Microstructural modification of in-situ aluminum matrix composites via pulsed electromagnetic processing of crystallizing melt

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Cast hypereutectic Al – Mg_2Si in-situ aluminum matrix composites are promising for industrial application as lightweight structural materials with high resistance under conditions of dry and abrasive wear, elevated temperatures and loads. In this work, the effect of melt irradiation by nanosecond electromagnetic pulses during crystallization on the structure formation of Al + 25 wt.% Mg_2Si composites was studied. The application of nanosecond electromagnetic pulses to the crystallizing composite melt at the tested frequency parameters (0.5 and 1 kHz) and pulse amplitude (21.7, 31.5, 36.5, 42 kV) allows to decrease the average size of primary Mg_2Si particles to values in the range from 40 to 65 μm. It was shown that during irradiation of crystallizing composite melt with frequency 1 kHz and amplitude 21.7 kV the most finely dispersed eutectics of completely rod-like morphology is revealed in the structure of the samples. At these parameters of pulsed electromagnetic processing, a decrease in the average size of Mg_2Si particles to 44.12 μm was achieved, while in untreated composites their size averaged 147.69 μm. The observed number of Mg_2Si particles in the section field increases by more than an order of magnitude compared to the initial state. The obtained data show a high potential of practical use of the tested technical solutions for the modifying treatment of hypereutectic composites of the Al – Mg_2Si system.
Key words: cast aluminum matrix composites, crystallization, nanosecond electromagnetic pulses, morphological transformation of the structure

DOI: 10.17580/nfm.2023.01.06

Introduction

Cast aluminum matrix composites are currently considered as one of the effective alternatives to traditional metals and alloys in the manufacture of critical engineering parts in the aerospace, automotive, and other high-tech industries [1]. This is largely due to the growing need for lightweight structural materials with high resistance to dry and abrasive wear, elevated temperatures and loads. Liquid-phase technologies for producing aluminum matrix composites are associated with the necessity of solving the problem of physical and chemical compatibility of the matrix and the reinforcing phase while ensuring a defined degree of their interfacial interaction [2, 3]. Promising technologies for producing aluminum matrix composites are based on the formation of endogenous reinforcing phases directly in the matrix melt in the processes of melting and solidification (in-situ-process) [4]. Such approaches have a significant potential for integration into existing technological processes of castings production under the conditions of industrial enterprises. The in-situ formed phases are distinguished by high thermodynamic stability and good adhesion to the matrix, as well as uniform distribution in the matrix alloy [5]. Among the endogenous reinforcing phases, the Mg_2Si compound attracts special attention, since it can be easily obtained with a large volume fraction in standard casting and metallurgical processes without the use of powder precursors [6].

The effectiveness of reinforcement action in cast metal matrix composites to a decisive extent depends on the characteristics of their structure, including the volume fraction, size, shape, and distribution of reinforcing particles, as well as the presence of various casting defects, such as microporosity [7]. In practice, the mechanical properties of cast Al – Mg_2Si composites obtained without additional processing of melts or castings, as a rule, are insufficient for many critical applications [8]. To a large extent, this is due to the fact that Mg_2Si crystals under

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normal melting and casting conditions are large and have an unfavorable morphology, which leads to stress localization at the sharp edges and corners of the particles [9]. In this case, the tendency to enlargement of primary particles increases with an increase in the volume fraction of the Mg_2Si phase [10]. In addition, the mechanical properties of the resulting composites are further reduced due to the coarse lamellar structure of the pseudobinary eutectic (α + Mg_2Si) [11]. The mentioned preconditions determine the necessity of the development of effective and economical methods of modifying all structural components of Al – Mg_2Si cast composites.

In recent years, the influence of the addition of various modifying elements (mainly rare-earth and alkaline-earth) on the structure of materials based on the Al – Mg_2Si system has been actively studied, mostly in the hypereutectic region of compositions. In particular, quite high efficiency of using elements such as Gd, Nd, Pr, Eu, and some others was confirmed to reduce the average size and change the morphology of primary Mg_2Si particles, as well as to modify the pseudobinary eutectic [12–17]. At the same time, many of the used rare-earth elements are expensive and difficult to access, which may limit their use in industrial technologies of melting and casting of the Al – Mg_2Si aluminum matrix composites. Another direction of the modifying treatment of composite melts is the imposition of various physical influences on them [18]. To date, good results in terms of influencing the structural components of the eutectic matrix and primary Mg_2Si particles have been achieved using the treatment of melts by high-temperature overheating [19], ultrasonic and vibrational processing [20, 21], as well as melt crystallization with high cooling rates [22]. One of the promising methods to influence the dispersity and morphology of various structural components of aluminum alloys is the treatment of their melts with nanosecond electromagnetic pulses (NEMP) [23]. Previously, we showed that with an increase in the amplitude of the NEMP generator to 15 kV during irradiation of melts of the Al – Mg_2Si system, the degree of refinement of the α-solid solution and the pseudobinary eutectic increases [24]. However, it was noted that the treatment of melts with NEMP in the tested amplitude range practically does not affect the size and morphology of the primary Mg_2Si particles. It was suggested that a more effective way to influence these structural components could be the irradiation of melts with NEMP directly in the process of crystallization.

Under the action of electromagnetically induced stirring of solidifying metallic melts, the nature of the nucleation and growth of crystals can significantly change, which causes structural and morphological changes in the as-cast structure [25]. It has been experimentally confirmed that a strong pulsed magnetic field can dramatically improve solidification structures and reduce the segregation of elements in aluminum alloys [26]. The role of convection and its contribution to grain refinement during the processing of aluminum melts by pulsed magnetic oscillation is emphasized [27]. The thermodynamics and kinetics of crystallization of aluminum and its alloys during melt treatment by magnetic field has been studied [28, 29], and it has been found that the magnetic field changes the temperature of the melt-crystal phase equilibrium, the latent heat of phase transition, and the melt supercooling temperature during crystallization. Electromagnetic stirring during solidification of aluminum alloys of the Al – Mg_2Si system in the hypoeutectic range of compositions was accompanied by an essential morphological modification of the crystallizing structural constituents [30]. However, published sources do not yet provide experimental data on changes in the structural components of Al – Mg_2Si composites of hypereutectic composition during their crystallization under the influence of nanosecond electromagnetic pulses.

The purpose of this work is to determine the effect of NEMP irradiation of melts during crystallization on the formation of the structure of Al – Mg_2Si hypereutectic composites (on the example of Al + 25 wt.% Mg_2Si).

Materials and methods

Cast aluminum matrix composites with the nominal composition of Al + 25 wt.% Mg_2Si were obtained by direct melting of pure aluminum (≥99.99 % Al), magnesium (≥99.9 % Mg) and silicon (≥99.0 % Si). The charge materials were preliminarily dried in a thermal furnace for at least three hours at 150 °C. Melting was carried out in graphite crucibles with a capacity up to 1 kg (for aluminum) in an electric resistance furnace GRAFICARBO (Italy). Firstly, aluminum was loaded into the furnace, and after its melting argon of technical frequency was fed into the upper part of the crucible, and the feeding did not stop until the end of melt pouring. Aluminum melt was superheated to a temperature of 730–750 °C, and silicon and foil-wrapped magnesium were sequentially added with holding and stirring until the complete dissolution in the melt. The melting process temperature was controlled during the entire experiment by *K*-type thermocouple. Prepared melt was poured at a temperature of 720±5 °C into graphite molds. Electrodes connected to the NEMP generator were placed in the graphite mold beforehand. Due to the characteristics of graphite mold, which is an open mold with dimensions of 300×90 mm and wall thickness of 10 mm, electrodes of different shapes were considered. In order to irradiate the entire volume of the melt in the mold and to reduce the losses of amplitude and frequency of NEMP pulses, electrodes in the form of plates were designed and manufactured.

Irradiation of the melt by NEMP during crystallization was carried out according to the scheme shown in **Fig. 1**. The source of electromagnetic waves was the FID Technology generator (Germany) with the following characteristics: variable pulse amplitude from 10 to 50 kV, variable frequency of the generated pulses up to 1 kHz, pulse front 2–3 ns. Emitters were made in the form of steel plates 10 mm wide and 300 mm long with a protective coating of boron nitride. An asbestos plate was laid to prevent short-circuiting on the mold.

Samples for comparative studies were cut at a distance of 20 mm from the edge of each ingot. The structure was studied using a Planar MICRO 200 metallographic microscope and a Hitachi SU-70 scanning electron microscope (Japan) with energy dispersive (EDX) and wave dispersive (WDX) micro *X*-ray spectroscopy attachments. For all samples, the structure areas in the central part, located at the same distance from the cast surface, were examined. Quantitative analysis of the metallographic images was performed using ImageJ v.1.53 software.

Results and discussion

Fig. 2 shows optical images of the structure of Al + 25 wt.% Mg_2Si composite samples obtained at different parameters of frequency and amplitude of NEMP irradiation during crystallization in graphite mold. In all cases, Mg_2Si particles were characterized by a dendritic morphology and exhibited anisotropic crystal growth behavior, which is typical for hypereutectic aluminum matrix composites with a high content of the primary Mg_2Si phase.

NEMP irradiation leads to an increase in the observed number of primary Mg_2Si particles in the section field by more than an order of magnitude (in particular, from 19 pc in the initial state to 211 pc at a frequency of 1 kHz and an amplitude of 21.7 kV). The average linear particle size, measured as the Feret diameter, in the untreated composite was 147.69 ± 48.27 μm. Application of NEMP to the crystallizing composite melt at the frequency and amplitude parameters tested in this work allows reducing the average particle size of the primary phase to values in the range from ~40 to ~65 μm. In a series of experiments at a frequency of 1 kHz, the smallest average particle sizes (44.12 ± 23.98 μm) were achieved after irradiation with an amplitude of 21.7 kV. A further increase of amplitude was accompanied by a slight increase of average particle sizes in comparison with the indicated one, but this increase in all cases remained within the statistical scatter of values.

Analysis of SEM images (**Fig. 3**) indicates radical morphological changes of the psedobinary eutectic after the crystallization of melts under the action of NEMP.

In the untreated composite, the eutectic (α + Mg_2Si) is characterized by a coarse lamellar morphology, with variations in the observed morphological types of eutectic colonies include long plates (up to 80–90 μm in some cases) and occasionally rod-like inclusions. The most finely dispersed eutectic with a completely rod-like morphology in all areas of the section was revealed after irradiation with a frequency of 1 kHz and an amplitude of 21.7 kV. The repetition rate of

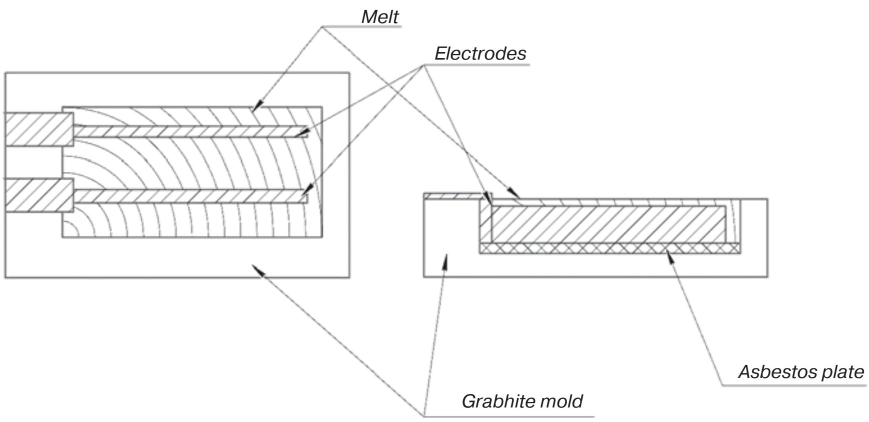

Fig. 1. Scheme of the melt irradiation process by NEMP during crystallization in a graphite mold

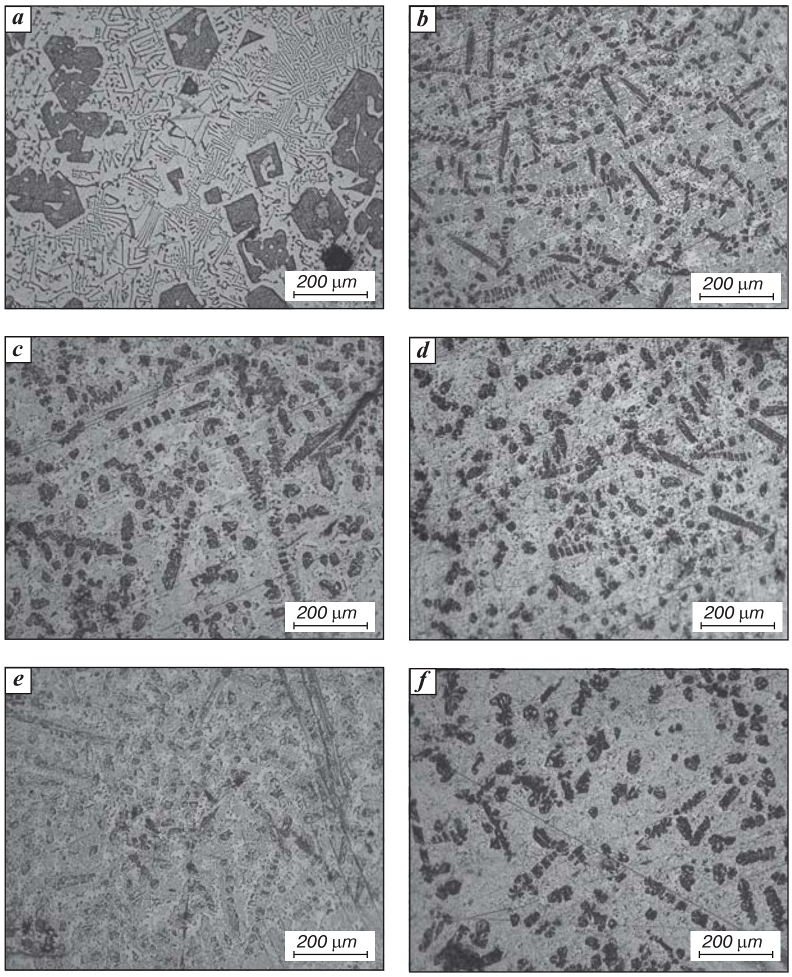

Fig. 2. Optical images of the structure of Al + 25 wt.% Mg_2Si aluminum matrix composites (×200):
a — original; *b* — 36.5 kV amplitude and 0.5 kHz frequency; *c* — 42 kV amplitude and 0.5 kHz frequency; *d* – 21.7 kV amplitude and 1 kHz frequency; *e* — 31.5 kV amplitude and 1 kHz frequency; *f* — 42 kV amplitude and 1 kHz frequency

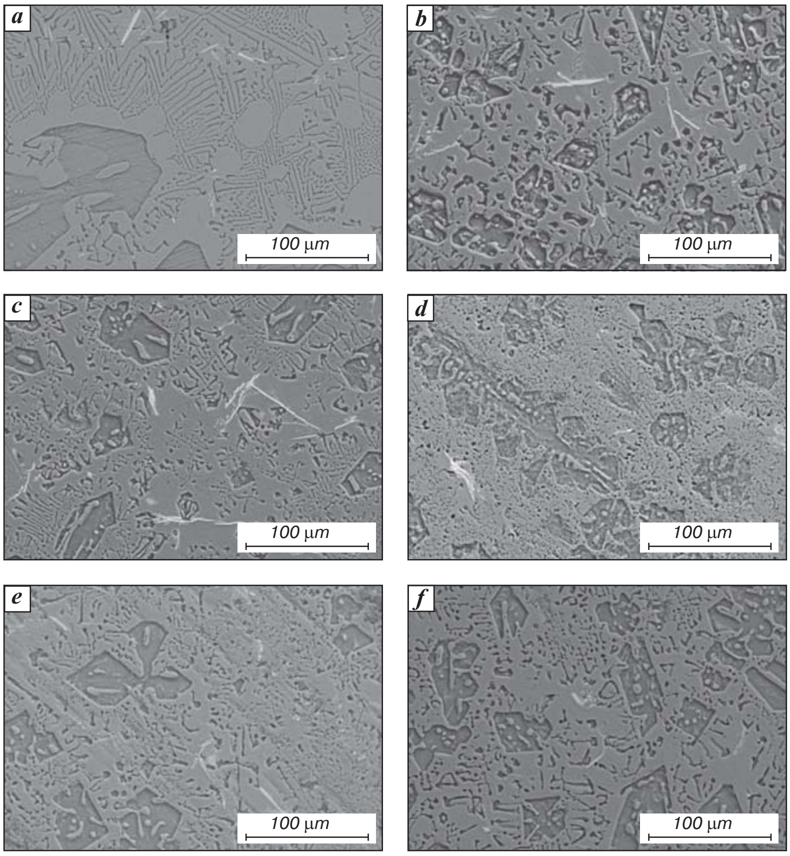

Fig. 3. SEM images of the structure of Al + 25 wt.% Mg_2Si aluminum matrix composites: *a* – original; *b* – 36.5 kV amplitude and 0.5 kHz frequency; *c* – 42 kV amplitude and 0.5 kHz frequency; *d* – 21.7 kV amplitude and 1 kHz frequency; *e* – 31.5 kV amplitude and 1 kHz frequency; *f* – 42 kV amplitude and 1 kHz frequency

the generated pulses, to a much greater extent than the amplitude, affects the dispersity and morphology of the eutectic. This is confirmed by the refinement of the eutectic and the change in its morphology to a more compact one with an increase in frequency from 0.5 to 1 kHz at the same parameters of the irradiation amplitude of the crystallizing melt. Along with this, a clearly observed significant fragmentation of the eutectic matrix regions inside the primary Mg_2Si particles during irradiation of melts with NEMP should be noted.

Thus, the application of NEMP to crystallizing melts of Al + 25 wt.% Mg_2Si metal matrix composites is a promising method of complex influence on the structural components (eutectic matrix and primary particles of the reinforcing phase), allowing to achieve a strong modifying effect, in many cases exceeding similar effects from use of chemical modifiers. NEMP irradiation is one of the environmentally safe and economically attractive options for melt processing, which makes it possible to reduce the use of expensive modifying elements while maintaining or even exceeding the effectiveness in terms of the totality of all indicators. At the same time, the existing theoretical substantiations of the effect of NEMP on the structure of liquid and solidifying metals need further understanding and development, including the processing of melts of metal matrix composites, and yet do not sufficiently reveal the reasons of high efficiency of the NEMP influence on the structural components of metallic and composite materials. Apparently, in further studies it is necessary to continue the accumulation and generalization of experimental data on the effect of various parameters and conditions of irradiation of melts by NEMP on the crystallization behavior and structural and morphological characteristics of aluminum matrix composites reinforced with endogenous and exogenous phases.

Conclusions

The performed series of experiments confirmed the possibility of a strong modifying influence on the eutectic matrix and primary particles of Mg_2Si reinforcing phases by applying NEMP to the crystallizing melts of Al + 25 wt.% Mg_2Si composites. It was shown that irradiation of the composite melt with a frequency of 1 kHz and an amplitude of 21.7 kV during its crystallization leads to the most finely dispersed eutectic of completely rod-like morphology in the structure of the samples. At these NEMP parameters, a decrease in the average size of primary Mg_2Si particles to 44.12 ± 23.98 μm was achieved, while in untreated composites their size averaged 147.69 ± 48.27 μm. During irradiation of crystallizing melts with NEMP, the observed number of primary Mg_2Si particles in the section field increases by more than an order of magnitude in comparison with the initial state.

Acknowledgments

This research was funded by the Russian Science Foundation (Project № 20-19-00687).

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