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DETERMINATION OF THE INFLUENCE OF THE METHOD OF INTRODUCING C₆₀ FULLERENES AND FUNCTIONALIZED CARBON NANOTUBE ON THE FORMATION OF THE PROPERTIES OF ALUMINUM ALLOY

The object of research is the influence of carbon nanotubes and fullerene nanomaterials C₆₀ when introduced into the aluminum alloy AK12 on the formation of the eutectic microstructure.

The problem solved during the research is the insufficient effectiveness of existing modifiers such as Sr, Na, TiC and SiC to improve silicon globularization, as well as the lack of simple and effective methods for introducing carbon nanomaterials.

In the work, two methods for introducing carbon nanoparticles into the aluminum alloy were developed. Improved silicon globularization, mechanical and physical properties were achieved. The thickness of the silicon dendritic axis was reduced to almost 20–25 microns, the size of silicon inclusions was reduced from 2–10 microns, and the microhardness was increased almost twice, depending on the method. The improvement of properties is due to the fact that nanoparticles become centers of crystal nucleation and do not allow them to grow, which leads to a finer, more homogeneous structure of the alloy. Pre-treatment of nanomaterials allows them to be evenly distributed in the alloy, and the addition of magnesium improves the wetting properties.

The features and distinctive features of the obtained results are that two technologically simple methods of introducing nanoparticles into the liquid AK12 alloy have been proposed, without the use of ultrasound. A significant improvement in the mechanical and physical properties of the alloy has been achieved compared to the reference AK12 alloy. Controlled grinding of the silicon structure has been ensured. Available materials and equipment, which are available in Ukraine and suitable for scaling up in industrial volumes, have been used. The modified AK12 alloy allows it to be used for the manufacture of castings of critical importance, such as pistons, transmission mechanisms, and engine housings.

Keywords: aluminum alloy AK12, fullerene C₆₀, carbon nanotubes, nanomodification, microstructure, hardness.

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1. Introduction

Improving the physical and mechanical properties of aluminum alloys used in mechanical engineering, aviation and automotive industries is an important aspect for foundry production to be used in modern production. Standard alloys used in accordance with current regulations do not always meet the requirements for strength, wear resistance and durability of parts of modern technology. Knowing this, the purpose of the experiment is to use nanomaterials to improve the structure and properties of alloys.

Recently, there has been a clear trend in scientific circles towards the use of nanodispersed modifiers to improve Al-Si alloys, as previous modifiers (Sr, Na) have limitations in controlling the eutectic morphology and structural stability. One of the well-known methods is the introduction of carbides. TiC and SiC as heterogeneous nuclei that stimulate the formation of uniformly dispersed particles and increase

the hardness of alloys. Having studied the research, it is possible to conclude that TiC nanoparticles, which were mechanically and chemically activated together with aluminum powder, allow to grind the structure of Al-Si alloys and improve their mechanical and physical characteristics (strengthening through fine-grained structure) [1]. The article describes the use of TiC, SiC and B₄C to increase the wear resistance of matrix alloys. The hardness increases due to the rigidity of these carbides and the effect of scattering loads in the matrix [2]. One of the promising directions is the use of carbon nanostructures, in particular carbon nanotubes (CNTs). These structures can provide load distribution from the matrix to the guiding elements, the effect of dislocation blocking and Orowan-strengthening, if their uniform distribution and proper adhesion with the aluminum matrix are ensured. The above-mentioned article emphasizes that the key to the effectiveness of Al and CNT compositions is good CNT dispersion, interface control and control of interfacial reactions [3]. The authors' work shows how Ni-

coated CNTs affect the microstructure of Al and 20Si alloys, increasing the interaction between CNTs and the matrix, allowing control over the occurrence of interfacial compounds [4]. Also the direction of hydride reinforcement, which is associated with the connection of CNTs with ceramic particles. Such a system can combine the rigidity of carbides and the flexibility and strength of CNTs.

Another direction is hydride reinforcement, which is based on the combination of CNTs with ceramic particles (SiC or B₄C). Such a system can combine the advantage of carbide hardness and mechanical flexibility and strength of CNTs. In the author's work, an Al-composite with SiC, B₄C and CNTs was obtained, in which the formation of intermetallic phases (Al₃BC, Al₄C₃), the effect of dislocation strengthening and an increase in nano-hardness compared to conventional compositions was described [5].

The use of oxide modifiers, such as Al₂O₃, is due to the high thermal stability and rigidity of these particles. However, there is a risk of agglomeration or delamination due to poor wettability, so auxiliary methods such as ultrasound, mechanical alloying or pre-functionalization of the particles are often used in the works.

It is worth mentioning modifiers based on carbon spherical molecules, such as fullerene (C₆₀). Their permitted introduction can lead to a transformation of the morphology of the silicon eutectic from lamellar to fine-fibrillar, which reduces the concentration of stresses on sharp edges and increases plasticity. Compared to CNTs, there are fewer such works, but the tendency to use them is increasing. Nowadays, it is popular to combine the methods of introducing nanoparticles into the melt: high shear stir-casting, ultrasonic cavitation, mechanical alloying with light remelting. Much attention is paid to the pretreatment of nanoparticles (coating, functionalization), as well as to the alloying of the melt (addition of Mg, Ti) for better wettability and stabilization of interfaces. The aim is to overcome the problems of agglomeration and nanoparticles in large-scale melting.

Characterization methods are developing at the same level as experimental ones: the transition from traditional optical microscopy to TEM, EBSD, 3D X-ray microtomography (X- μ CT), nanoindentation of individual phases. In addition to visualization of morphology, this allows for quantitative assessment of local mechanical properties and internal stresses.

Nowadays, the trend in improving aluminum-carbon alloys is the desire to control the microstructure at a new level. Combine several strengthening mechanisms, such as inoculation, dispersion strengthening, load transfer. Adapt the process of introducing additives using ultrasound, alloying, and also expand the spectrum of nanomaterials in particular CNTs, C₆₀, ceramics.

This makes it possible to create alloys with excellent strength, wear resistance, and improved ductility that can be used in industry.

A promising nanomaterial is fullerene C₆₀, which has a unique molecular structure and chemical activity and can effectively influence the crystallization process and the formation of the phase composition of aluminum alloys. Previous studies have shown that it is possible to introduce fullerenes into the AK12 alloy using special mixtures that were immersed in the melt using the "bell" method. The results obtained showed a uniform distribution of nanoparticles in the matrix and positive changes in the microstructure of the metal, namely the effect on the silicon structure [6].

Further studies were aimed at experimentally comparing the original AK12 alloy with samples modified within the framework of two approaches. The first experiment used fullerene C₆₀, which was introduced into the alloy as a pressed compound (ligature) with aluminum powder. The second experiment involves the use of carbon nanomaterial processing to ensure better interaction with the metal matrix. The combined analysis, which included the formulation of the elemental composition, strength measurements, microstructure studies and X-ray diffraction analysis, allowed to establish differences

between the original alloy and the modified samples, as well as to evaluate the effectiveness of various methods of introducing nanoparticles into the AK12 alloy.

Al-Si alloys are aimed at controlling nanostructures, such as classical Sr-Na modification to the use of carbon nanoparticles. All of these components can affect the nucleation and morphological growth of grains in eutectic Si. Even at the theoretical level, it was proven that the transition to nanomodifiers can significantly improve properties such as microhardness, wear resistance and structural stabilization, which became the basis for the introduction of nanomodifiers on an industrial scale [7, 8]. For Al-Si alloys, this led to the control of the microstructure through grain formation using nanomodifiers TiC, SiC, B₄C. Dispersion strengthening by means of the so-called "Orwan blocking" led to the fact that the introduction of ceramic nanoparticles helped to grind the dendritic network in α -Al and convert the eutectic Si from a lamellar to a finely dispersed form. The above process helped to increase such characteristics as mechanical friction and hardness by almost 10% [9]. At the moment, carbon nanostructures are also being studied with ceramic nanoparticles. C₆₀ fullerenes mainly affect the Si structure and matrix texture, which corresponds to the ideas about the mechanical properties of C₆₀ phases and the further potential of their participation in crystallization [10]. An even greater impetus in nanoparticles is given by carbon nanotubes (CNTs), which, due to their strength and flexibility, implement the load transfer mechanism. The critical points in the application of CNTs are their uniform distribution and interaction with the Al alloy, in particular brittle reactions at the interface [11]. Therefore, world practice is more inclined to combined methods of introducing nanoparticles and ultrasonic mixing of the melt. To solve the issue of wettability, it is proposed to carry out a preliminary functional treatment of CNTs, which includes the use of COOH and OH acids and the use of Mg in the Al-Si alloy itself [12]. The authors' work demonstrates that the use of Ni-coated CNTs in Al-Si allows simultaneously increasing the strength and homogeneity of the microstructure. This is achieved due to better adhesion and controlled interphase reactions. The correct use of CNTs allows increasing wear and friction coefficient in bearing assemblies and piston alloys [13]. An additional vector is the hybrid systems SiC-B₄C + CNTs, which combine the rigidity of ceramics and the high specific strength of CNTs; demonstrates a significant increase in hardness and wear resistance compared to single-phase reinforcement [5]. Collectively, this captures the transition from "passive" alloying to controlled nanomodification with multi-mechanism strengthening, which paves the way for industrial Al-Si materials with a specified microstructure and a balanced set of properties [8, 9]. Moreover, technological solutions with ultrasonic mixing of the melt and pre-prepared alloys are considered the most suitable for scaling in casting cycles [13].

Thus, the unsolved issue remains the development of simple methods for introducing carbon nanomaterials into liquid Al alloys and their uniform distribution throughout the alloy. These methods do not require complex equipment and the use of ultrasound. They also partially solve one of the more important problems, such as the wettability of carbon nanomaterials in the liquid alloy.

The object of research is the microstructure and properties of the aluminum alloy AK12, after modification with carbon nanotubes and C₆₀ fullerenes.

The aim of this research is identifying the influence of the method of introducing C₆₀ fullerenes and functionalized carbon nanotubes into the melt on the formation of the properties of the AK12 aluminum alloy.

To achieve the above aim, it is necessary to solve the following objectives:

1. To investigate the features of the formation of the microstructure of the reference and modified samples and to determine changes in the morphology of structural components depending on the content of the nanomodifier.

2. To determine the phase composition of the alloy and evaluate structural changes based on the results of X-ray diffraction analysis.
3. To establish the effect of modification on the hardness and microhardness of the AK12 alloy.
4. To determine the effectiveness of comparative methods for introducing functionalized carbon nanotubes into the AK12 alloy melt.

2. Materials and Methods

Two input methods were used:

- the "fullerene" method;
- "functionalized CNT" method.

The "fullerene" method

This method is based on the mechanical mixing and pressing of C₆₀ fullerenes with finely dispersed PA-4 aluminum powder as a carrier matrix and their subsequent immersion in a liquid aluminum alloy.

In the first method, the main material for the research was the aluminum alloy AK12 according to DSTU 2839-94 [14]. Fullerene C₆₀ was selected for modification, which was previously mixed with aluminum powder of the PA-4 brand. The chemical composition of the AK12 alloy and PA-4 powder is given in Tables 1 and 2, respectively [5].

Chemical composition of AK12 DSTU 2839-94 alloy, %

Al	Yes	Fe	Mn	Ti	Cu	Zr	Mg	Zn	Impurities, total
84.3–90	10–13	up to 1.5	up to 0.5	up to 0.1	up to 0.6	up to 0.1	up to 0.1	up to 0.3	2.7

PA-4 chemical composition

Powder brand	Bulk density, g/cm ³	Active aluminum, %	Impurities, no more than, %			
			Fe	Yes	Cu	Moisture, no more
PA-4	0.96	98	0.35	0.4	0.02	0.2

In order to prepare the modifying ligature, fullerene and aluminum powder were mixed in a special drum mixer (manufactured by ZNTU, Ukraine), Fig. 1, for 24 hours at a rotation speed of 60 rpm. After that, the mixture was pressed into cylindrical briquettes with dimensions $h = 20$ mm, $d = 20$ mm under a pressure of 150 MPa. The obtained samples had different fullerene contents – 0.75; 2.6 and 4 g per 20 g of PA-4 powder. Samples with a high content (more than 3.5 g) were unstable and did not pass pressing due to loss of strength.

The introduction of the modifying ligature into the melt was carried out using the "bell" method. Melting was carried out in an induction furnace IST 0.16 (Termolitmash, Ukraine) at a temperature of 650°C, the ligature was held in the melt for 6 minutes. After melting, the alloy was poured into pre-prepared molds.



Fig. 1. Special mixing drum [5]

The method of "functionalized CNTs".

This method involves preliminary chemical activation of the surface of carbon nanotubes (CNTs) followed by incorporation together with magnesium to improve wettability.

The method consisted of the following, for the introduction of carbon nanotubes (CNTs) into 1 kg of AK12 aluminum alloy, preliminary functionalization was applied to improve wettability and uniform distribution nanomaterial.

To begin with, 2.08 g of carbon nanotubes were immersed in a mixture of nitric (HNO₃, 70%, 25 ml) and sulfuric (H₂SO₄, 98%, 75 ml) acids. The ratio of acids was 1:3 at a temperature of 60–80°C. The immersion period lasted 4 hours, the acids were periodically mixed. When preparing the mixture, the following rule was followed: saturated sulfuric acid was added to nitric to avoid a dangerous exothermic reaction.

After the reaction, the nanotubes were washed with distilled water 5–10 times until a neutral pH (~7) was reached, filtered to remove moisture, and washed twice with 96% ethyl alcohol (50 ml each), which helped reduce clumping and accelerate drying.

During the functionalization and washing process, the mass of nanotubes increased from 2.08 g to 21.33 g, which is explained by the formation of oxygen-containing functional groups on the surface of carbon nanotubes.

Drying of carbon nanotubes was carried out in a thin layer at 80–100°C for 4–6 hours on a metal surface with low-temperature heating, avoiding foil and temperatures above 150°C to preserve the functional groups.

Next, 1 kg of AK12 alloy was melted at a temperature of 720°C in a one-kilogram induction furnace of the Physics and Technology Institute of Metals and Alloys of the National Academy of Sciences of Ukraine. Furnace characteristics: Maximum temperature 1100°C. Voltage: 220V. Power: 1400 W Crucible capacity: 1 kg. To reduce surface tension and remove the oxide film, 10.47 g of magnesium was introduced into the melt, stirring with a mechanical mixer at a speed of 300 rpm for 2–3 minutes until it was completely dissolved.

The functionalized CNTs were divided into 4 portions of ~5.3 g each. They were gradually introduced through a quartz tube (one portion every 2 minutes) directly into the melt, maintaining the temperature at 720–740°C. After each addition, mixing was carried out with a mixer (mini pro France) at a speed of 400–500 rpm. The total mixing time was 4–5 minutes. The total heating time did not exceed 15 minutes to avoid nanotube degradation or carbide formation.

In the final stage, the melt was quickly poured into prepared molds with controlled cooling to fix the composite material.

3. Results and Discussion

3.1. Microstructure of reference and modified samples

The micrograph of the AK12 alloy samples is homogeneous, with evenly spaced small silicon inclusions up to 10 μm in size, which increases the mechanical properties. In the sample with the addition of 20 g of PA-4 and 0.75 g of fullerene, a more thin-layered, uniform structure with thin silicon plates (3–10 μm) was formed, which confirms the efficiency of the transformation and the uniform distribution of fullerene in the volume of the alloy, Fig. 2.

After studying the samples, the results were obtained with the conclusion that the microstructure of the samples is homogeneous. Against the background of the matrix solid solution, small, evenly distributed conglomerations (silicon) with sizes not exceeding 10 μm are observed, which is positively reflected in the complex of mechanical characteristics. The inclusions partially have a lamellar morphology with a plate size in the cross section not exceeding 3 μm, Fig. 3.

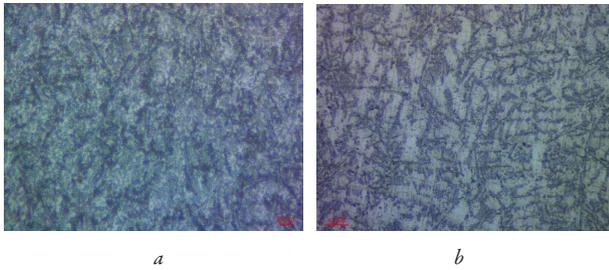


Fig. 2. Comparative analysis of the microstructure of the reference sample AK12 and the fullerene-modified sample AK12: *a* – microstructure of the reference sample AK12; *b* – microstructure of the fullerene-modified sample AK12

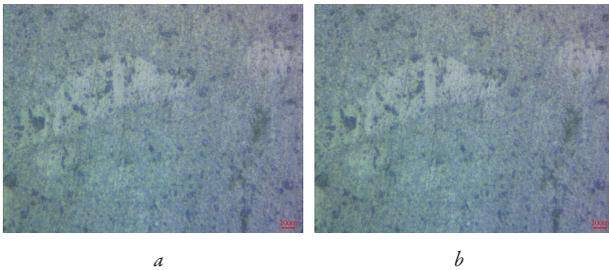


Fig. 3. Comparative analysis of the microstructure of the reference sample AK12 and the modified CNT sample AK12 in the digestion mode, $\times 500$: *a* – microstructure of the reference sample AK12; *b* – microstructure of the modified CNT sample AK12

3.2. Results of X-ray diffraction and phase analysis

Below are the diffractograms from the samples and the distribution of phases and elements, Fig. 4. The presence of fullerene is observed in the modified samples.

The diffractogram of the modified alloy samples contains peaks indicating C_{60} phases and a change in the structure of the AK12 aluminum alloy compared to the equivalent alloy is observed, which indicates the influence of nanomaterials in the processes of crystallization and their inclusion in the alloy matrix, Fig. 3.

The phase composition after the introduction of C_{60} was: 85.1% AL, 9.5% Si and 5.5% of the carbon phase. The size of the C_{60} clusters, calculated by the Scherrer formula, was 24.9 nm. This suggests that the nanomaterials retain a nanoscale state in the structure after crystallization. Compared with fullerenes, the use of functionalized CNTs provides a more pronounced formation of new phases and greater stability of carbon inclusions in the matrix.

3.3. Results of determination of hardness and microhardness of aluminum alloy AK12 after introduction of modifying agents nanomaterials

Method C – introduction of fullerenes as part of the ligature ("bell").

Hardness and microhardness. Measurements showed that the average hardness increased from 54.9 HB (reference sample) to 60.1 HB in the modified samples. The most noticeable changes occurred in the microhardness of the dendrites.

In the original sample (0x), the microhardness of dendrites and interdendritic space was almost the same (~ 450 MPa). After adding fullerenes in a ratio of 1×3 , it is possible to observe an increase in the microhardness of dendrites by 1.7–2 times (745–897 MPa), while the interdendritic space remained relatively plastic (393–415 MPa) the comparison is given in Table 3. This suggests that the strengthening of the dendritic phase occurs due to nanomaterials, which contributes to increasing strength and simultaneously preserving crack resistance.

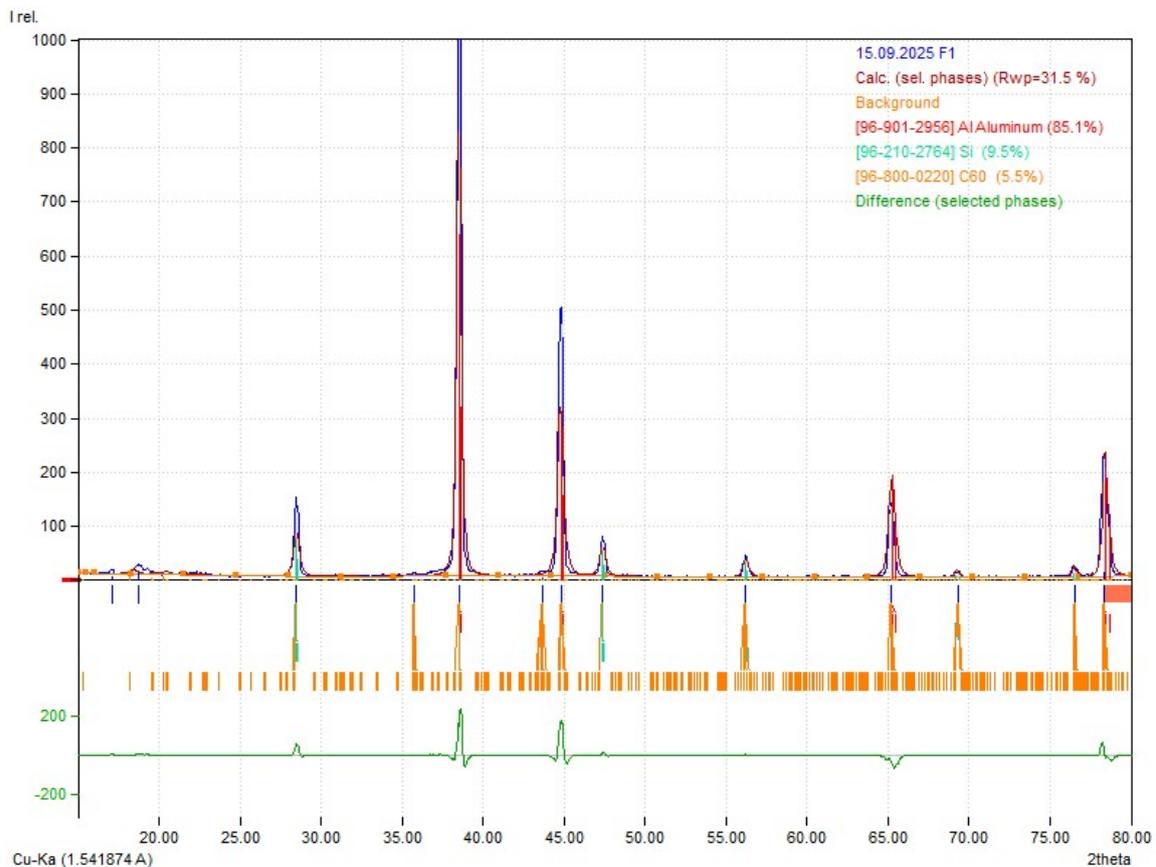


Fig. 4. Results of X-ray structural analysis

Hardness of samples (method)

Table 3

Sample	HBW	H20 interdendritic space, MPa	H20 dendrite axis, MPa
0x	54.9	449.8	450.5
1x	55.0	393.8	897.3
3x	60.1	414.8	745.1

The microstructure of the modified samples is characterized by a crushed dendritic network with a thickness of axes up to 25 μm (versus 40 μm for the original AK12). Silicon inclusions are finely dispersed (coarse fraction 3–10 μm) and are evenly distributed over the entire area of the section. This confirms the modified effect of fullerenes on the crystallization of alloys.

3.4. Efficiency of comparative methods of introducing functionalized carbon nanotubes into the AK12 alloy melt

The obtained samples, using functionalized CNTs, had better hardness indicators: on average 87–95HV. This is 45–55% higher than in the samples after the first method, and approximately twice as high as in the original AK12 (~42–55 HV, depending on the series of measurements). Therefore, this method provides a more pronounced strengthening of the material.

The microstructure of CNT samples is even more homogeneous compared to fullerenes: the dendritic network is smaller, silicon inclusions are reduced to 2–3 μm. They are evenly distributed in the matrix, which indicates the high efficiency of the pre-functionalization, nanotubes and the use of magnesium to improve wettability.

The "fullerene" method, which is simple to implement, provides noticeable grinding of the dendritic network, increases hardness by 10%, and dramatically increases the microhardness of dendrites by 1.7–2 times.

The "functionalized CNT" method is more technologically complex, but gives a higher effect, increasing the hardness almost twice compared to the original AK12 and grinding the microstructure to 2–3 microns.

The above results are also shown in Table 4 for comparison.

Thus, both methods showed the effectiveness of application, but functionalization and introduction of CNTs demonstrated a more functional effect on the alloy structure. It can be said that the first method is more appropriate for industrial conditions due to its simplicity, while the second is promising for special applications where the highest possible material performance is required.

Table 4

Comparison of the results of modifying the AK12 alloy

Indicator	Initial alloy AK12	Method (fullerenes, ligature + "bell")	Method (functionalized CNTs + Mg)
Hardness, HBW	42–55	55–60	87–95
Microhardness of dendrites, MPa	450	745–897	>900 (average up to 950)
Microhardness of the interdendritic space, MPa	450	393–415	400–420
Thickness of dendritic axes, μm	40	25	20
Size of silicon inclusions, μm	8–15	3–10	2–3
Phase composition (X-ray)	Al + Si	Al + Si + C ₆₀ (fullerene peaks)	85.1% Al; 9.5% Si; 5.5% C (cluster C ₆₀ ~24.9 nm)
Features	Typical structure of eutectic AK12	Dendritic mesh crushing, enhanced dendritic strengthening	Highest hardness, homogeneous structure, stable nanophases

3.5. Discussion

A distinctive feature of the obtained results is the establishment of the regularities of the influence of fullerenes on the structure formation of the AK12 alloy. In foundry production conditions, this ensures not only the grinding of the dendritic structure, but also a more uniform distribution of eutectic silicon without the formation of agglomerates of nanoparticles.

Unlike scientific publications, which mainly investigate the introduction of carbon nanomaterials into deformable aluminum alloys or powder compositions, the work proves the effectiveness of their application specifically for the cast AK12 alloy using an adapted introduction technology.

The obtained results solve the problem of structural heterogeneity and insufficient wear resistance of cast aluminum alloys. This provides an increase in microhardness and stabilization of the phase composition without significantly complicating the technological process.

Practical significance of the results: The obtained results are of significant importance for the growth of modern foundry production. Modification of the AK12 alloy with C₆₀ fullerenes and functionalized CNTs significantly increases the hardness and uniformity of the structure, which in turn makes it possible to use such alloys in the production of parts with a high level of thermal and mechanical stress.

The specified methods of modification of aluminum alloys have high potential for scaling up in industrial conditions. The technological process of extracting modified alloys makes it possible to integrate the process into foundry sections without significant changes. To adapt the process to industrial scales, it is possible to use ready-made nanomodified alloys or pre-functionalized powder mixtures, which will ensure the stability of the results when they are used.

Also, one of the advantages is the possibility of using nanomaterials of Ukrainian production, in particular fullerenes C₆₀, CNT. This contributes to the creation of a domestic technology for nanomodification of aluminum alloys and allows to increase the competitiveness of Ukrainian metallurgy in the world market. Therefore, the research results have not only scientific, but also practical value, ensuring the introduction of nanomaterials into the industrial production of aluminum alloys.

The limitations of the research are due to the use of a specific composition of the AK12 alloy and certain technological parameters of modification. The results obtained can be used provided that the melting and introduction modes of fullerenes are observed, similar to those studied. It should also be noted that the experiments were carried out in laboratory conditions, therefore the technological processes for implementation in industrial volumes require a number of additional improvements, namely:

1. Additional verification of structural stability and properties for large-sized castings.
2. The effectiveness of modification depends significantly on the methods of introducing the starting materials, their concentration and functionalization, which requires a slight optimization of technological processes in foundry production.
3. For implementation in industrial volumes, it is also necessary to evaluate the long-term stability of the structure, the mechanical behavior of castings under various loads, for example, mechanical and thermal.
4. The studied materials can be used for the manufacture of critical cast parts in mechanical engineering, in particular, housing elements, covers, brackets, transmission elements, as well as parts operating under conditions of increased friction and moderate mechanical loads.

Further research should be directed at optimizing the composition and concentration of C₆₀ fullerenes and functionalized carbon nanotubes, as well as the melting and crystallization modes of the AK12 alloy. In order to improve and stabilize its mechanical and operational properties. It is promising to study the long-term stability of the structure, corrosion and wear resistance of the nanomodified alloy. It is

also necessary to develop industrially suitable methods for introducing nanomaterials that will ensure the reproducibility of results in serial foundry production.

4. Conclusions

1. It was investigated that the introduction of carbon nanomaterials into the AK12 alloy leads to a significant change in the morphology of eutectic silicon and the dendritic structure of the reference sample. In the original alloy, the thickness of the dendritic axes was about 40 μm , and the size of the silicon inclusions was 8–15 μm . After the introduction of the C_{60} fullerene, the dendritic network is crushed to approximately 25 μm . Silicon inclusions are up to 3–10 μm . The use of functionalized CNTs provides an even more pronounced effect. The thickness of the dendritic axes is reduced to approximately 20 μm , and the size of the silicon particles is up to 2–3 μm . The obtained results confirm that the nanoparticles play the role of additional crystallization centers and limit the growth of phases, ensuring the formation of a more homogeneous finely dispersed structure, which is the basis for improving mechanical properties.

2. X-ray structural analysis showed that the initial alloy consists mainly of Al and Si phases. In the modified samples, the appearance of an additional carbon phase of about 5.5% was recorded along with 85.1% Al and 9.5% Si. The size of the C_{60} clusters calculated by the Scherrer formula is approximately 24.9 nm, which indicates the preservation of the nanoscale state of the particles after crystallization. The obtained data confirm the integration of carbon nanomaterials into the alloy matrix and their stability during the melting process, which justifies the effectiveness of the proposed approach to nanomodification of the cast Al-Si alloy.

3. The research proved that when modified with fullerenes, the hardness of the alloy increases to 60 NV and when modified with functional nanotubes up to 87–95 HB.

4. Comparative analysis showed that the method of introducing fullerenes provides an increase in hardness from 42–55 HB to 55–60 HB and an increase in the microhardness of the dendritic phase to 745–897 MPa. At the same time, the method with functionalized CNTs and the introduction of Mg is more effective: the hardness reaches 87–95 HB, and the microhardness exceeds 900 MPa. Thus, the functionalization of CNTs and the improvement of wettability provide a more uniform distribution of nanoparticles and the maximum strengthening effect. At the same time, the method with fullerenes is technologically simpler and more suitable for scaling up in industrial conditions.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or other, that could influence the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

Artificial intelligence was used in the preparation of the article in the following ways:

- Grok 4 was used;

- throughout the entire text of the article;
- checking grammar, spelling, and punctuation without changing the text;
- the authors checked the text of the article for any changes that are not relevant to the content of the article;
- the result provided by the AI tool did not in any way affect the conclusions of the research.

Declaration submitted by Mykola Trenov.

Authors' contributions

Mykola Trenov: Conceptualization, Investigation, Resources, Writing – original draft, Writing – review and editing; **Olga Ponomarenko:** Validation, Formal analysis, Supervision, Writing – review and editing.

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