Elaboration of technological parameters for the recycling of cast aluminum matrix composites

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This study worked out the temperature-time parameters for processing conditioned waste of cast aluminum matrix composites with exogenous carbide phases through direct remelting. Using mathematical planning of the experiment and statistical analysis, it was found that the main factor influencing the change in the mechanical and tribological properties of composite materials during remelting is the duration of melt exposure before pouring. Using the example of the composite material AlSi12 + 10 vol.% SiC, it was demonstrated that, in general, an exposure duration of up to 15 min does not critically affect the change in the properties of aluminum matrix composites during remelting. However, a further increase in the exposure duration is accompanied by a significant decrease in hardness and compressive strength, as well as a significant scatter of friction coefficient values under dry sliding friction conditions. An analysis of the reasons for the change in the nature of the mechanical and tribological behavior of cast composite materials at various temperature-time parameters of remelting was carried out based on consideration of the characteristics of the properties of recycled composites in relation to their structure. The results obtained allow us to recommend reducing the duration of liquid-phase contact of the components at elevated temperatures to maximize the preservation of the level of properties of aluminum matrix composites after recycling via remelting.

Key words: cast aluminum matrix composites, recycling, remelting, factorial experimental design, mechanical and tribological properties

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Introduction

In key sectors of modern industry, there is a steady increase in the need for new high-tech materials that can comprehensively satisfy various, often contradictory requirements under difficult operating conditions of machine parts and mechanisms. In this regard, the focus of attention of researchers and practitioners remains on the problems of searching for compositions, developing industrially scalable technologies for obtaining advanced materials and manufacturing final products to meet current and future market demands, and the successful solution of these problems determines the competitiveness of enterprises in a rapidly changing world [1]. The development and mastery of new structural and functional materials provides significant economic advantages, helping to reduce material consumption and increase the reliability and durability of machinery and equipment, reduce service life between repairs, and increase labor productivity, which ultimately leads to improved economic performance of manufacturing enterprises and sustainable development of industry in general [2, 3].

A special place among promising materials is occupied by cast metal matrix composites based on aluminum alloys, the distinctive feature of which is the possibility of their development for the given operating conditions of future products by designing the required properties of the material at an early stage of its creation [4, 5]. This is achieved, in particular, through a scientifically based selection of reinforcing and alloying components, volume fraction, fractional and morphological characteristics of reinforcement, its spatial distribution in the volume of the cast part, etc. [6]. Experimental data accumulated to date indicate that the most important characteristics of cast composite materials are high compressive strength, hardness, specific stiffness, wear resistance, and in these indicators, they are significantly superior to standard aluminum alloys [7–10]. These advantages determine the prospects for the use of aluminum matrix composites for the industrial production of cast parts of various types, operating under conditions of intense wear and compressive loads in wide temperature and force operating ranges [11–13]. At the same time, the level of technological properties of cast composite materials containing up to 20 vol.% of the reinforcing phase, as a rule, are sufficient

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to produce castings using gravity casting methods, which allows us to consider such technologies as universal and adaptable to the production conditions of most foundries. However, the scale and pace of industrial development of aluminum matrix composites, especially in developing countries, still remain relatively low.

Experience shows that expanding the volumes and areas of commercial use of aluminum matrix composites is associated with the need to solve a number of interrelated technological and economic problems [14]. Difficulties in producing cast aluminum matrix composites, which arise primarily due to poor wettability of exogenous ceramic reinforcements with metal melts, have now been quite successfully overcome through preliminary preparation of particles, rational alloying of matrix alloys and optimization of parameters of the mechanical stirring process [15, 16], as well as through the use of additional methods for processing composite melts, for example, the imposition of various physical influences [17]. At the same time, a significant limiting factor remains the insufficient development of technological issues for recycling aluminum matrix composite materials, which entails irrecoverable losses of materials in the form of production waste and increases the cost of the final product from them, since the accumulated waste is not returned to the production cycle [18]. Cast aluminum matrix composites with exogenous reinforcements have a thermodynamically nonequilibrium nature, which leads to the likelihood of degradation of the reinforcing phase and the formation of harmful intermediate phases due to physical and chemical processes of interaction of components during the primary production or secondary processing of materials using metallurgical technologies [19]. Despite some progress in studying the recyclability of aluminum matrix composites of various compositions and identifying the peculiarities of the behavior of exogenous reinforcing phases during repeated remelting [20], there is still a critical lack of specific practical recommendations for choosing modes for processing waste cast composite materials by direct remelting. Along with this, reliable information about the influence of remelting on the quality of cast aluminum matrix composites is necessary when organizing production sites for the production of certified charge for the supply of ingots to foundries and metallurgical enterprises that are not equipped with specialized technological equipment for producing primary composite materials.

The objective of this study is to establish the temperature-time parameters for remelting aluminum matrix composites reinforced with exogenous SiC carbide phases, employing the method of mathematical experimental design, and to identify the significant factors influencing changes in the mechanical and tribological properties of the composites during the remelting process.

Materials and Methods

Industrial aluminum alloy AlSi12 (GOST 1583–93) was used as a matrix alloy to produce recycled aluminum matrix composites; powdered particles of silicon carbide (main fraction 75–63 μm) served as exogenous reinforcing components. Melting was carried out in alundum crucibles with a capacity of up to 1 kg (for aluminum) in a vertical electric resistance furnace of the GRAFICARBO type (Italy). All charge materials and tools were preheated in a furnace at a temperature of 150–170 °C. The powder component of the charge was subjected to preliminary heat treatment for 2 hours at 700 °C to remove adsorbed moisture and other surface contaminants. The matrix alloy was used as delivered, loaded in pieces into a furnace heated to 600–700 °C and overheated to 850 °C. Mechanical mixing of particles was carried out using a four-blade impeller made of AISI 316 stainless steel (ASTM A831) with a protective coating. After removing the slag, a sample of powder was fed into the zone of mechanical mixing of the melt based on a nominal content of 10 vol.% in the finished composite. The immersion of a rotating impeller under the surface of the liquid metal was accompanied by the formation of flows that facilitate the transfer of supplied particles from the surface into the volume of the matrix melt. The mixing time was 10 minutes at an impeller rotation speed of 300 rpm. Upon completion of the introduction of particles, the slag was again removed from the surface of the melt and the resulting composite was poured at a temperature of 750 °C into a vertical steel mold to obtain ingots with a diameter of 20 mm and a height of 100 mm.

Investigations to establish the influence of melt overheating temperature and holding time on the mechanical and tribological properties of recycled composite materials was carried out using methods of mathematical design of experiments (DoE). The composites were remelted without the use of an impeller, and the melt was thoroughly mixed with a graphite rod before casting to eliminate possible structural heterogeneity. The smelting temperature conditions were monitored throughout the experiment with a submersible K-type thermocouple using a ViER-104K recorder. All experiments were carried out with uniform duplication; for each value of the response function, three parallel experiments on remelting the composite were carried out. The obtained data on the properties of recycled composite materials were processed in the Minitab statistical software package. When developing the experimental program, we used a two-level full factorial design. The levels of experimental factors are given in **Table 1**. When varying the overheating temperature, values were chosen that, as a rule, are extreme in the processes of liquid-phase production of metal matrix composites based on aluminum alloys using the stir casting method. To visualize the

Table 1
Initial data for experiments

Factors		Levels of variation			
		–1	0	+1	ΔX_i
Overheating temperature (T), °C	X_1	800	850	900	50
Exposure duration (t), min	X_2	5	20	35	15

results in each case, response surfaces and contour plots were constructed.

The structure of the resulting materials in the cast state was studied on unetched sections using an Altami MET 1T metallographic microscope (Russia). The hardness of the samples was measured on the *HRB* scale at a load of 1000 N using a Time Group TH300 hardness tester, and the result obtained was averaged over data from at least ten measurements. Mechanical compression tests were carried out on a Time Group WDW-100E universal testing machine with a loading speed of 0.1 s^{-1} at room temperature. Cylindrical samples for compression tests with a diameter of 6 mm were obtained by electrical discharge cutting of ingots on a Mitsubishi BA8 machine.

To carry out wear resistance tests, disc-shaped samples with a thickness of 5 mm and a diameter of 20 mm were cut from the ingots. Tests were carried out according to the “stationary ball (100Cr6) – rotating disk (sample)” scheme using a TRB tribometer (CSM Instruments, Switzerland) under dry friction conditions at room temperature in accordance with international standards ASTM G99-959 and DIN50324. The linear rotation speed was 20 cm/s with a load on the indenter of 10 N, the friction path length was 300 m, and the radius was 5 mm. The friction coefficient values were recorded continuously depending on the length of the friction path and processed using the InstrumX program. Wear resistance was assessed by the change in sample mass before and after testing with an accuracy of $\pm 10^{-4}$ g.

When determining the properties and characteristics of cast composite materials during direct measurements, for each series of experiments, the arithmetic mean of the obtained values of the measured value was calculated, as well as the confidence limits of the error of the results.

Results and Discussion

Fig. 1 shows the response surfaces, **Fig. 2** — contour graphs reflecting the influence of the melt overheating temperature and holding time before casting on the change in properties during remelting of the composite material AlSi12 + 10 vol.% SiC.

Recovering regression coefficients for first-order predictive mathematical models:

$$HRB = 49.28 + 0.00833\ T + 0.00333\ t - 0.000267\ T \cdot t$$

$$CS = 362.1 + 0.9697\ T + 22.21\ t - 0.02853\ T \cdot t$$

$$COF = 0.8532 - 0.000615\ T + 0.001767\ t + 1 \cdot 10^{-6}\ T \cdot t$$

$$I_m = 4.867 - 0{,}003333\ T - 0.07333\ t + 0.000067\ T \cdot t$$

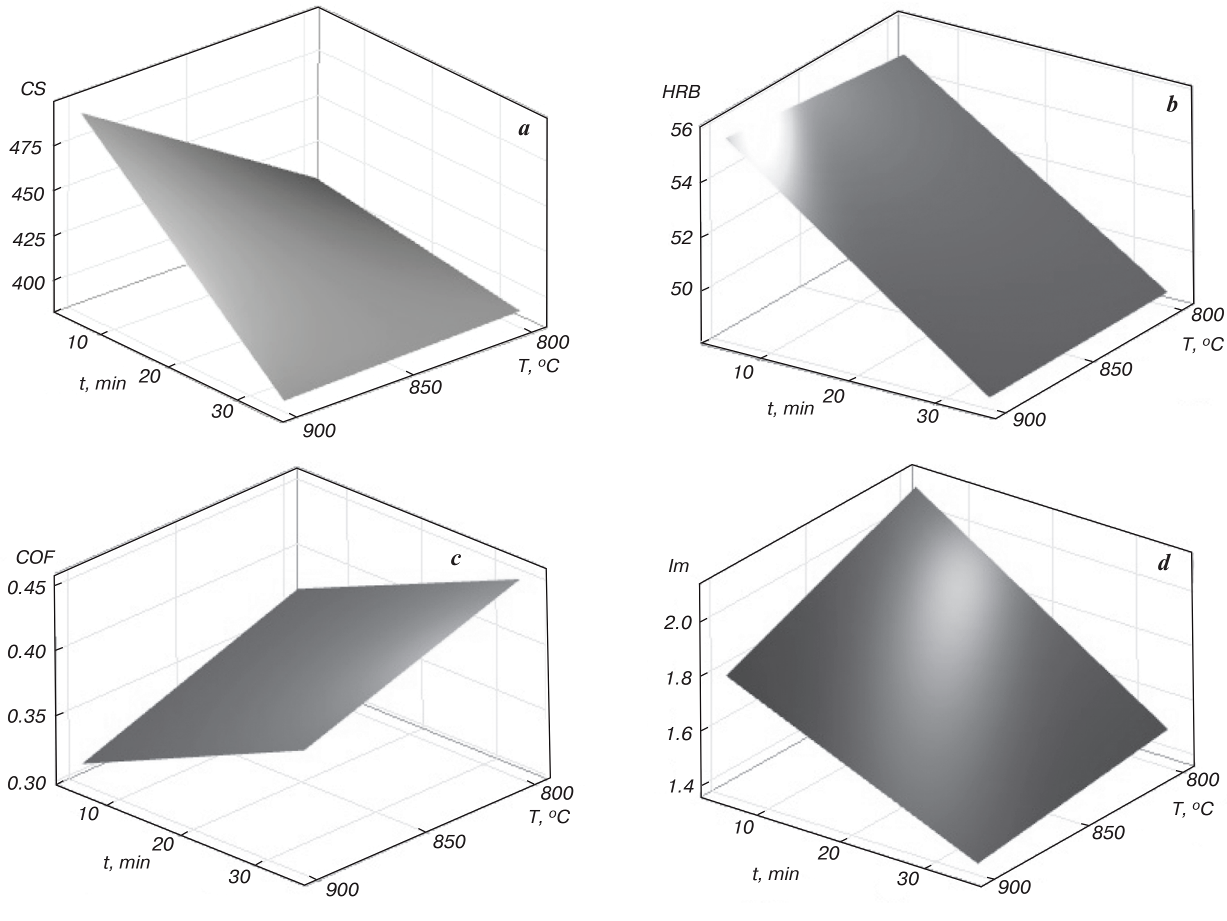

Fig. 1. Response surfaces showing the influence of the melt overheating temperature and holding time on the change in the properties of AlSi12 + 10 vol.% SiC during remelting:
a – hardness (HRB); *b* – compressive strength (CS), MPa; *c* – coefficient of friction (COF); *d* – mass wear (I_m), g

Analysis of the results obtained shows that in all cases, the predominant factor in changing the mechanical and tribological properties of cast metal matrix composites during recycling by remelting is the duration of melt exposure. Thus, for the composite AlSi12 + 10 vol.% SiC, a decrease in HRB hardness by 15...20% was noted with an increase in the melt holding time to 35 minutes, while an increase in the melt temperature to 900 °C had virtually no effect on the hardness values of the material. For compressive strength, a nonlinear nature of the change with increasing temperature and holding time was recorded, while the contour graphs showed a drop in values below 400 MPa with increasing holding time to 25...35 minutes. The dry friction coefficient increases from 0.36...0.38 at 800 °C and 5 minutes to values of more than 0.44 at 35 minutes. At the same time, mass wear decreases slightly from 1.9...2.1 g to values less than 1.5 g with increasing temperature to 900 °C and holding time to 35 minutes. The data obtained allow us to recommend, in order to maximize the preservation of the level of mechanical and operational properties of aluminum matrix composites after recycling by remelting, reducing the duration of liquid-phase contact of the components of the composition at elevated temperatures, which will help limit the interfacial reactions of the reinforcing particles with the matrix material. Judging by the data obtained, in general, a holding duration of up to 15 minutes does not critically affect the change in the mechanical and tribological properties of aluminum matrix composites during remelting, however, a further increase in holding duration is accompanied by a significant decrease in hardness and compressive strength.

To understand the potential reasons for changes in the nature of the mechanical and tribological behavior of cast composite materials at different temperature-time parameters of remelting, it is necessary to consider in more detail the features of the properties of recycled composites in relation to their structure. In particular, **Fig. 3** shows the change in the coefficient of friction of samples of cast composite materials AlSi12 + 10 vol.% SiC depending

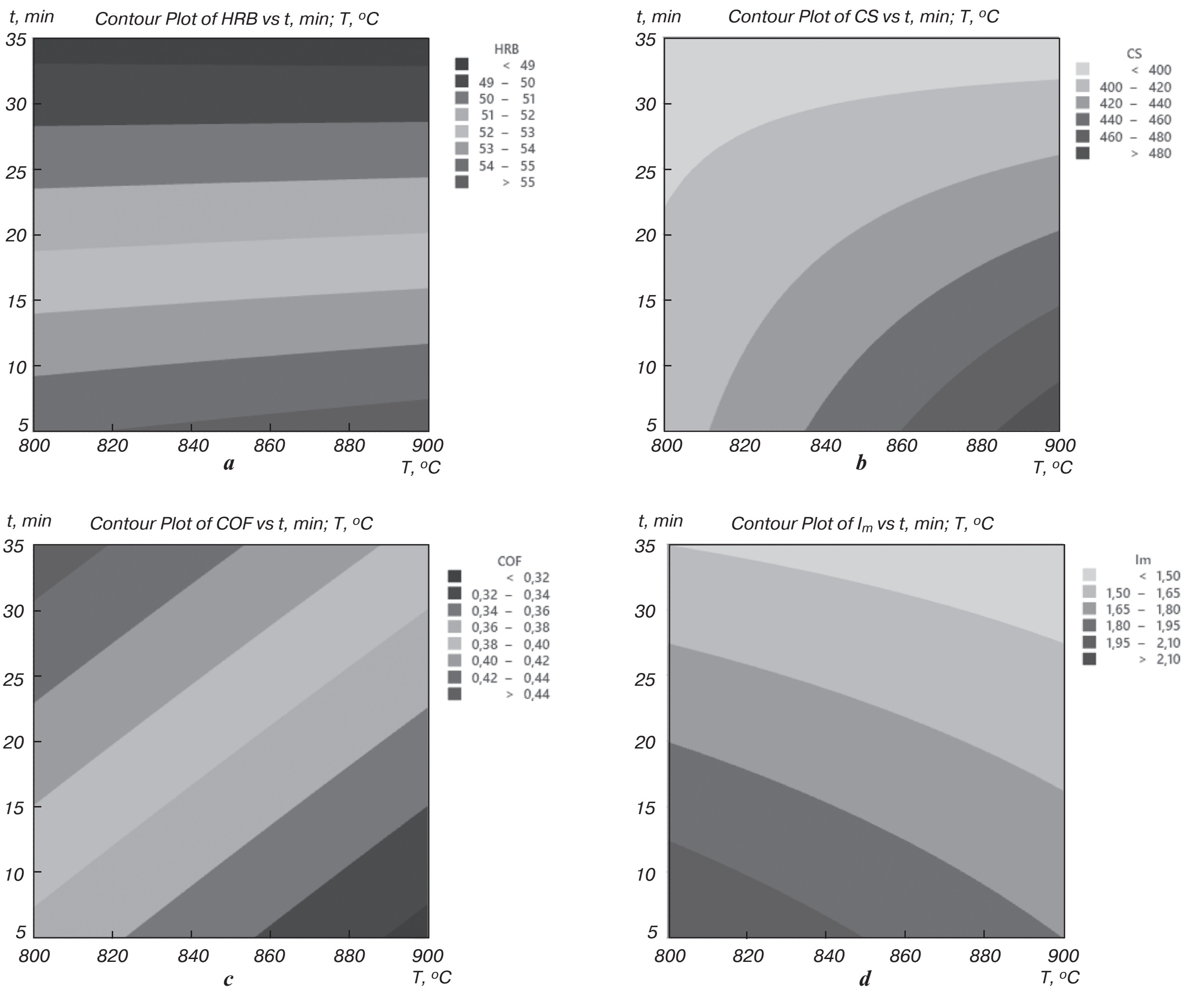

Fig. 2. Contour graphs showing the influence of the melt overheating temperature and holding time on the change in the properties of AlSi12 + 10 vol.% SiC during remelting:
a – hardness (HRB); *b* – compressive strength (CS), MPa; *c* –coefficient of friction (COF); *d* – mass wear (I_m), g

on the friction path at different overheating temperatures and the duration of exposure of the melt during remelting.

When the composite melt is held for 5 minutes, the nature of the change in the dry friction coefficient at overheating temperatures of 800 and 900 °C does not differ significantly, and the scatter of values is minimal, indicating stability in the friction and wear process along the entire path traversed by the counter body. The average values of the friction coefficient during overheating to 900 °C and short-term exposure are slightly lower, which may be due to some improvement in the uniformity of particle distribution in the cast structure due to a decrease in the viscosity of the melt. Remelting under optimized conditions can have a beneficial effect on the structure of composites due to the redistribution of reinforcing particles in the volume of the resulting cast workpiece, even in the absence of additional stirring of the melt with an impeller, as was previously proven by quantitative metallography methods on large samples of samples [21]. At the same time, the samples obtained by prolonged exposure of the melt for 35 min were characterized by a significant scatter in the values of the friction coefficient as they passed the friction path, especially after a distance of 200 m. Apparently, this may be due to the accumulation of crumbling particles of the reinforcing phase and fragments of oxide captivity, changing the nature of contact-friction interaction with the counter body. Presumably, as the friction process develops, the wear of such composites becomes adhesive in nature due to the propagation of cracks and delamination, which leads to significant fluctuations in the values of the friction coefficient and transition to scuffing [22]. Taken together, this leads to the fact that the average values of the friction coefficient are higher than when held for 5 min, and tend to increase with increasing distance traveled. Further detailed studies of structural changes in wear surfaces and debris fragments will allow us to establish the prevailing friction mechanisms depending on various influencing factors and further expand our understanding of the influence of remelting on the tribological characteristics of aluminum matrix composite materials.

Microstructural analysis of recycled aluminum matrix composites exposed to overheating temperatures of 800 and 900 °C for 5 min did not reveal any substantial differences **(Fig. 4)**. In turn, in the structure of samples obtained by prolonged exposure of the melt, regardless of the overheating temperature, the presence of fragments of

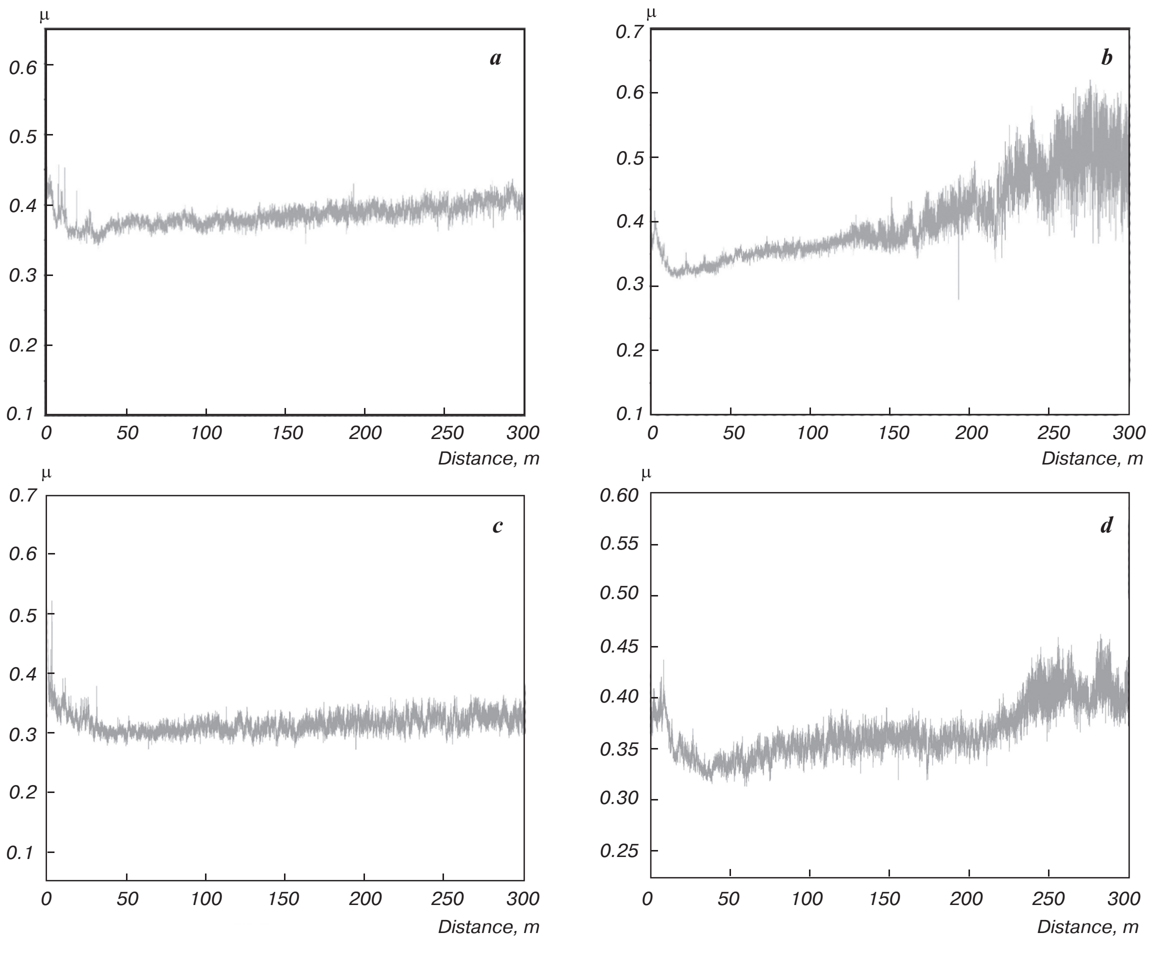

Fig. 3. Change in the coefficient of friction of samples of cast composite materials AlSi12 + 10 vol.% SiC depending on the friction path at different overheating temperatures and holding times:
a – 800 °C, 5 min; *b* – 800 °C, 35 min; *c* – 900 °C, 5 min; *d* – 900 °C, 35 min

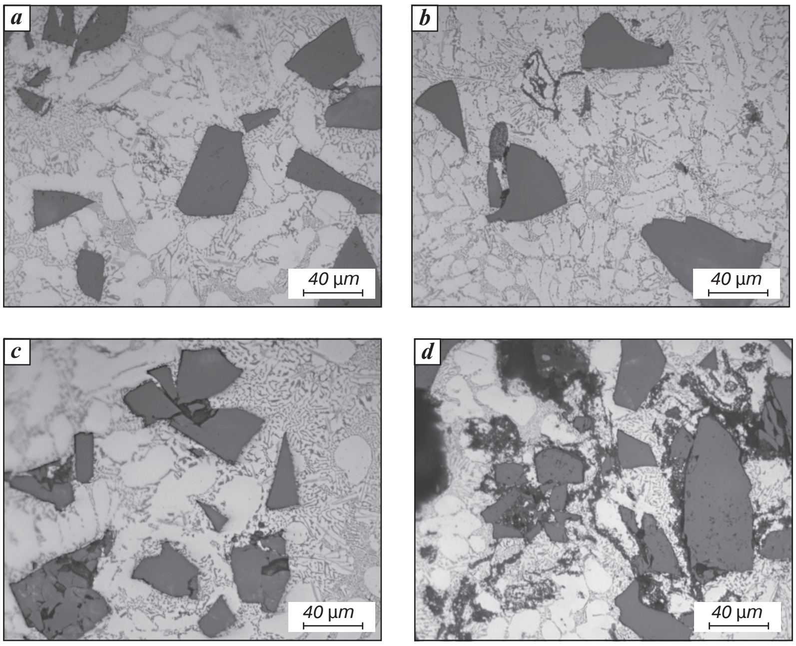

Fig. 4. Representative photographs of the microstructure of cast composite materials AlSi12 + 10 vol.% SiC at different overheating temperatures and holding times: *a* – 800 °C, 5 min; *b* – 800 °C, 35 min; *c* – 900 °C, 5 min; *d* – 900 °C, 35 min

oxide films was detected. Signs of initiation of interfacial reactions between the matrix and SiC particles according to a known mechanism [19], leading to the formation of a brittle phase of silicon carbide Al_4C_3, were observed only on samples obtained by holding melts at 900 °C for 35 min. In other cases, pure interphase boundaries were observed without any intermediate reaction products. In addition, the presence of relatively large pores was noted in the structure of the composites after prolonged high-temperature exposure, which may be one of the reasons for the decrease in the hardness of the material and peeling during dry friction.

In general, determining the most appropriate directions and methods for recycling cast aluminum matrix composites of various systems in all cases should be based on an understanding of the behavior of reinforcing particles under the conditions of the processing processes being implemented, including the nature of the interphase interaction of particles with the metal matrix, the processes of redistribution of particles during metallurgical processing, the formation of various types of casting defects. Making decisions on the commercial use of developed technologies for processing waste aluminum matrix composites, depending on their type and condition, requires an integrated approach, taking into account technical, economic and environmental factors. The results obtained indicate that for standard waste aluminum matrix composites, the Al – Si – SiC system in the form of used parts, defective castings, fragments of gating systems, etc. A completely effective processing method that does not require specialized expensive equipment can be direct remelting, subject to strict control of the temperature-time parameters of the process. At the same time, remelting composites using optimized technological conditions can have a beneficial effect on the properties of castings and ingots due to the redistribution of reinforcing particles in the as-cast structure.

Conclusions

Recommendations on technological parameters for processing waste cast composite materials using the remelting method have been developed. It has been shown that the predominant factor influencing the mechanical and tribological properties of cast aluminum matrix composites during recycling through remelting is the duration of the melt exposure before casting. It has been shown that, in general, a holding duration of up to 15 min does not critically affect the change in the properties of aluminum matrix composites during remelting. However, a further increase in holding duration is accompanied by a significant decrease in hardness and compressive strength, as well as a significant scatter in the values of the friction coefficient under conditions of dry sliding friction.

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