T6 heat treatment accelerated the aging process and increased hardness overall. The authors attributed this to the enhanced density of dislocations in the composites and the difference in elastic moduli between the matrix and the reinforcing phase.

These studies provide convincing evidence that producing and thermally treating composites based on silumins is promising. However, it is also clear that domestic developments mainly focus on obtaining composites through mechanical stirring and primarily use silicon carbide as the filler. In contrast, foreign studies cover a wider range of production methods and composite structures. For instance, foreign researchers show significant interest in titanium carbide, both introduced from the outside and formed in the melt of silumins by the SHS method [17—20]. In [20], researchers added an Al + Si powder mixture in amounts of 0—40 % to a charge of titanium and graphite, then mixed, pressed in an argon atmosphere, and introduced it into the Al—Si eutectic melt heated to 900 °C. *X*-ray phase analysis showed that at any content of Al and Si powders, the final composite structure included only Al, Si, and TiC phases, confirming that SHS of the carbide phase can be conducted directly in the silumin melt.

Care must be taken when selecting the temperature modes for creating and heat treating such composites, as several studies indicate that the titanium carbide phase becomes thermally unstable at high

temperatures and long holding periods in the presence of silicon [21—24]. In [22], 10 wt.% TiC particles were introduced into the Al—7%Si melt heated to 700 °C. After crystallization, the samples were oven-exposed at temperatures ranging from 500 to 1000 °C for 6 hours. It was found that in the range of 600—800 °C, titanium carbide decomposes, forming Ti—Al—Si ternary phase and Al_4C_3 intermetallic phase, while at temperatures above 800 °C, the reverse process occurs, and the carbide phase content nearly restores to the initial level. However, [23] demonstrated that during a 20-minute holding at 800 °C of the Al—12Si/TiC composite, titanium carbide decomposes completely and irretrievably because silicon atoms diffuse into the lattice of titanium carbide.

A similar conclusion was made in [24]. At temperatures of 750 and 800 °C, TiC particles decompose to form Al_4C_3 and $TiAl_xSi_y$ phases, and at 900 and 1000 °C, they form Al_4C_3 and $TiAl_xSi_y$ phases, and at $t = 900$ and 1000 °C, to form Al_4C_3 and Ti_3SiC_2.

All authors agree that the carbide phase can degrade at high temperatures of the silumin melt and during prolonged holding times. Therefore, the SHS method is particularly relevant, as it requires minimal time and the entire cycle of obtaining the composite material, from charge input to crystallization of the finished product, lasts no more than 10 minutes, which is insufficient for carbide phase decomposition.

Another important issue is phase formation in the presence of other alloying elements and carbide phase particles. The study [25] explores the influence of 1 % Fe on the structure and properties of the Al—12%Si—1%Fe—(0.4—0.8)%TiC composite obtained by the SHS method. It was found that with increasing titanium carbide content, α-Al_8Fe_2Si of favorable morphology forms instead of the sharp-angled β-Al_5FeSi phase, enhancing the tensile strength from 148.2 to 198.7 MPa, the yield strength from 84.7 to 93.5 MPa, and the relative elongation from 2.3 to 4.93 %.

Several studies have focused on the addition of magnesium, with varying findings. The authors of [26] mixed 10 wt.% TiC into the silumin composition Al—14.2%Si—0.3%Mg, additionally introduced 1 wt.% Mg, and subjected the mixture to heat treatment (holding at 525 °C, quenching in cold water, and aging at 151—155 °C). They attributed the significant increase in wear resistance to the uniform carbide phase distribution, decreased surface tension, and increased wettability caused by the presence of magnesium. However, in [27], which studied phase formation in an Al—Mg—Si alloy reinforced with 2 % TiC during aging at 160 °C, it was found that the carbide phase prevents the formation of Guinier—Preston zones and the release of strengthening metastable Mg—Si phases in the aluminum matrix. As a result, after heat treatment, the maximum hardness of the composite (75.8 HV) was lower than that of the matrix alloy (123 HV). The role of magnesium is also negatively evaluated in [28], where the Al—3.5vol.%TiC alloy obtained by the SHS method was introduced into the Al—10%Si melt at 850 °C to form 2 vol.% TiC, with 0.2—0.4 wt.% Mg added to some samples. After synthesis, the samples were subjected to heat treatment (holding at 540 °C, quenching in cold water, and aging at 160 °C). Based on the microstructure analysis, the authors concluded that the Mg_2Si compound forms but segregates near TiC particles and facilitates the interaction between carbide particles and silicon. This leads to the formation of complex phases such as $Al_3TiSi_xC_y$ and Al_3Ti, which slightly enhance hardness and strength but significantly reduce the material's ductility.

Thus, the process of structure formation in composites based on special silumins is not entirely clear, but it is evident that their aging kinetics differ significantly from those of initial silumins, and the phase composition can undergo significant changes. However, all studies indicate that the presence of a carbide phase contributes to enhanced hardness and wear resistance [29; 30]. This suggests that such reinforcement is most appropriate for tribological materials requiring this complex of properties, such as heat-resistant piston aluminum alloys. In this group, the most widespread materials are special silumins with nickel, particularly the AK10M2N alloy, which is extensively used to manufacture piston castings for internal combustion engines. Previous studies conducted by Samara State Technical University demonstrated the feasibility of conducting SHS with AK10M2H silumin containing 10 wt.% TiC. This process reduced the friction coefficient of the composite material by three times without subsequent heat treatment, while increasing the seizure load by at least 1.5 times compared to the matrix alloy [31].

To further enhance the material's characteristics, we conducted this study to select the optimal heat treatment mode and investigate its effect on the structure and properties of the AK10M2N-10%TiC composite material obtained via SHS in the melt.

Research methodology

The AK10M2N alloy produced by "Sammet" LLC (Russia) according to GOST 30620-98, was used as

a matrix for the melt. To obtain a charge mixture, powders of titanium (TPP-7, TS 1715-449-05785388) and carbon (P-701, GOST 7585-86), taken in a stoichiometric ratio for the SHS reaction Ti + C = TiC, were mixed with salt Na_2TiF_6 (GOST 10561-80) in the amount of 5 % of the charge mass. The resulting composition was then divided into 3 equal portions, wrapped in aluminum foil and alternately introduced into the silumin melt heated to a temperature of 900 °C in a graphite crucible of a PS-20/12 melting furnace (Russia) for conducting SHS reaction and obtaining composites.

To study the microstructure, the samples were etched with a solution of 50%HF + 50%HNO_3 for 10—15 s. Metallographic analysis was carried out on a JSM-6390A scanning electron microscope ("Jeol", Japan) equipped with a JSM-2200 module for micro *X*-ray spectral analysis (MXSA).

The phase composition was determined by *X*-ray diffraction (XRD) phase analysis. *X*-ray spectra were recorded on an ARL X'trA automated diffractometer ("Thermo Scientific", Switzerland) using CuK_α-radiation with continuous scanning in the range of angles $2\theta = 20°\div80°$ at a speed of 2 degrees/min. HighScore Plus software (PANalytical B.V., the Netherlands) was used to analyze the diffractograms.

The samples were subjected to thermal treatment in a SNOL laboratory chamber furnace with an operating temperature reaching 1300 °C.

The density of experimental samples was determined by hydrostatic weighing on VK-300 scales (Russia) of the 4th accuracy class according to GOST 20018-74.

The method based on measuring the elongation of cylindrical rods, 60 mm long and 7 mm in diameter, during heating was used to estimate the coefficient of thermal linear expansion (CTLE). The CTLE value was measured on a mechanical dilatometer under the following conditions: TXA thermocouple, type K; duration — 5 h; temperature limit value — 300 °C; the measurement interval — 25 °C. CTLE was calculated according to the formula

$$\alpha = \frac{l_2 - l_1}{l_1(t_2 - t_1)},$$

where α is the temperature coefficient of linear expansion, K^{-1}; t_1 and t_2 are initial and final test temperatures, K; l_1 and l_2 are sample lengths corresponding to t_1 and t_2, mm.

Hardness of samples was determined on TSH-2M hardness tester (Russia) according to GOST 9012-59, after which the impression diameter was assessed on a Motic DM-111 microscope (Russia) and analyzed using the Motic Educator software. The microhardness of the samples was measured on a standard PTM-3 microhardness tester (Russia) according to GOST 9450-76 using a diamond-pyramid hardness test with a square base and an interface angle at the apex of 136°; the weight on the indenter was 100 g. Compression tests were carried out according to GOST 25.503-97 on type III samples with the diameter $d_0 = 20$ mm under a load up to 300 kN. To evaluate the heat resistance, compression tests were performed at temperatures of 150 and 250 °C using an Instron 8802 universal machine (USA) with a 3119-406 thermal chamber at a load of 100 kN; the thermocouple was mounted directly on the sample; the traverse speed reached 1 mm/min.

Corrosion resistance was evaluated according to GOST 13819-68 in the Coat Test 3.3.150.150 autoclave complex under the following conditions: an aqueous solution of 5 % NaCl; gas phase CO_2 (1 Pa) + H_2S (0.5 MPa) + N_2 (3.5 MPa) at 80 °C; duration — 240 h; total pressure — 5 MPa. Corrosion resistance parameters were calculated according to GOST 9.908-85.

Tribological tests were carried out using the "Universal-1B" universal tribological complex (Russia), according to the ring-plane test scheme, which simulates the operating conditions of friction surfaces "piston — piston pin" in the internal combustion engine in the following mode: normal contact load — 400 N; counterbody rotation speed — 600 rpm (average linear velocity in the contact zone is 0.157 m/s); test duration — 60 min (or until complete seizure).

Results and discussion

During the TiC synthesis, an active and rapid SHS reaction with bright flashes was observed in the AK10M2N melt. The fractures of AK10M2N-10%TiC samples obtained after solidification were characterized by homogeneous gray color, had neither foreign inclusions nor residues of unreacted charge.

The AK10M2N alloy belongs to the group of special piston silumins with nickel addition. The T1 mode, that includes artificial aging only, can be used for its heat treatment aimed at enhancing its strength characteristics. Moreover, the material partially hardens during cooling in the casting mold, but in this case hardening will not be significant. More frequently the T6 mode is used. It includes hardening within the range of 515—535 °C and artificial aging in the interval of 160—190 °C [32—34]. Based on the review of the recommended modes, the following were selected as experimental ones:

1) heating for hardening at t = 515 °C for 1—2 h with cooling in cold water and aging at t = 190 °C for 1—6 h;

2) heating for hardening at t = 535 °C for 1—2 h with cooling in cold water and aging at t = 160 °C for 1—6 h.

Hardness was used as a quantitative criterion to evaluate the heating effect.

The analysis of the obtained results showed that the maximum hardness values are achieved by heating for hardening at t = 515 °C followed by artificial aging at t = 190 °C for 2 h, but with different periods of holding for hardening: for the AK10M2N matrix alloy the maximum hardness of 152 HB was observed after 2 h of holding, while for the AK10M2N—10%TiC sample, the hardness of 171 HB was registered after 1 h of holding (Fig. 1). The highly dispersed particles of titanium carbide obviously contribute to the increase in vacancy concentration, dislocation density, grain refinement, which, in combination, intensify structural transformations. The above modes were found to be optimal, and further studies were performed after these types of heat treatment.

The microstructural study of the samples after heat treatment revealed that many rounded particles, their sizes ranging from 180 nm to 2 μm, were present in the composite (Fig. 2). MXSA that was conducted further (Fig. 3) indicates the presence of Ti and C in the composite structure, which confirms their assimilation in the melt, as well as other elements (Si, Cu, Mg, Ni, and Fe) included in the initial AK10M2N alloy.

According to the sources [1; 32], after heat treatment of piston silumins, magnesium is usually present in their structure in an amount of about 1% in the form of eutectic inclusions of the Mg_2Si phase, but it can also form other Mg-containing compounds. Copper in alloys with nickel forms the main strengthening phases Al_2Cu and $Al_5Cu_2Mg_8Si_6$, as well as ternary compounds Al_7Cu_4Ni and Al_3CuNi. Nickel with iron can form the Al_9FeNi compound, eutectic inclusions of which are undesirable due to rough morphology. However, the following phases are most likely to form: Al_3Ni, Al_6Cu_3Ni and $Al_3(Ni,Cu)_2$. The XRD analysis was performed to clarify the obtained phase composition, which revealed the presence of Al_2Cu and Al_3Ni intermetallic phases in the matrix alloy and TiC ceramic phase (9 wt.%) in the composite, which is quite an acceptable level, taking into account some inhomogeneity of its distribution, as well as the presence of the same Al_2Cu, Al_3Ni phases (Fig. 4). We can also assume the presence of other phases from the above-mentioned list in too small an amount to be detected by the XRD method.

Investigation of properties of the AK10M2N alloy and the AK10M2N—10%TiC composite material after heat treatment

We conducted comparative studies of the samples of the initial alloy and the AK10M2N—10%TiC composite material before and after heat treatment according to the recommended modes.

Initially, the density and porosity of the samples were determined. The obtained data are presented in Table 1. The comparison of theoretical (ρ_t) and experimental (ρ_e) density revealed that these values are very close and the porosity is 0. This phenomenon is not typical for pro-

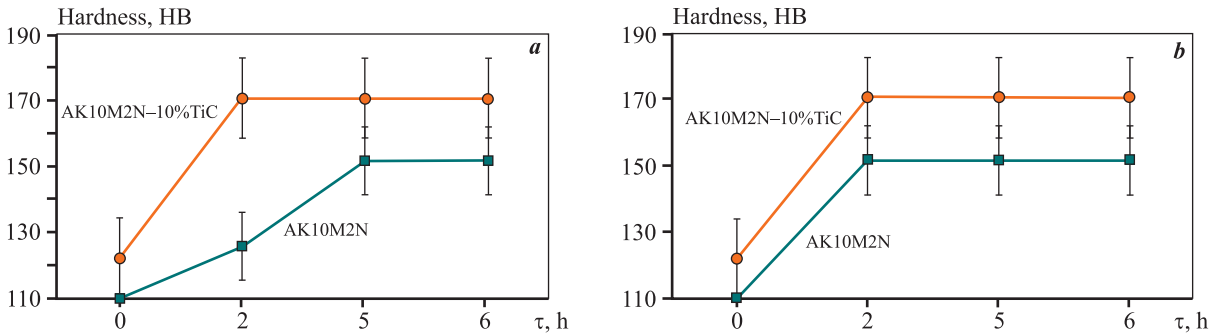


Fig. 1. The hardness change of the AK10M2N alloy and the AK10M2N–10%TiC composite material after heating for hardening with holding for 1 h (***a***) and 2 h (***b***) at t = 515 °C, cooling in cold water and artificial aging at a temperature of t = 190 °C for 1–6 h

Рис. 1. Изменение твердости сплава АК10М2Н и композиционного материала АК10М2Н–10%TiC после нагрева под закалку с выдержкой 1 ч (***a***) и 2 ч (***b***) при t = 515 °C, охлаждения в холодной воде и искусственного старения при t = 190 °C в течение 1–6 ч

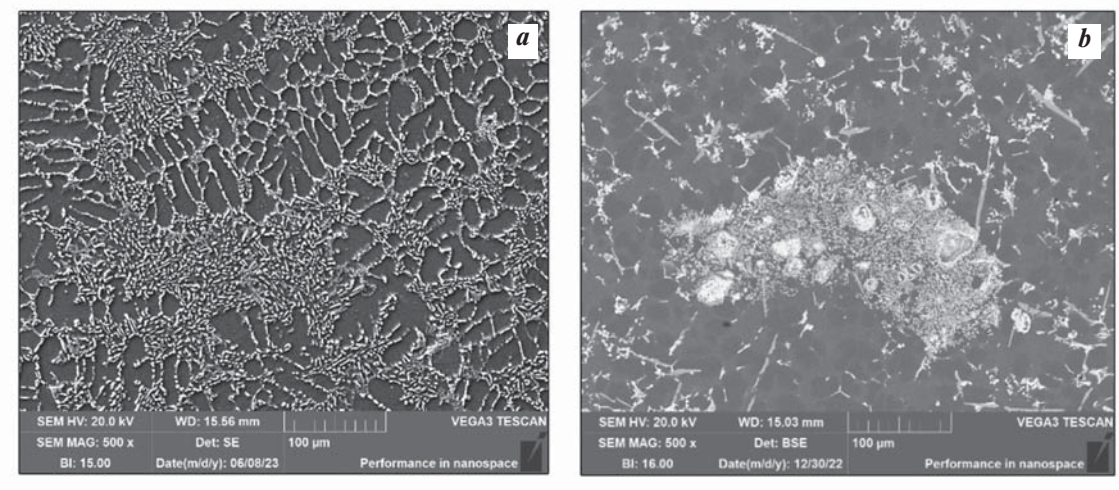
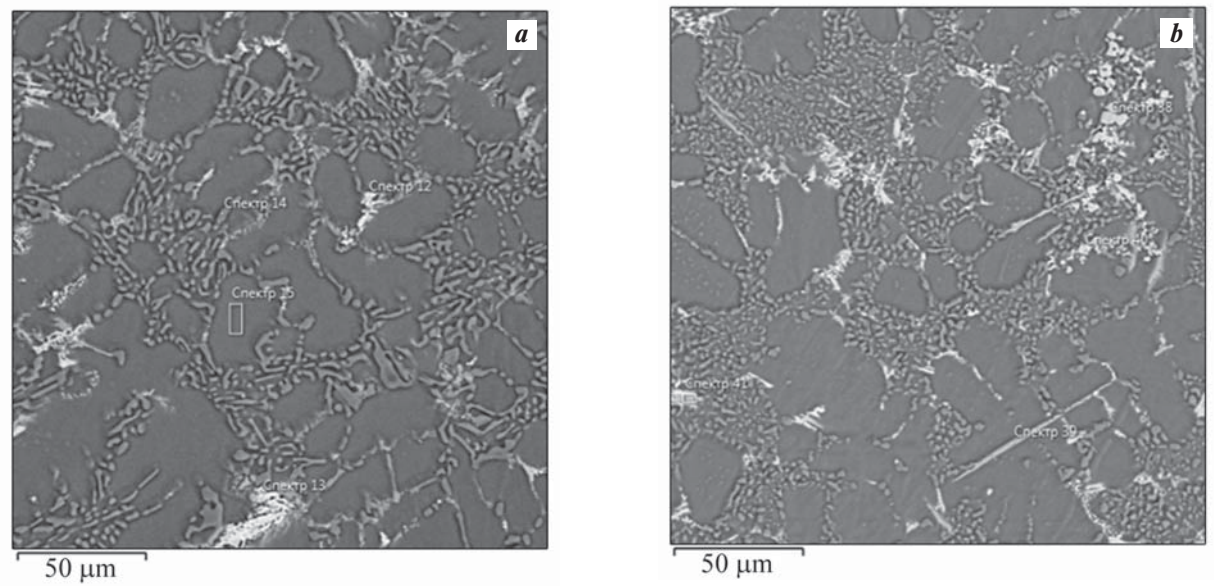


Fig. 2. Microstructure (×500) of the AK10M2N alloy (***a***) and the AK10M2N–10%TiC composite material (***b***) after heat treatment according to optimal modes

Рис. 2. Микроструктуры (×500) сплава АК10М2Н (***a***) и композиционного материала АК10М2Н–10%TiC (***b***) после термической обработки по оптимальному режиму



Marker number	Element content, wt.%				
	Al	Si	Ni	Cu	Mg
12	45.86	1.93	23.00	28.24	0.96
13	41.56	3.26	28.65	26.53	–
14	28.01	70.89	1.10	–	–
15	97.15	0.97	–	1.72	0.17

Marker number	Element content, wt.%						
	Al	Si	Ti	C	Ni	Cu	Fe
38	0.44	0.13	79.98	19.45	–	–	–
39	57.71	12.84	28.09	1.36	–	–	–
40	14.78	0.30	58.02	23.15	1.96	1.23	0.57
41	64.47	2.79	–	5.58	14.04	8.96	4.15

Fig.3. MXSA analysis of the AK10M2N alloy (***a***) and the AK10M2N–10%TiC composite material (***b***) after heat treatment according to the optimal mode

Рис. 3. Результаты МРСА сплава АК10М2Н (***a***) и композиционного материала АК10М2Н–10%TiC (***b***) после термической обработки по оптимальному режиму

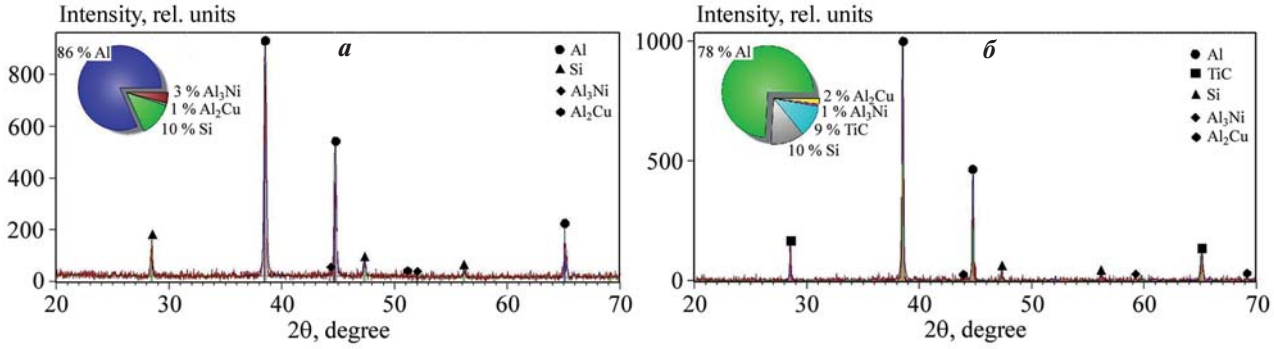


Fig. 4. *X*-ray diffraction patterns of the AK10M2N alloy (***a***) and the AK10M2N–10%TiC composite material (***b***) after heat treatment according to the optimal mode

Рис. 4. Дифрактограммы сплава АК10М2Н (***а***) и композиционного материала АК10М2Н–10%TiC (***b***) после термической обработки по оптимальному режиму

ducts obtained by SHS, but in this case it may indicate a high level of adhesive bonding at the interfaces.

For piston silumins, which include the AK10M2N alloy, the coefficient of thermal linear expansion (CTLE) is an important parameter [35; 36]. Figure 5 presents the results obtained at temperatures ranging from 30 to 300 °C. The maximum CTLE values were $29.6 \cdot 10^{-6}$ K^{-1} and $25.1 \cdot 10^{-6}$ K^{-1} for the AK10M2N sample and $27.8 \cdot 10^{-6}$ K^{-1} and $26.1 \cdot 10^{-6}$ K^{-1} for AK10M2N—10%TiC before and after heat treatment, respectively. The obtained values are close and after heat treatment in both cases slightly decrease, but the main conclusion is that reinforcement does not lower this index. This is especially important if we keep in mind that the titanium carbide compound's own CTLE is higher than, for example, that of silicon carbide ($6.52 \div 7.15 \cdot 10^{-6}$ K^{-1} and $4.63 \div 4.7 \cdot 10^{-6}$ K^{-1}, respectively).

It should be noted that the obtained results are not consistent with the conclusions given in [37]. The latter study proves that CTLE of the composite material based on the aluminum alloy of the Al—Cu—Mg system reinforced with 60 vol.% SiC using the compression impregnation method depends on the size of reinforcing particles. It was also found that as the size of silicon carbide particles increase (from 50 to 320 μm), the CTLE value decreases by 15—20 % at t = 20 °C due to the shrinking proportion of interfacial boundaries with an unstable structure. In our case, there are highly dispersed particles that obviously form a significant number of interfacial boundaries, however, no increase in CTLE is registered. This can probably be attributed to the high degree of the particles coherence with the aluminum matrix as crystal lattice parameters are quite similar.

To evaluate the mechanical properties, we investigated the flow stress under uniaxial compression (until the first crack emerges), relative strain, hardness and microhardness (Table 2).

The results obtained showed that reinforcement with TiC particles to be followed by heat treatment can significantly enhance the strength and hardness values while maintaining sufficient plasticity reserve. These results are particularly noteworthy in view of

Table 1. **Density and porosity of the AK10M2N alloy and the AK10M2N–10%TiC composite material**

Таблица 1. Плотность и пористость образцов АК10М2Н и АК10М2Н–10%TiC

Composition	ρ_t, g/cm^3	ρ_e, g/cm^3	P, %
AK10M2N without HT	2.720	–	–
AK10M2N after HT (hardening t = 515 °C, τ = 2 h + aging 190 °C, 2 h)	2.720	–	–
AK10M2N–10%TiC without HT	2.847	2.831	0
AK10M2N–10%TiC after HT (hardening 515 °C, 1 h + aging 190 °C, 2 h)	2.847	2.840	0

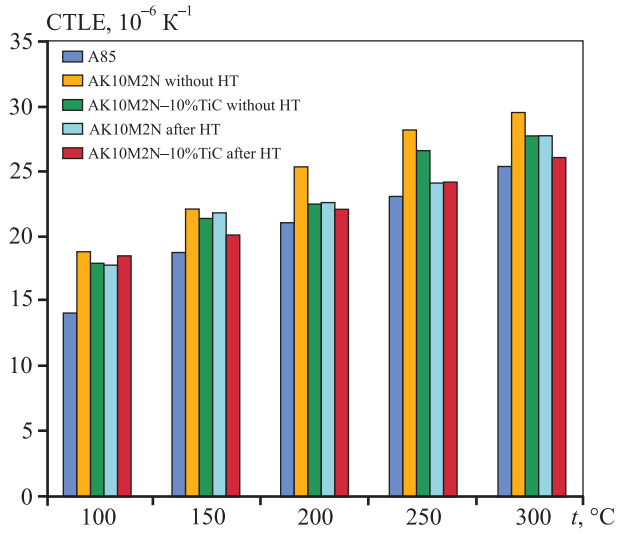


Fig. 5. Change in CTLE of the AK10M2N alloy and the AK10M2N–10%TiC composite material as a function of temperature

Рис. 5. Изменение КТЛР сплава АК10М2Н и композиционного материала АК10М2Н–10%TiC в зависимости от температуры

the fact that, according to [5], the introduction of 10 wt.% of reinforcing TiC particles, 40—100 μm in size, into the AK12M2MgN aluminum alloy leads to a decrease in compressive strength from 489 to 470 MPa, and that of the deformation degree from 17.01 to 12.65 %. Obviously, the increased strength in our study can be attributed to the higher dispersion of the reinforcing phase and, consequently, its good wettability and adhesion.

The AK10M2N alloy belongs to the group of heat-resistant alloys, therefore, the compressive strength was further evaluated at elevated temperatures of 150 and 250 °C under a constant load of 100 kN (Fig. 6).

The analysis of the obtained data indicates that the values of the flow stress of both the matrix alloy and the composite material do not change throughout the temperature range.

Table 3 presents the results of evaluating the reinforcement and heat treatment impact on the samples corrosion resistance. The composites had a slightly higher corrosion depth index. However, in general, as

Table 2. **Mechanical and technological properties of the AK10M2N alloy and the AK10M2N–10%TiC composite material**

Таблица 2. Механические свойства сплава АК10М2Н и композиционного материала АК10М2Н–10%TiC

Sample composition	Hardness, HB	Micro-hardness *HV*, MPa	Compression tests	
			σ_s, MPa	ε, %
AK10M2N without HT	1100	1135	464	24
AK10M2N after HT (hardening 515 °C, 2 h + aging 190 °C, 2 h)	1360	1363	558	33
AK10M2N–10%TiC without HT	1520	1502	447	22
AK10M2N–10%TiC after HT (hardening 515 °C, 1 h + aging 190 °C, 2 h)	1710	1779	587	20

Table 3. **Corrosion parameters of the AK10M2N alloy and the AK10M2N–10%TiC composite material**

Таблица 3. Коррозионные показатели сплава АК10М2Н и композиционного материала АК10М2Н–10%TiC

Sample composition	Mass loss, g	Mass loss per unit area, kg/m^2	Change in sample thickness, m	Corrosion rate, g/(m^2·h)	Corrosion depth index, mm/year
AK10M2N without HT	0.0009	0.0003	0.0001	0.0012	0.000004
AK10M2N after HT (hardening 515 °C, 2 h + aging 190 °C, 2 h)	0.0038	0.0012	0.0004	0.0050	0.000020
AK10M2N–10%TiC without HT	0.0238	0.0076	0.0027	0.0316	0.000009
AK10M2N–10%TiC after HT (hardening 515 °C, 1 h + aging 190 °C, 2 h)	0.2193	0.0698	0.0245	0.2910	0.000090

Table 4. **Results of comparative tribological tests of the AK10M2N alloy and the AK10M2N–10%TiC composite material**

Таблица 4. Результаты сравнительных триботехнических испытаний сплава АК10М2Н и композиционного материала АК10М2Н–10%TiC

Sample	Wear rate, μm/h	Friction coefficient	Self-heating temperature at friction, °C
AK10M2N without HT	22.25	0.57	75
AK10M2N after HT (hardening 515 °C, 2 h + aging 190 °C, 2 h)	4.25	0.12	70
AK10M2N–10%TiC without HT	0.5	0.09	60
AK10M2N–10%TiC after HT (hardening 515 °C, 1 h + aging 190 °C, 2 h)	0.25	0.03	66

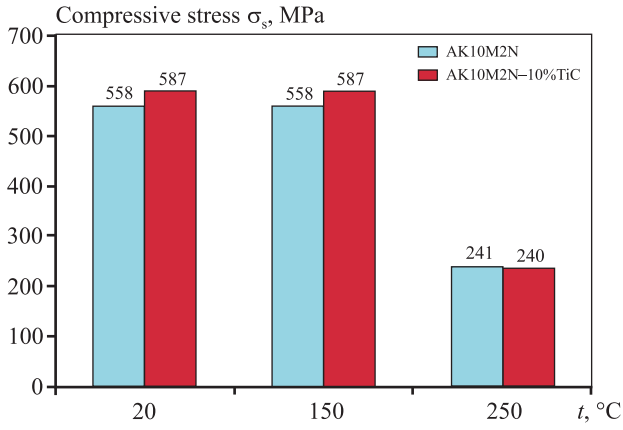


Fig. 6. Evaluation of the heat resistance of the AK10M2N alloy and the AK10M2N–10%TiC composite material after heat treatment according to the optimal mode

Рис. 6. Оценка жаропрочности сплава АК10М2Н и композиционного материала АК10М2Н–10%TiC после термической обработки по оптимальному режиму

it is the case with the matrix alloy, it does not exceed 0.001 mm/year, so we can state that the obtained materials are quite resistant to corrosion [38].

For the final analysis of tribological characteristics of prototypes, the conditions for operating friction surfaces "piston-piston pin" in the internal combustion engine were modeled (Table 4).

During the tests, the AK10M2H sample showed a tendency for seizure at friction and deep grooves were detected along the direction of friction, characteristic of abrasive wear. Heat treatment of the AK10M2N alloy significantly reduced the rate of wear and tearing, but the friction coefficient also increased by the end of the test. Reinforcement of the matrix alloy with the titanium carbide phase led to a significant improvement of tribological characteristics of the AK10M2N—10%TiC composite, however, it is heat treatment that enables to achieve the minimum values of wear rate and friction coefficient.

Conclusion

The conducted studies showed that heat treatment of composite materials with a silumin AK10M2N matrix reinforced with a highly dispersed titanium carbide phase is an effective way to control their structure and properties. The study established that SHS of the AK10M2N-10%TiC composite, followed by hardening at 515 °C and aging at 190 °C, produces a practically non-porous material and increases hardness by 35 HB, microhardness by 416 MPa, and compression yield stress by 29 MPa. Additionally, it reduces the wear rate by 17 times and the friction coefficient by 4 times, while maintaining the values of the coefficient of thermal linear expansion, corrosion resistance, and heat resistance at levels typical for the matrix alloy.

References

1. Belov N.A. Phase composition of aluminum alloys. Moscow: MISIS, 2009. 234 p. (In Russ.).
Белов Н.А. Фазовый состав алюминиевых сплавов. М.: МИСИС, 2009. 234 с.
2. Nyafkin A.N., Kosolapov D.V., Kurbatkina E.I. Influence of thermomechanical treatment on the formation of the structure in dispersed-reinforced aluminum alloy-based metal composite materials. *Powder Metallurgy and Functional Coatings.* 2023;17(3):22—29.
https://doi.org/10.17073/1997-308X-2023-3-22-29
Няфкин А.Н., Косолапов Д.В., Курбаткина Е.И. Влияние деформационно-термической обработки

на формирование структуры дисперсно-армированного металлического композиционного материала на основе алюминиевого сплава. *Известия вузов. Порошковая металлургия и функциональные покрытия*. 2023;17(3):22—29.
https://doi.org/10.17073/1997-308X-2023-3-22-29

3. Golla C.B., Babar Pasha M., Rao R.N., Ismail S., Gupta M. Influence of TiC Particles on mechanical and tribological characteristics of advanced aluminium matrix composites fabricated through ultrasonic-assisted stir casting. *Crystals*. 2023;13:1360.
https:// doi.org/10.3390/cryst13091360
4. Kurbatkina E.I., Kosolapov D.V., Khodykin L.D., Nigmetov M.S. Study of the influence of silicon additives on the phase composition of aluminum composite materials reinforced with silicon carbide particles. *Aviatsionnyye materialy i tekhnologii*. 2014;S6:35—38. (In Russ.).
https:// doi.org/10.18577/2071-9140-2014-0-s6-35-38
Курбаткина Е.И., Косолапов Д. В., Ходыкин Л.Д., Нигметов М.С. Исследование влияния добавки кремния на фазовый состав алюминиевых композиционных материалов, армированных частицами карбида кремния. *Авиационные материалы и технологии*. 2014;S6:35—38.
https:// doi.org/10.18577/2071-9140-2014-0-s6-35-38
5. Mikheyev R.S., Chernyshova T.A. Aluminum-matrix composite materials with carbide hardening for solving problems of new technology. Moscow: Izdaniye RFFI, 2013. 353 p. (In Russ.).
Михеев Р.С., Чернышова Т.А. Алюмоматричные композиционные материалы с карбидным упрочнением для решения задач новой техники. М.: Издание РФФИ, 2013. 353 с.
6. Kurganova Yu. A., Kolmakov A. G. Structural metal matrix composite materials: textbook. Moscow: MGTU im. N. E. Baumana, 2015. 141 p. (In Russ.). https://urss.ru/images/add_ru/202831-1.pdf (accessed: 19.01.2024).
Курганова Ю.А., Колмаков А.Г. Конструкционные металломатричные композиционные материалы: Учебное пособие. М.: Издательство МГТУ им. Н.Э. Баумана, 2015. 141 с. https://urss.ru/images/add_ru/202831-1.pdf (дата обращения: 19.01.2024).
7. Arunkumar S., Subramani Sundaram M., Suketh Kanna K.M., Vigneshwara S.A review on aluminium matrix composite with various reinforcement particles and their behavior. *Materials Today: Proceedings*. 2020;33(1):484—490.
https://doi.org/10.1016/j.matpr.2020.05.053
8. Luts A.R., Sherina Yu.V., Amosov A.P., Kachura A.D. Liquid matrix SHS manufacturing and heat treatment of Al—Mg composites reinforced with fine titanium carbide. *Izvestiya. Non-Ferrous Metallurgy*. 2023;29(4):70—86.
https://doi.org/10.17073/0021-3438-2023-4-70-86
Луц А.Р., Шерина Ю.В., Амосов А.П., Качура А.Д. Жидкофазное получение методом СВС и термическая обработка композитов на основе алюминиево-магниевых сплавов, упрочненных высокодисперсной фазой карбида титана. *Известия вузов. Цветная металлургия*. 2023;4:70—86.
https://doi.org/10.17073/0021-3438-2023-4-70-86
9. Nath H., Amosov A.P. SHS amidst other new processes for in-situ synthesis of Al-matrix composites: A review. *International Journal of Self-Propagating High-Temperature Synthesis*. 2016;(25):50—58.
http://doi.org/10.3103/S106138621601009X
10. Amosov A.P., Luts A.R., Latukhin E.I., Ermoshkin A.A. Application of SHS processes for in situ production of aluminum-matrix composite materials discretely reinforced with nanoscale titanium carbide particles: Overview. *Russian Journal of Non-Ferrous Metals*. 2016;57(2):106—112.
http://doi.org/10.3103/S1067821216020024
Амосов А.П., Луц А.Р., Латухин Е.И., Ермошкин А.А. Применение процессов СВС для получения in situ алюмоматричных композиционных материалов, дискретно армированных наноразмерными частицами карбида титана: Обзор. *Известия вузов. Цветная металлургия*. 2016;(1):39—49.
http://doi.org/10.17073/0021-3438-2016-1-39-49
11. Kurganova Yu.A., Kolmakov A.G., Yijin Chen, Kurganov S.V. Study of the mechanical properties of promising aluminum matrix composite materials reinforced with SiC and Al_2O_3. *Materialovedeniye*. 2021;6:34-38. (In Russ.).
http://doi.org/10.31044/1684-579X-2021-0-6-34-38
Курганова Ю.А., Колмаков А.Г., Ицзинь Чэнь, Курганов С.В. Исследование механических свойств перспективных алюмоматричных композиционных материалов, армированных SiC и Al_2O_3. *Материаловедение*. 2021;6:34—38.
http://doi.org/10.31044/1684-579X-2021-0-6-34-38
12. Mikheev R.S., Kobernik N.V., Kalashnikov I.E., Bolotova L.K., Kobeleva L.I. Tribological properties of antifriction coatings based on composite materials. *Perspektivnyye materialy*. 2015;3:48—54.
Михеев Р.С., Коберник Н.В., Калашников И.Е., Болотова Л.К., Кобелева Л.И. Триботехнические свойства антифрикционных покрытий на основе композиционных материалов. *Перспективные материалы*. 2015;3:48—54.
13. Kurbatkina E.I., Shavnev A.A., Kosolapov D.V., Gololobov A.V. Features of thermal treatment of composite materials with aluminum matrix (Review). *Trudy*

VIAM. 2017;11:82—97. URL: http://viam-works.ru/ru/articles?year=2017&num=11 (accessed: 19.01.2024). (In Russ.).
http://dx.doi.org/ 10.18577/2307-6046-2017-0-11-9-9
Курбаткина Е.И., Шавнев А.А., Косолапов Д.В., Гололобов А.В. Особенности термической обработки композиционных материалов с алюминиевой матрицей (обзор). *Труды ВИАМ*. 2017;11:82—97. URL: http://viam-works.ru/ru/articles?year=2017&num=11 (дата обращения: 19.01.2024).
http://dx.doi.org/ 10.18577/2307-6046-2017-0-11-9-9

14. Prusov E.S., Panfilov A.A., Kechin V.A. Role of powder precursors in production of composite alloys using liquid-phase methods. *Russian Journal of Non-Ferrous Metals*. 2017; 58(3):308—316.
http://doi.org/10.3103/S1067821217030154
Прусов Е.С., Панфилов А.А., Кечин В.А. Роль порошковых прекурсоров при получении композиционных сплавов жидкофазными методами. *Известия вузов. Порошковая металлургия и функциональные покрытия*. 2016;2:47—58.
http://doi.org/10.17073/1997-308X-2016-2-47-58
15. Aksenov A.A. Optimization of the composition and structure of composite materials on aluminum and copper bases, obtained by liquid-phase methods and mechanical alloying: Abstract of dissertation of Dr. Sci. (Eng.). Moscow: MISIS, 2007. (In Russ.).
Аксенов А.А. Оптимизация состава и структуры композиционных материалов на алюминиевой и медной основах, получаемых жидкофазными методами и механическим легированием: Автореф. дис. ... д.т.н. М.: МИСИС, 2007.
16. Churyumov A.Y., Mohamed I.A. Microstructure and mechanical properties of composite materials based on the Al—Si—Mg system reinforced with sic particles and obtained by pressure crystallization. *Metal Science and Heat Treatment*. 2019; 60(9-10):571—573.
http://doi.org/10.1007/s11041-019-00321-5
Чурюмов А.Ю., Мохамед И.А. Микроструктура и механические свойства композиционных материалов на основе системы Al—Si—Mg армированных частиц SiC и полученных кристаллизацией под давлением. *Металловедение и термическая обработка металлов*. 2018;9:19—22.
17. Joseph O.O., Afolalu A.S., Abioye A.A., Agbo S.E., Olatunde S.F., Omotehinwa O.S. Effect of TiC addition on the mechanical properties and microstructure of Al—Si alloy. *Materials Today: Proceedings*. 2021;38(2): 784—788.
https://doi.org/10.1016/j.matpr.2020.04.544
18. Honglei Xi, Wenlong Xiao, Heng Li, Yu Fu, Ge Yi, Juhong Qie, Xiaozhao Ma, Chaoli Ma. Effects of sub-micron-sized TiC particles on the microstructure modification and mechanical properties of Al—Si—Mg alloy. *Journal of Alloys and Compounds*. 2023; 968:171963.
https://doi.org/10.1016/j.jallcom.2023.171963
19. Reese C.W., Gladstein A., Fedors J.M., De Andrade V., Mishra B., Shahani A.J., Taub A.I. In situ Al—TiC composites fabricated by self-propagating high-temperature reaction: insights on reaction pathways and their microstructural signatures. *Metallurgical and materials transactions*. 2020;51A:3587—3600.
https://doi.org/10.1007/s11661-020-05786-1
20. Mengxian Zhang, Yanqiu Huo, Li Ma. In situ TiC ceramic particles locally reinforced Al—Si matrix composites prepared by SHS-casting method from the Al—Si—Ti—C system. *International Journal of Applied Ceramic Technology*. 2014;11(4):723—731.
https://doi.org/10.1111/ijac.12097
21. Rui-Fen Guo, Ya Wang, Yun-Hai Ma, Ping Shen. Role of Si in the wetting of TiC by Al. *Journal of Materials Science*. 2021;56:7791—7798.
https://doi.org/10.1007/s10853-020-05496-4
22. López V.H., Scoles A., Kennedy A.R. The thermal stability of TiC particles in an Al7wt.%Si alloy. *Materials Science and Engineering*. 2003;A356:316—325.
https://doi.org/10.1016/S0921-5093(03)00143-6
23. Xia F., Liangc M.X., Gaoc X.S., Guo Y.C., Li J.P., Yang W., Zhang Z.K. Instability of in situ TiC particles in an Al—12Si alloy. *Journal of Materials Research and Technology*. 2020;9(5):11361—11369.
https://doi.org/10.1016/j.jmrt.2020.07.063
24. Ding Hai-min, Liu Xiang-fa. Influence of Si on stability of TiC in Al melts. *Transactions of Nonferrous Metals Society of China*. 2011;21:1465—1472.
https://doi.org/10.1016/S1003-6326(11)60882-0
25. Tang P., Zhou Y., Lai J. Lin Y., Lv S., Deng S. Preparation, Microstructure and mechanical properties of in-situ TiC/Al—Si—Fe aluminum matrix composites. *Transactions of the Indian Institute of Metals*. 2023;76:1893—1903. https://doi.org/10.1007/s12666-023-02885-6
26. Anilkumar V., Shankar K.V., Balachandran M., Joseph J., Nived S., Jayanandan J., Jayagopan J., Surya Balaji U.S. Impact of heat treatment analysis on the wear behaviour of Al—14.2Si—0.3Mg—TiC composite using response surface methodology. *Tribology in Industry*. 2021;43(4):590—602.
https://doi.org/10.24874/ti.988.10.20.04
27. Chen Ch.-L., Lin Ch.-H. A study on the aging behavior of Al6061 composites reinforced with Y_2O_3 and TiC. *Metals*. 2017;7(11). https://doi.org/10.3390/met7010011
28. Shuaihang Pan, Jie Yuan, Kaiyuan Jin, Narayanan Murali, Aaron Gladstein, Yuxin Zeng, Alan Taub, Xiaochun Li. Influence of Mg on reaction and properties

of Al—Si/TiC nanocomposites. *Materials Science and Engineering*. 2022;A840:142992.
https://doi.org/10.1016/j.msea.2022.142992

29. Pan S., Jin K., Wang T., Zhang Z., Zheng L., Umehara N. Metal matrix nanocomposites in tribology: Manufacturing, performance, and mechanisms. *Friction*. 2022;10:1596—1634.
https://doi.org/10.1007/s40544-021-0572-7
30. Prusov E.S., Deev V.B., Aborkin A.V., Ri E.K., Rakhuba E.M. Structural and morphological characteristics of the friction surfaces of in-situ cast aluminum matrix composites. *Journal of Surface Investigation*. 2021;15(6):1332—1337.
https://doi.org/10.1134/S1027451021060410
31. Sherina Yu.V., Luts A.R., Ibatullin I.D. Development of a composite material based on the AK10M2N alloy and study of its tribological properties. *Naukoyemkiye tekhnologii v mashinostroyenii*. 2022;2(128):11—16. (In Russ.).
https://doi.org/10.30987/2223-4608-2022-2-11-16
Шерина Ю.В., Луц А.Р., Ибатуллин И.Д. Разработка композиционного материала на основе сплава АК10М2Н и исследование его триботехнических свойств. *Наукоемкие технологии в машиностроении*. 2022;2(128):11—16.
https://doi.org/10.30987/2223-4608-2022-2-11-16
32. Арзамасов Б.Н., Сидорин И.И., Косолапов Г.Ф., Макарова В.И., Мухин Г.Г., Рыжов Н.М., Силаева В.И., Ульянова В.И. Материаловедение. М.: Машиностроение, 1986. 384 с.
Arzamasov B.N., Sidorin I.I., Kosolapov G.F., Makarova V.I., Mukhin G.G., Ryzhov N.M., Silaeva V.I., Ulyanova V.I. Material science. Moscow: Mashinostroenie, 1986. 384 p. (In Russ.).
33. Muratov V.S. Directed formation of the structural state of cast billets from aluminum alloys. Part 1. The influence of crystallization cooling on the structure and properties of cast billets. *Zagotovitel'nyye proizvodstva v mashinostroyenii*. 2003;5:3—8. (In Russ.).
Муратов В.С. Направленное формирование структурного состояния литых заготовок из алюминиевых сплавов. Часть 1. Влияние кристаллизационного охлаждения на структуру и свойства литых заготовок. *Заготовительные производства в машиностроении*. 2003;5:3—8.
34. Man Zhu, Zengyun Jian, Gencang Yang, Yaohe Zhou. Effects of T6 heat treatment on the microstructure, tensile properties, and fracture behavior of the modified A356 alloys. *Materials and Design*. 2012;36:243—249.
https://doi.org/10.1016/j.matdes.2011.11.018
35. Nikitin K.V., Nikitin V.I., Timoshkin I.Yu. The influence of modifiers on the change in the mechanical properties of silumins. *Izvestiya. Non-Ferrous Metallurgy*. 2017;3:72—76. (In Russ.).
https://dx.doi.org/10.17073/0021-3438-2017-3-72-76
Никитин К.В., Никитин В.И., Тимошкин И.Ю. Влияние модификаторов на изменение механических свойств силуминов. *Известия вузов. Цветная металлургия*. 2017; 3:72—76.
https://dx.doi.org/10.17073/0021-3438-2017-3-72-76
36. Nikitin K.V., Nikitin V.I., Kripovalov D.S. Modification of AK10M2N piston alloy with fine-crystalline alloys and remelting. *Liteyshchik Rossii*. 2013;10:28—31. (In Russ.).
Никитин К.В., Никитин В.И., Кривопалов Д.С. Модифицирование поршневого сплава АК10М2Н мелкокристаллическими лигатурами и переплавами. *Литейщик России*. 2013;10:28—31.
37. Nyafkin A.N., Shavnev A.A., Kurbatkina E.I., Kosolapov D.V. Study of the influence of silicon carbide particle size on the temperature coefficient of linear expansion of a composite material based on an aluminum alloy. *Trudy VIAM*. 2020;86:41—49. (In Russ.).
https://dx.doi.org/ 10.18577/2307-6046-2020-0-2-41-49
Няфкин А.Н., Шавнев А.А., Курбаткина Е.И., Косолапов Д.В. Исследование влияния размера частиц карбида кремния на температурный коэффициент линейного расширения композиционного материала на основе алюминиевого сплава. *Труды ВИАМ*. 2020;86:41—49.
https://dx.doi.org/ 10.18577/2307-6046-2020-0-2-41-49
38. Perelygin Yu. P., Los I. S., Kireev Yu. S. Corrosion and protection of metals from corrosion. Penza: PGU, 2015. 88 p. URL: https://elib.pnzgu.ru/files/eb/u36mWX4yGz0I.pdf (accessed: 19.01.2024). (In Russ).
Перелыгин Ю. П., Лось И.С., Киреев С.Ю. Коррозия и защита металлов от коррозии. Пенза: Изд-во ПГУ, 2015. 88 с. URL: https://elib.pnzgu.ru/files/eb/u36mWX4yGz0I.pdf (дата обращения: 19.01.2024).

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