Features of the structure formation in the process of obtaining cast aluminum matrix nanocomposites using ultrasonic melt treatment

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Abstract. The paper presents modern representations about the effect of ultrasonic treatment on the behavior of nanoscale reinforcing particles in aluminum melts. Advantages and potential directions of application of the ultrasonic melt processing method for producing cast aluminum matrix nanocomposites are presented.

1. Introduction

To date, traditional metal-based alloys have practically exhausted their potential from the standpoint of a breakthrough change in the level of properties and characteristics of critical products [1]. A promising direction for improving the mechanical and operational properties of alloys is their reinforcement with dispersed particles of high-modulus refractory compounds, which leads to the formation of heterophase structures characteristic for metal-matrix composites [2].

Such approach opens up wide opportunities for improving the functional characteristics of products and is relatively easy to adapt to the conditions of existing industrial enterprises. Metal matrix composites (primarily based on light alloys) have a unique combination of such valuable properties as high specific strength, low density, low coefficient of thermal expansion and high heat conductivity, high wear resistance and many others [3].

However, a significant limiting factor for industrial applications of metal matrix composites with micro-sized reinforcing phases is the relatively low ductility and impact strength, high abrasion on the counterbody, and high wear of the cutting tool during machining [4]. One way to overcome these limitations is to use nanoscale reinforcing phases [5].

The introduction of nanoparticles into metal melts presents significant technological difficulties due to their strong tendency to form agglomerates because of the action of the van der Waals forces, as well as rapid oxidation even at relatively low temperatures and poor wettability with liquid metals [6-8].

In this regard, the well-known liquid-phase methods for producing exogenously reinforced aluminomatrix composites with micro-sized particles (mechanical mixing of particles into the melt using an impeller, injection of an inert gas, etc. [9]) are low-efficient in the preparation of nanostructured composite materials. Practice shows that the production of high-quality foundry metal-
matrix nanocomposites in most cases requires the use of external physical effects on the melt, one of which may be ultrasonic treatment [10-12]. At present, the use of ultrasound in metallurgy has already become one of the traditional solutions for degassing melts and modifying treatment [13]. The possibility of a fundamental change in the structure of alloys using ultrasonic treatment in acoustic cavitation mode is confirmed by many years of research by prof. Eskin G.I. [14].

In these fundamental works it was found that ultrasonic treatment of liquid and crystallizing melt destroys the branches of growing dendrites, fragments of which act as additional centers of crystallization. The resulting excess of crystallization nuclei ensures the formation of a finely ground non-dendritic structure with a grain size approximately equal to the size of the dendritic parameter. The aim of the work is to assess the prospects of using the method of ultrasonic melt treatment for the preparation of aluminomatrix nanocomposites by liquid-phase methods based on an analysis of modern ideas about the processes of their structure formation under conditions of cavitation influences.

2. The technological process and equipment for producing cast aluminomatrix nanocomposites using ultrasonic melt treatment

The synthesis of nanomaterials based on the use of ultrasound is currently considered by researchers as one of the most promising [15]. When metal matrix nanocomposites are prepared by liquid-phase methods, the melt treatment by ultrasonic vibrations is carried out, as a rule, in the frequency range 18–25 kHz directly during the introduction of the reinforcing phase or immediately after it. A diagram of a typical installation for ultrasonic melt treatment in the preparation of nanocomposites is shown in figure 1 (a) and includes a radiating waveguide 1, magnetostrictive transducer 2 and ultrasonic oscillation generator 3. In some cases, nanoparticles (4) are supplied in the inert gas protective atmosphere (5 – balloon with gas).

The waveguide is usually made of a titanium alloy, stainless steel, or niobium-based alloys because of their effective transmission of ultrasound and dimensional stability at elevated temperatures [16]. Niobium waveguides have higher chemical resistance in contact with the matrix melt, withstand high processing temperatures with minimal cavitation erosion, but are the most expensive. The destruction of agglomerates of nanoparticles during melt processing is associated with the phenomenon of acoustic cavitation (figure 1, b), which is the process of formation and growth (stage I), pulsation and collapse (stage II) of tiny bubbles during cyclic exposure to high-intensity ultrasonic waves.

Foci of cavitation appearing and disappearing near agglomerates of nanoparticles create excessive pressure, which allows the melt to pass into the capillary spaces and pores between the particles even when they are poorly wetted by a liquid metal [17]. The saturation of the agglomerates by the melt leads to their decomposition into individual particles (stage III) due to the force of viscous friction at the leading edge of the ultrasonic wave. It was shown in [18] that the deagglomeration process will proceed most efficiently during the formation and collapse of cavitation bubbles directly inside agglomerates of nanoparticles.

To create acoustic cavitation in melts of light alloys, the ultrasound intensity should be at least 80 W/cm² [13]. Assuming that the surface of the waveguide-emitter is completely wetted by the melt, the intensity I can be expressed as follows [13, 19]:

\[ I = \frac{1}{2} \rho_L c_L \left(2\pi f A_0 \right)^2, \]

where \( f \) is the oscillation frequency, \( \rho_L \) is the density of the metal melt, \( c_L \) – the propagation velocity of sound waves in the melt, \( A_0 \) – the initial amplitude. The calculations performed using the above expression allow us to establish the theoretical nature of the change in the intensity of ultrasonic treatment depending on the frequency of oscillations and the initial amplitude, taking into account the type of alloy being processed.
3. The effect of ultrasonic treatment on the structure formation and formation of properties of cast aluminomatric nanocomposites

Specific examples of the implementation of ultrasonic technologies in the production of cast aluminum matrix composites with exogenous nanoparticles are so far presented in the scientific literature to a limited extent, however, these methods are gradually beginning to attract more and more attention of researchers and specialists. In particular, in [20], ultrasonic melt treatment was used to obtain nanocomposites based on Al-7Si-0.3Mg with the addition of 0.5 wt.% Cu and 1 wt.% of Al₂O₃ nanoparticles. A niobium probe operating at a frequency of 20 kHz with a maximum power of 600 W was used. Nanoparticles were wrapped in a two-layer aluminum foil before being fed into the melt. The waveguide was immersed into the matrix melt to a depth of 12 mm at a temperature of 700°C and ultrasonic vibrations were applied with a frequency of 20 kHz and an amplitude of 60 μm while feeding heated capsules with nanoparticles. The treatment time was 15 minutes for each capsule administered. The combined modifying effect of nanoparticles and ultrasonic treatment on all phase components, including primary $\alpha$-dendrites, eutectic silicon, and Al₂Cu inclusions, was noted.

In [21], 1 mass% SiC (50 nm) and Al₂O₃ (20 nm) nanoparticles were blown with an argon stream into the melt of the A356 aluminum alloy with simultaneous ultrasonic treatment at a power of 1.75 kW and a frequency of 18 kHz. When nanoparticles were introduced together with ultrasonic processing of the melt, significant refinement of the average grain size in the matrix alloy and eutectic structure was achieved, as well as a decrease in the distance between the secondary axes of the dendrites by more than 36% compared with the matrix alloy. Ultrasonic treatment was accompanied by degassing of the alloy, providing a significant reduction in the porosity of the castings. The addition of SiC nanoparticles according to the proposed regimes contributed to an increase in tensile strength from 228 to 283 MPa and an increase in the ductility of the material from 4 to 11.2%.

The effect of ultrasonic vibrations on the dispersion and distribution of graphite particles in the preparation of Al – 2 vol.% Graphite composites by mechanical mixing was studied [22]. Graphite powder with an average particle size of 21 μm was introduced into the aluminum melt using an impeller, followed by ultrasonic treatment for 1.3 and 5 minutes. A Ti-6Al-4V alloy emitter was used at a frequency of 20 kHz and a power of 2.5 kW. It was shown that ultrasonic treatment for 1 min sharply reduces the porosity of materials and destroys the accumulation of graphite particles.

A further increase in the treatment time does not significantly affect the change in porosity, however, it affects the size and morphology of graphite inclusions, which are reduced to 100-130 nm during processing for 5 min. The influence of different temperatures of ultrasonic treatment was studied in [23] when producing aluminomatric composites with 1% mass. Al₂O₃ nanoparticles. Powders of Al (80-100 μm) and Al₂O₃ (65 nm) were mixed in a ball mill in stearic acid to obtain a composite powder and sintered at 400°C for 2.5 h. The matrix melt was superheated to 750°C, then for 10 min the resulting powder was mixed using an impeller. After that, ultrasonic vibrations with a frequency of 20 kHz were applied for 60 s at a power of 300 W and melt temperatures of 650, 670, 680, and 700°C. Processing at 670°C leads to the best microstructure parameters with an average $\alpha$-grain size of 25 μm and an increase in tensile strength by 37%.

![Figure 1. Schematic diagram of a typical installation for ultrasonic melt treatment (a) and the proposed model of destruction of nanoparticles agglomerates (b)](image)
It was confirmed [24] that the presence of Al₂O₃ nanoparticles in an aluminum melt leads to a significant intensification of the process of formation of cavitation centers, as well as to an increase in the melt velocity near the waveguide by an average of 20%. It has been suggested that the noted trends may be due to the nucleating action of alumina nanoparticles with respect to cavitation bubbles. However, an excessive increase in the volume of cavitation bubbles is accompanied by a weakening of the distribution of ultrasonic energy, which can lead to a localized distribution of cavitation effects.

The above examples convincingly indicate the technological feasibility of using ultrasonic treatment when introducing nanosized reinforcing particles into aluminum melts. Available experimental data confirm an improvement in the wettability and uniformity of the distribution of nanoparticles over the melt volume due to the destruction of agglomerates. Modern ideas about the structure formation of aluminomatrix nanocomposites using ultrasonic treatment link the mechanism of deagglomeration of nanoparticle clusters with the sonocapillary effect and the phenomenon of ultrasonic cavitation. Surface activation of nanoparticles during processing increases the thermodynamic stability of the system as a whole. An additional result is a reduction in the porosity of composite castings due to the degassing effect of ultrasonic treatment, as well as a modifying effect on the structure of the matrix alloy. However, the industrial implementation of ultrasonic technologies in the synthesis of cast aluminomatrix nanocomposites is still hampered by the lack of recommendations on the selection of optimal processing conditions depending on the composition of the synthesized materials, taking into account the physicochemical nature of the components.

4. Conclusion

- The advantages and potential directions of the use of ultrasonic melt treatment in the production of aluminomatrix composite materials with nanoscale reinforcing particles in liquid-phase technological processes are presented.
- Modern ideas of the structure formation of aluminomatrix nanocomposites using ultrasonic melt treatment are presented, linking the mechanism of deagglomeration of clusters of nanoparticles with the sonocapillary effect and the phenomenon of ultrasonic cavitation.
- The presented practical examples confirm the improvement in the wettability and uniformity of the distribution of nanoparticles over the volume of the matrix melt, the reduction in the porosity of composite castings, and the combined modifying effect of nanoparticles and ultrasonic treatment on the structure of the material.

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