Structure and properties of cast in-situ metal matrix composites with strontium addition

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The paper investigates the influence of a strontium modifying additive in the range of 0.05 to 0.3 wt.% on the structure formation and tribological properties of cast aluminum matrix composites based on the pseudo-binary Al – Mg_2Si system (in the hypereutectic composition range). It is shown that strontium modification (0.2 wt.% Sr) of cast aluminum matrix composites Al + 15 wt.% Mg_2Si leads to a reduction in the average size of Mg_2Si reinforcing particles to 24 μm (by Feret diameter) with an aspect ratio of 1.28 and a particle distribution uniformity index in the cast material structure of 0.44. For a highly hypereutectic composition (25 wt.% Mg_2Si), strontium modification in the same amount results in a decrease in the average size of Mg_2Si particles to 44.8 μm and a change in their morphology to blocky, compact, and close to equiaxed, with a distribution uniformity index of 0.24. Further increase in the concentration of the modifying additive lead to some particle coarsening, likely due to the over-modification effect, as well as the precipitation of excess intermetallic phases with needle-like morphology. Tribological tests under dry friction conditions using a ball-on-disc scheme in conjunction with steel reveal a significant reduction in the coefficient of friction (by 25–30%) and mass wear (by more than an order of magnitude) for strontium-modified cast samples of Al – Mg_2Si composites.

Key words: cast aluminum matrix composites, strontium, modification, primary Mg_2Si crystals, pseudobinary eutectic, structural and morphological characteristics, tribological properties

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Introduction

Cast metal matrix composites based on aluminum alloys are promising for use as an alternative to many traditional alloys in the production of high-performance castings of various types [1–3]. This is attributed, in particular, to the possibility of significantly enhancing compressive strength, hardness, wear and abrasion resistance, damping capacity, and other mechanical and operational properties of materials through reinforcement with particles of high-modulus refractory compounds [4–6]. Variations in the volume fraction, size, morphology, spatial distribution of reinforcing components in the matrix material, as well as the chemical composition of the matrix by the content of alloying elements, offer broad potential opportunities for controlling the structure of cast composite materials and achieving the desired level of their mechanical properties and operational characteristics [7].

The limiting factor for the widespread commercial adoption of cast metal matrix composites and their integration into key industrial sectors, considering the provided techno-economic advantages of their usage, primarily lies in the significant technological complexities associated with introducing exogenous reinforcing particles into aluminum melts [8]. An alternative approach to obtaining cast metal matrix composites involves the controlled synthesis of endogenous (in-situ) reinforcing phases directly in the matrix melt through chemical reactions between the initial components or as a result of the precipitation of primary reinforcing phase particles during the melt crystallization [9]. Implementation of this approach to obtaining metal matrix composites with phases of crystallization origin is possible, in particular, in the production of cast materials based on the Al – Mg – Si system in the region of the quasi-binary section Al – Mg_2Si (mass ratio Mg : Si = 1.73 ... 1.74), in the hypereutectic region of which primary crystals of the Mg_2Si phase are released [10, 11].

The high tribological characteristics of cast aluminum matrix composites based on the Al – Mg_2Si system substantiate their prospects as an alternative to many traditional aluminum alloys, especially eutectic Al – Si alloys [12, 13]. However, the potential structural applications of such composites, especially for critical engineering components, are limited because the primary crystals of the Mg_2Si phase have relatively large sizes and a coarse dendritic morphology, which adversely affects mechanical properties and significantly reduces the overall attainable reinforcing effect [14]. In this context, to expand the industrial application of cast composites based on the Al – Mg_2Si system, it is necessary to search for rational options

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for their modifying processing aimed at purposefully controlling the structural-morphological parameters of the Mg_2Si reinforcing particles. Published works report significant positive effects achieved by modifying alloys and composites based on the Al – Mg_2Si system with small additions of rare-earth metals such as Ce, Nd, Pr, Eu, Ho, La, etc. [15–20]. At the same time, considering the high cost and, in some cases, low commercial availability of most rare-earth metals, there is significant interest in experimentally assessing the modifying efficiency of more available elements, particularly alkaline-earth metals.

The aim of the present work is to establish the influence of strontium modifying additive on the structure formation and change of tribological properties of cast aluminum matrix composites based on the Al – Mg_2Si pseudobinary system.

Materials and methods

To obtain cast aluminum matrix composites of the Al – Mg_2Si system, pure components were utilized: aluminum (≥99.99% Al), magnesium (≥99.9% Mg), and silicon (≥99.0% Si). Melting was performed in graphite crucibles with a capacity of up to 1 kg (by aluminum) in a resistance-type electric furnace of the GRAFICARBO model (Italy). The preheated furnace was loaded with primary aluminum, which was melted and superheated to a temperature of 750 ... 760 °C. Silicon and magnesium were added into the liquid aluminum at the same temperature. All charge materials and tools were preheated in the furnace at a temperature of 150 ... 155 °C. After dissolving all components and modifying with the Al – Sr master alloy (calculated for Sr content of 0.05, 0.1, 0.15, 0.2, 0.25, or 0.3 wt.%), the melt was stirred with a graphite rod and poured at 720 °C into a cylindrical steel mold with an internal diameter of 20 mm and a height of 100 mm. Cast metal matrix composites with Mg_2Si reinforcing phase content of 15 and 25 wt.% were fabricated.

Samples for comparative studies were cut at a distance of 15 mm from the lower end face of the obtained ingots. The structure of the obtained materials was examined on unetched specimens using the Altami MET 1T metallographic microscope (Russia) equipped with a Ximea MQ013CG-E2 digital camera. Statistical data on the parameters of reinforcing particles were obtained by processing randomly selected images of the specimen surface in ImageJ 1.53v software (NIH, Bethesda, MD, USA). The mathematical assessment of the uniformity of the distribution of reinforcing particles in the structure of composites was carried out using an original software based on the methodology detailed in a previous study [21], employing the index v, which is the ratio of the root mean square of the average number of particles per unit surface area to the average number of particles per unit surface area, ranging from 0 (perfectly uniform distribution) to 1 (clustered distribution).

To conduct wear resistance tests, samples were cut from ingots in the form of disks with a thickness of 5 mm and a diameter of 20 mm. The tests were performed using the “fixed ball (steel counterbody) – rotating disk (specimen)” scheme with a tribometer TRB (CSM Instruments, Switzerland) under dry friction conditions at room temperature, in accordance with international standards ASTM G99-959 and DIN50324. The linear rotational speed was set at 20 cm/s with a load on the indenter of 10 N, a friction path length of 300 m, and a radius of 5 mm. Friction coefficient values were continuously

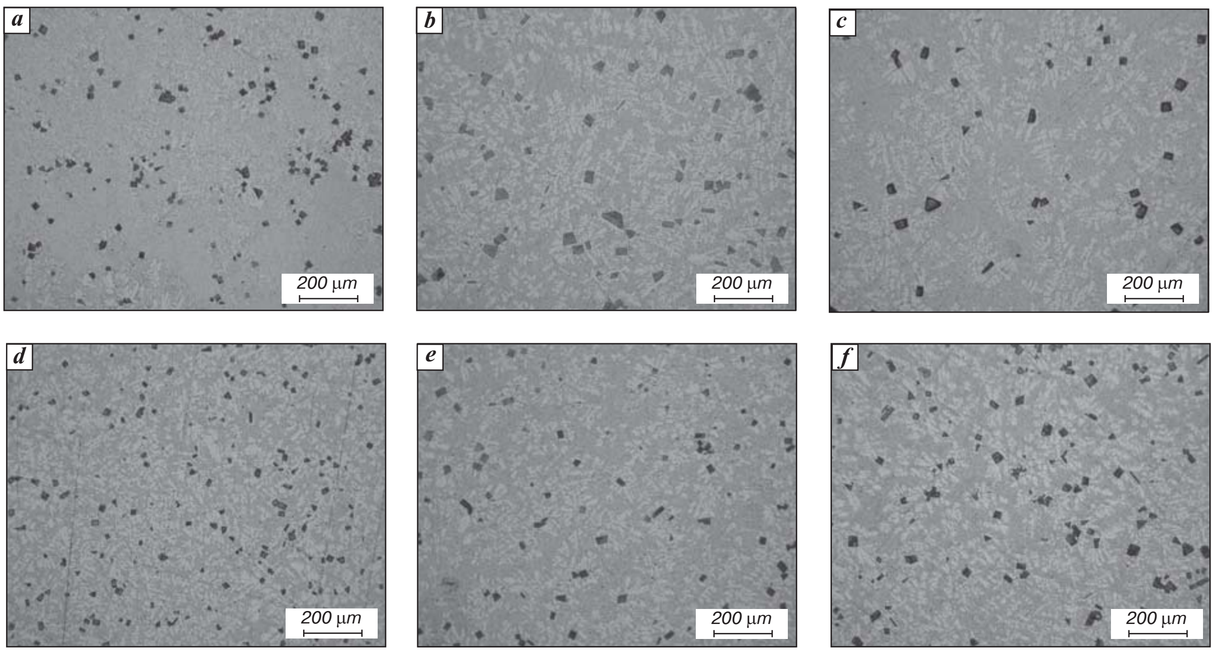

Fig. 1. Microstructure of Al + 15 wt.% Mg_2Si aluminum matrix composite after addition of strontium in the amount of 0.05 wt.% (*a*); 0.1 wt.% (*b*); 0.15 wt.% (*c*); 0.2 wt.% (*d*); 0.25 wt.% (*e*); 0.3 wt.% (*f*)

recorded based on the friction path length and processed using the InstrumX program. Wear resistance evaluation was conducted by measuring the change in sample mass before and after testing with an accuracy of $\pm 10^{-4}$ g.

Statistical analysis of experimental data and visualization of results were performed using the built-in features of Origin Pro and Microsoft Excel software packages. In the investigation of properties and characteristics of cast composite materials, direct measurements were employed for each experimental series, calculating the arithmetic mean of the obtained values of the measured quantity and establishing confidence intervals for the accuracy of the results.

Results and discussion

Fig. 1 illustrates characteristic microstructures of Al + 15 wt.% Mg_2Si aluminum matrix composite specimens in the as-cast condition, obtained with varying amounts of Sr addition. The structural constituents of the aluminum matrix composite with 15 wt.% Mg_2Si in its unmodified state consist of primary silicides identified by dark irregularly shaped inclusions, as well as a pseudo-binary eutectic (α + Mg_2Si), and a small number of α-solid solution dendrites. Quantitative metallographic analysis results (**Fig. 2**) indicate a significant influence of strontium on the sizes of primary Mg_2Si phase crystals. With

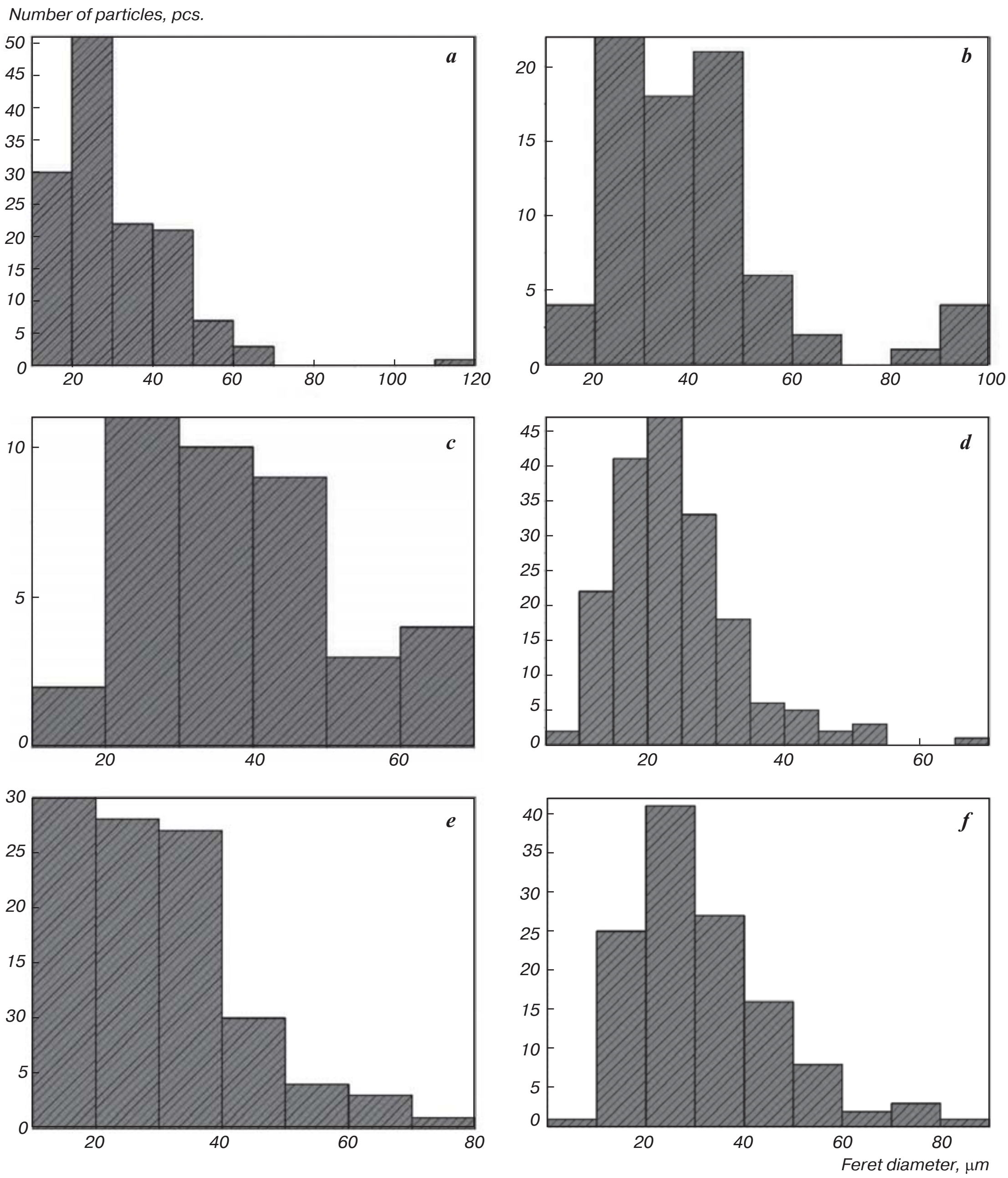

Fig. 2. Histograms of particle size distribution in the structure of Al + 15 wt.% Mg_2Si aluminum matrix composite after addition of strontium in the amount of 0.05 wt.% (*a*); 0.1 wt.% (*b*); 0.15 wt.% (*c*); 0.2 wt.% (*d*); 0.25 wt.% (*e*); 0.3 wt.% (*f*)

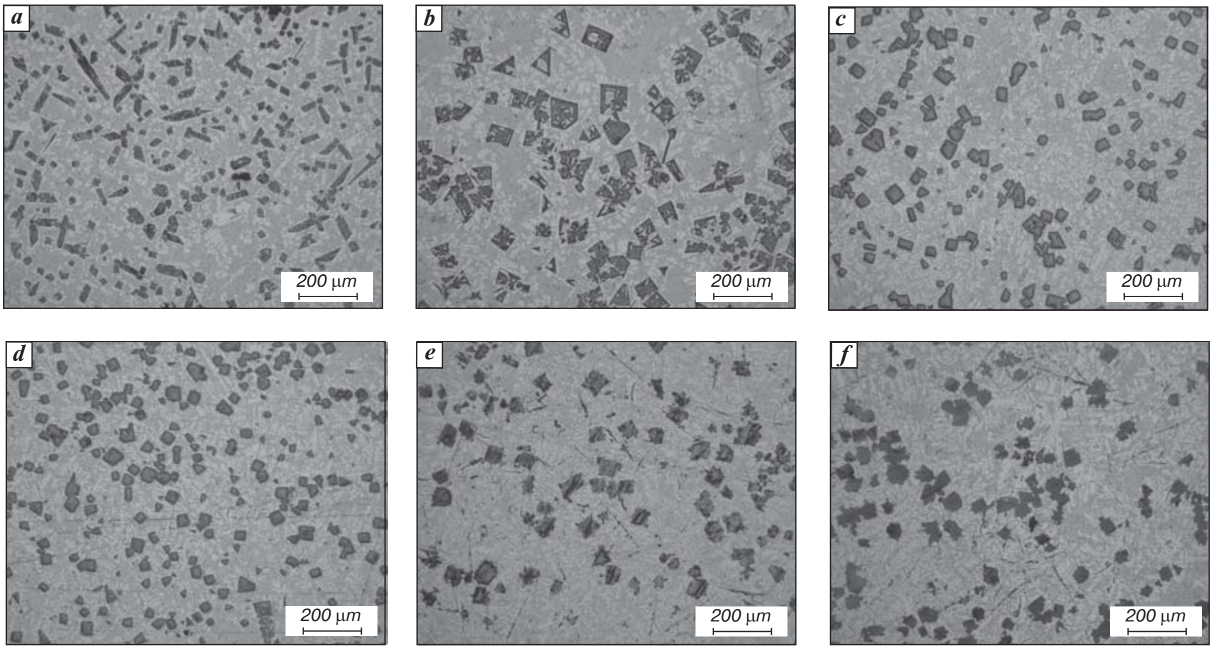

Fig. 3. Microstructure of Al + 25 wt.% Mg_2Si aluminum matrix composite after addition of strontium in the amount of 0.05 wt.% (*a*); 0.1 wt.% (*b*); 0.15 wt.% (*c*); 0.2 wt.% (*d*); 0.25 wt.% (*e*); 0.3 wt.% (*f*)

strontium content ranging from 0.05 to 0.15 wt.%, the average particle size, determined by Feret diameter, ranged from 30 to 40 μm. The smallest sizes were achieved at 0.2 wt.% Sr, where the Feret diameter was ~24 μm, and the aspect ratio was 1.28. Increasing the strontium concentration to 0.25 wt.% resulted in a slight increase in average particle size (to ~28.9 μm) but a decrease in the aspect ratio to 1.19. At 0.3 wt.% Sr, the average Mg_2Si particle size increased to ~32.3 μm with an aspect ratio of 1.44. Thus, for the Al + 15 wt.% Mg_2Si composite, a significant reduction in Mg_2Si particle sizes was observed with strontium modification, reaching a clear minimum at 0.2 wt.% Sr, followed by an increase in particle sizes with increasing in Sr content, presumably due to the over-modification effect. A distinct minimum at this strontium content was also noted for the uniformity index of reinforcing particle distribution (~0.44 compared to ~0.58 at 0.05 wt.% Sr and ~0.6 at 0.3 wt.% Sr). This is associated, in part, with the increase in the overall number of particles across the metallographic section.

The microstructure of Al + 25 wt.% Mg_2Si aluminum matrix composites in the as-cast condition with varying amounts of strontium addition is illustrated in **Fig. 3**. The micrographs in **Fig. 3, *a***, corresponding to 0.05 wt.% Sr, reveal dendrite fragments with a limited number of isolated particles. Overall, it is noteworthy that, from this perspective, the structure closely resembles that of unmodified Al + 25 wt.% Mg_2Si composites, typically characterized by primary Mg_2Si crystals forming large branched dendritic complexes, occasionally exceeding 200 μm in length, and a pseudo-eutectic (α + Mg_2Si). Simultaneously, the presence of strontium additive results in a reduction of the pseudo-binary eutectic fraction and the emergence of some dendrites of the solid solution. At 0.1 wt.% Sr, Mg_2Si dendrites almost entirely transform into isolated particles with an average size of ~62.8 μm. Particle size distribution histograms are presented in **Fig. 4**. Strontium modification at 0.2 wt.% leads to a further reduction in Mg_2Si particle size to ~44.8 μm, accompanied by a change in their morphology to blocky, compact, and close to equiaxed shapes. The uniformity index of their distribution reaches ~0.24, representing the optimal result in this experimental series. Presumably, strontium acts as a surface-active additive, restricting the anisotropic growth of primary Mg_2Si phase crystals. Further increases in strontium content are associated with a slight enlargement of Mg_2Si particle sizes (~50.8 μm at 0.3 wt.% Sr), as well as the blurring of their shapes and the emergence of new needle-like intermetallic phases. Consequently, the degree of particle distribution uniformity slightly deteriorates, ranging from 0.39 to 0.57.

The results of tribological tests under dry friction conditions indicate a significant reduction in the coefficient of friction and mass wear of cast specimens of Al-Mg_2Si composites upon the addition of strontium in quantities determined based on metallographic research findings **(Fig. 5)**. Specifically, with the addition of 0.2 wt.% strontium, the coefficient of friction decreased compared to the unmodified state from 0.458 to 0.338 for the Al + + 15 wt.% Mg_2Si composite and from 0.462 to 0.344 for the Al + 25 wt.% Mg_2Si composite. Concurrently, mass wear after traversing the specified frictional path decreased from 0.0357 g to 0.0216 g (15 wt.% Mg_2Si) and from 0.3731 g to 0.0143 g (25 wt.% Mg_2Si). The obtained data validate the effectiveness of strontium as a modifier in enhancing the tribological properties of Al-Mg_2Si in-situ composites, providing a practical reference for the development of substantiated technological parameters for the

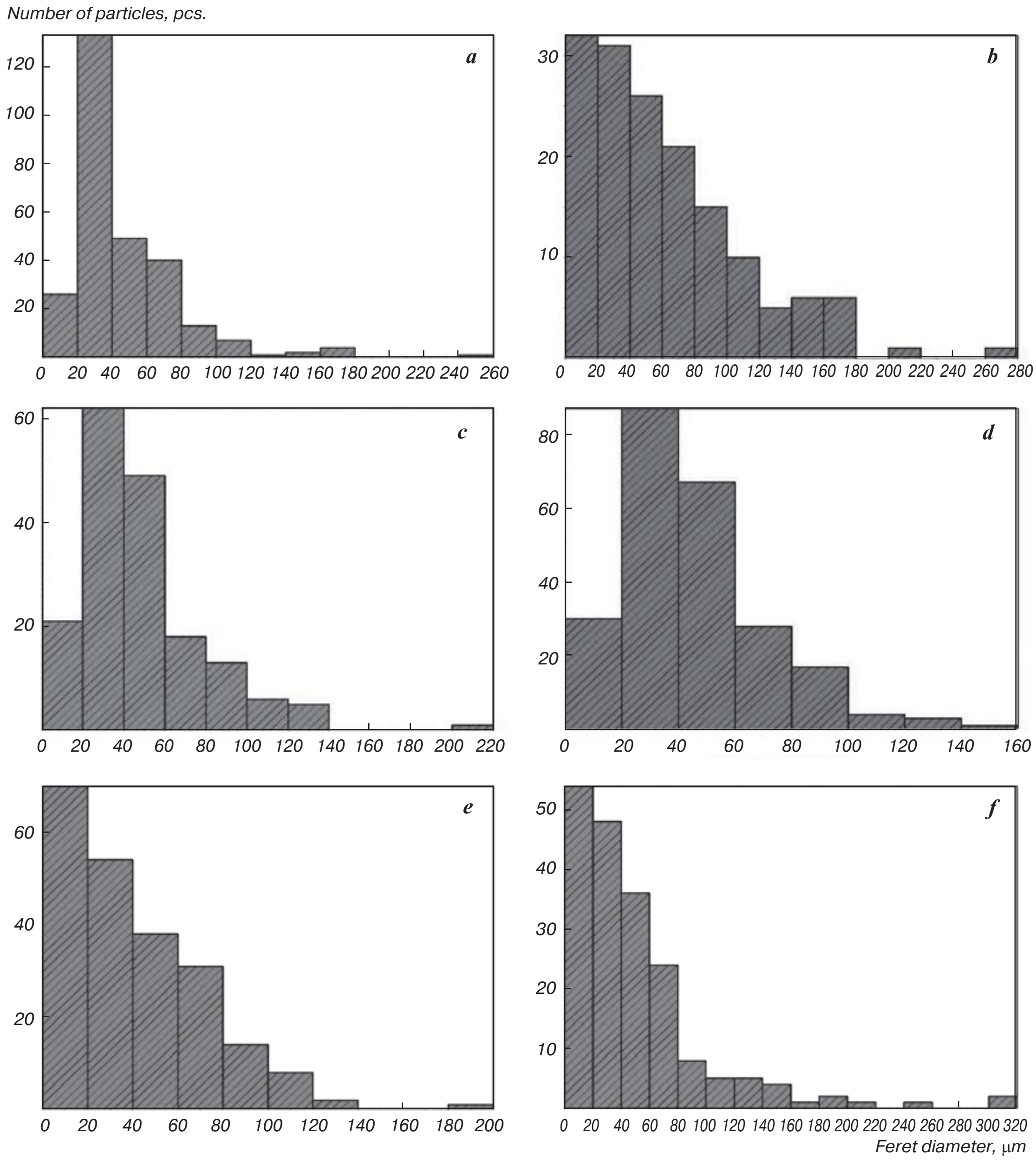

Fig. 4. Histograms of particle size distribution in the structure of Al + 25 wt.% Mg_2Si aluminum matrix composite after addition of strontium in the amount of 0.05 wt.% (*a*); 0.1 wt.% (*b*); 0.15 wt.% (*c*); 0.2 wt.% (*d*); 0.25 wt.% (*e*); 0.3 wt.% (*f*)

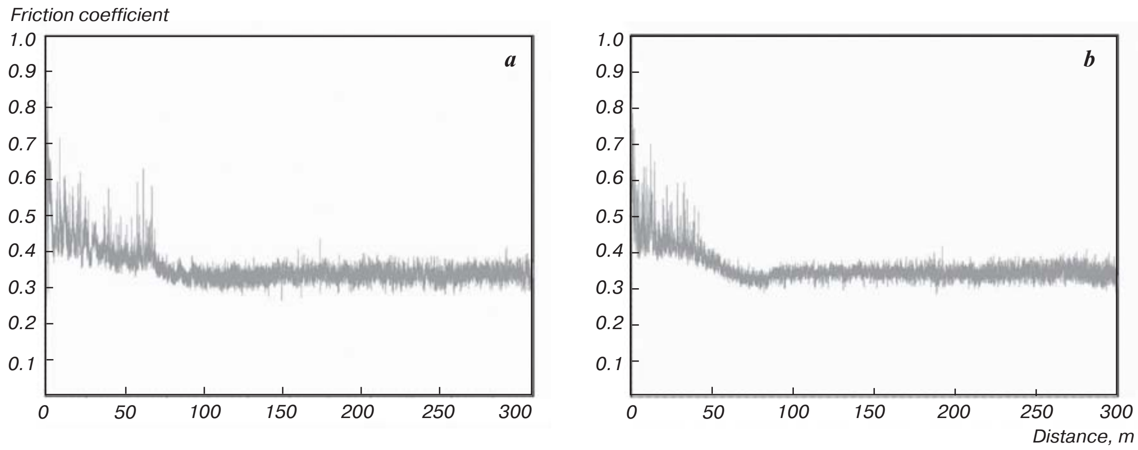

Fig. 5. Variation of friction coefficient of cast composite samples depending on the friction path: Al + 15 wt.% Mg_2Si + 0.2 wt.% Sr (*a*); Al + 25 wt.% Mg_2Si + 0.2 wt.% Sr (*b*)

melting processes of new composites used in the fabrication of tribotechnical parts.

In general, tribological tests demonstrate that the modification of aluminum matrix composites based on the Al-Mg_2Si system through the addition of strontium has a positive impact on their wear resistance. This finding holds potential for enhancing the durability of cast components and improving their operational efficiency across diverse engineering applications. Further research in the realm of structural changes in the worn surface is warranted to elucidate the friction mechanisms, thereby contributing to an expanded understanding of the influence of modification on the tribological behavior of these promising materials.

Conclusions

The effect of strontium addition from 0.05 to 0.3 wt.% on the change of structural and morphological characteristics of primary particles of Mg_2Si reinforcing phase at obtaining cast aluminum matrix composites based on pseudobinary Al-Mg_2Si system has been studied experimentally. It is shown that modification of composite melts with strontium in the amount of 0.2 wt.% promotes a significant decrease in the average size of Mg_2Si particles and a change in their morphology to blocky and close to equiaxed with simultaneous improvement in the uniformity of distribution over the ingot cross-section, which leads to a significant increase in wear resistance and a decrease in the coefficient of dry friction in the pair with steel.

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