Metallophysics and Advanced Technologies
Металофіз. новітні технол.
Metallofiz. Noveishie Tekhnol.
2023, vol. 45, No. 9, pp. 1125–1139
https://doi.org/10.15407/mfint.45.09.1125
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Printed in Ukraine.

PACS numbers: 06.60.Vz, 61.66.Dk, 61.72.Ff, 62.20.Qp, 81.07.Bc, 81.40.Cd, 83.60.Np

Impact of MHD-Processing on Technological Properties of High-Strength Casting Al–Cu Alloys

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Among many aluminium alloys, high-strength casting ‘aluminium–copper’ alloys are ones of the main structural materials in aircraft construction. According to the results of the latest research by specialists from different countries of the world, these alloys also have a perspective for application at manufacturing of parts (hulls and pistons) of engines for the aviation and automotive equipment. However, presence of toxic (cadmium) or expensive (silver) components in the composition of such alloys as strengthening additives limits significantly the potential of their industrial production and practical application. We propose using the energy of electromagnetic fields and magnetohydrodynamic (MHD) effects to process the alloy in liquid state. Implementation of such actions takes place in specialized casting magnetodynamic installation. The developed MHD processing of melts ensures refining of the structure and increasing main mechanical properties of aluminium alloys in the solid state. Actually, it is some kind of physical modifying without reagents. Regarding high-strength casting ‘aluminium–copper’ alloys, their MHD-processing in the liquid state in a foundry magnetodynamic installation allows to ensure quite high level of strength and plasticity even without application of strengthening additives. At the same time, the stand-

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Citation: O. M. Smirnov, O. D. Rud, V. N. Fikssen, Yu. P. Skorobagatko, T. O. Monastyrska, M. S. Goryuk, A. Yu. Semenko, and O. V. Yashchenko, Impact of MHD-Processing on Technological Properties of High-Strength Casting Al–Cu Alloys, *Metallofiz. Noveishie Tekhnol.*, **45**, No. 9: 1125–1139 (2023).
DOI: 10.15407/mfint.45.09.1125

ard-compliant level of the main technological properties (mainly fluidity and hot cracking susceptibility) is ensured. This indicates the possibility of obtaining thin-walled parts of complicated geometry from such alloys by casting methods. Further research will be focused on improving the mechanical and operational properties of experimental 'aluminium–copper' alloys due to the introduction of non-toxic and relatively cheap strengthening and modifying additives.

Key words: high-strength casting 'aluminium–copper' alloys, magnetohydrodynamic (MHD) processing, structure, strength, elongation, fluidity, hot cracking susceptibility.

Серед багатьох алюмінійових стопів саме високоміцні ливарні стопи системи «алюміній–мідь» є одними з основних конструкційних матеріялів у авіабудуванні. За результатами новітніх досліджень фахівців з різних країн світу ці стопи також мають перспективу щодо застосування для виготовленні корпусів і деталів двигунів авіаційної й автомобільної техніки. Однак наявність у складі таких стопів у якості зміцнювальних добавок токсичних (кадмій) або дорогих (срібло) компонентів істотно обмежує потенціял промислового виробництва їх і практичного застосування. Запропоновано використовувати енергію електромагнетних полів і магнетогідродинамічні (МГД) ефекти для оброблення стопу в рідкому стані. Реалізація таких дій відбувається у спеціялізованій ливарній магнетодинамічній установці. Розроблене МГД-оброблення розтопів забезпечує подрібнення структури та зростання основних механічних властивостей алюмінійових стопів у твердому стані та є фактично фізичним модифікуванням їх. Стосовно високоміцних ливарних стопів системи «алюміній–мідь», то МГД-оброблення їх у рідкому стані у ливарній магнетодинамічній установці уможливлює забезпечити достатньо високий рівень міцнісних і пластичних властивостей навіть без застосування зміцнювальних добавок. Цим способом забезпечується відповідний стандартам рівень основних технологічних властивостей (передусім рідкоплинности та схильности до утворення гарячих тріщин). Це свідчить про можливість одержання з таких стопів методами лиття тонкостінних деталів складної конфіґурації. Подальші дослідження будуть орієнтовані на підвищення механічних і експлуатаційних властивостей експериментальних стопів системи «алюміній–мідь» за рахунок введення нетоксичних і відносно дешевих зміцнювальних і модифікувальних добавок.

Ключові слова: високоміцні ливарні стопи системи «алюміній–мідь», магнетогідродинамічне (МГД) оброблення, структура, міцність, відносне видовження, рідкоплинність, схильність до утворення гарячих тріщин.

(Received 27 July, 2023; in final version, 5 August, 2023)

1. INTRODUCTION

The development of various branches of mechanical engineering necessitates the need to enhance the levels of mechanical, physical, technological, operational, and other properties of existing materials, particularly aluminium alloys widely used in the structures of modern machines and mechanisms for the production of high-tech equipment, primarily in aerospace, automotive, transportation, energy, and other industries. Therefore, the development of new technologies and equipment that will enable the practical implementation of these tasks is a relevant and promising direction for the advancement of science, technology, and industrial production.

Principal features of casting aluminium alloys are the unique combination of their physical properties (relatively low density), mechanical properties (high strength), and technological properties (for example, comparatively low preparation and casting temperatures), as well as their preference for operational temperature-time parameters (including cyclic strength). Most importantly, they offer the capability of obtaining complex-shaped parts through casting methods.

A special place is occupied by high-strength casting Al–Cu alloys, as they can compete with steels and titanium alloys in terms of specific strength (the strength-to-density ratio) can compete with steels and titanium alloys, and due to their significantly lower specific gravity, they have long been one of the main structural materials in the aircraft industry. On average, the total mass components from high-strength casting Al–Cu alloys in an aircraft amount to 300 kg, and in large aircraft, it can reach 2000 kg. Moreover, in recent years, developers, manufacturers, and consumers of such materials have been unsuccessfully striving to expand the scope of their application to the production of aircraft engine parts, both hull [1] and piston group [2, 3].

However, on this path, researchers and production workers have to solve a number of complex problems. For instance, the most common high-strength casting Al–Cu alloys include either the toxic element cadmium (AM4.5Cd alloy according to GOST 1583–93) [4, 5] or the expensive element silver [6] as a strengthening additive. Meanwhile, alloy counterparts without such additives exhibit significantly lower strength characteristics [6]. Moreover, due to the specific composition of these alloys (strict regulation of copper content within 4–5.5% by weight and silicon content not exceeding 0.2%) and in accordance with the state diagram of the Al–Cu system [7, 8], these materials have a wide solidification range. This leads to unsatisfactory casting properties, primarily low fluidity, and increased susceptibility to hot cracking during solidification, significantly limiting the ability to produce casings, especially thin-walled and critical components.

Therefore, experts worldwide strive to address these issues while ensuring environmental safety, economic feasibility, and relative technical and technological simplicity. These efforts are based on the development of new alloy compositions, melt preparation and out-of-furnace processing in the liquid state, the application of external physical effects, special casting methods, and heated modes [2, 3, 9–11].

In Ukraine, scientists from the Physical and Technological Institute of Metals and Alloys (PTIMA) and G. V. Kurdyumov Institute for Metal Physics (IMP) of the National Academy of Sciences of Ukraine have accumulated significant experience application of the energy of electromagnetic fields for processing casting aluminium alloys (both silumins and high-strength ones), with subsequent improvement of their structure and mechanical properties in the as-cast and heat-treated states [12–14].

2. EXPERIMENT PROCEDURE

At the first stage, the authors concentrated their efforts on the following research directions: 1) preparation of an experimental high-strength casting Al–Cu alloy, including the use of electromagnetic fields and magnetohydrodynamic (MHD) effects; 2) investigation of the structure and basic mechanical properties of the experimental alloy, comparing them with the properties of analogous alloys and requirements of the standards; 3) study of the main casting properties of the experimental alloy, particularly fluidity and susceptibility to hot cracking.

2.1. Features of Preparing the Experimental Alloy Using a Casting Magnetodynamic Installation

To verify the developed scientific approaches and technical solutions, an experimental batch (up to 100 kg) of an Al–Cu alloy was prepared, with its chemical composition in terms of major elements matching that of the most common high-strength aluminium casting alloys: AM4.5Kd (Ukraine) and A201 (USA) [6]. However, at this stage of the research, the experimental alloy did not include the strengthening additives typically present in standard alloys, such as the toxic cadmium or expensive silver. It should be noted that alloy analogues without such additives are known, such as AC1B (Japan) and A-U5GT (France) [6].

For the preparation of the experimental alloy, an experimental-industrial casting magnetohydrodynamic installation MDI-6A (Fig. 1) was used [12, 15].

The main function of the MDI is to provide the desired temperature of the liquid metal bath in the channel through adjustable induction heating, electromagnetic stirring by creating various modes of melt circulation (Fig. 2), perform controlled electromagnetic pouring of the liquid alloy into different metal receptacle, and, thus, technologically, the MDI functions as a mixer-batcher for liquid metal.

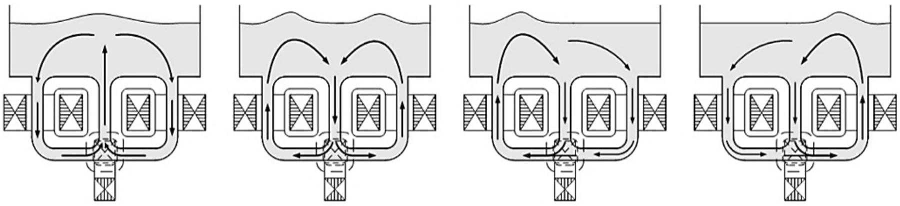
In obtaining the experimental alloy, two fundamentally new techno-

a *b*

Fig. 1. External view (*a*) and general scheme (*b*) of the magnetohydrodynamic installation MDI-6A: *1*—crucible; *2*, *3*, *4*—branches of the induction channel; *5*—closed magnetic cores of the inductors; *6*—inductor coils; *7*—open magnetic core of the electromagnet; *8*—electromagnet coils; *9*—detachable metal duct; *10*—crucible cover.

logical schemes for processing aluminium melt in the MDI were employed. The first type of processing, the complex MHD thermal & forced one, is realized through physical factors, while the second type (complex refining) involves the use of refining reagents and corresponding technological equipment.

In the liquid metal filling the induction channel of the MDI, a variable electric current is generated (with a density of up to $20\cdot106$ A/m^2), as well as a variable magnetic field (up to 0.3 T) and a volumetric electromagnetic force (up to $60\cdot10^3$ N/m^3), which moves the molten metal in the form of a submerged jet from the channel into the liquid metal bath in the crucible. Electromagnetic pressure is also created in the channel (up to $2.5\cdot10^5$ Pa) and electromagnetic vibration at a frequency of 100 Hz, can occur a controlled pinch effect, which is the compres-



a *b* *c* *d*

Fig. 2. Main schemes of melt circulation in the MDI under the influence of electromagnetic forces and MHD-effects: melt outflow mode from the central branch of the channel (*a*); melt suction mode into the central branch of the channel (*b*); mirror-symmetrical modes of lateral mixing (*c*, *d*).

sion of the liquid metal conductor with its own magnetic field, accompanied by local overheating and rarefaction in the melt. Additionally, vortex motion of the molten metal occurs in the channel itself and its outfalls due to MHD effects. The movement of the melt in the MDI bath influences predominantly by purely hydrodynamic effects.

Thus, during the residence time in the MHDU, the liquid alloy is subjected to sequential and multiple thermal and force effects, which, according to the theory of the liquid state of metallic melts, lead to dispersion of microneighbourhood regions within them and subsequently to the refinement of the structural components of solidified alloys [16–19].

In the continuation of the research previously conducted at the Institute for PTIMA NAS of Ukraine [20], it has been demonstrated that thermal&forced MHD processing of liquid aluminium alloys in the MDI can exert a physical impact on the liquid state of the metallic medium, comparable to the effect of modification, but without the use of substances-modifiers. This is manifested in the destruction of areas of microinhomogeneities caused by negative metallurgical inheritance of the charge and the technology of alloy preparation. These effects are further observed in the solid state of the alloy, leading to changes in its structure and primarily the improvement of plastic properties, which are more structurally sensitive characteristics compared to strength indicators. According to previous research conducted on hypo- and hypereutectic silumins, such MHD processing provides a certain increase in strength (up to 15–20%) and a significant increase (up to 2–4 times) in elongation compared to the standard requirements, including international standards, for aluminium alloys obtained through traditional melting technologies, processing, and pouring techniques [12, 21].

In addition, to ensure a high level of purity of the experimental alloy from hydrogen and non-metallic inclusions, a comprehensive refining scheme developed at the PTIMA NAS of Ukraine was applied. The complex t processing in MDI includes argon blowing of the aluminium melt in a controlled atmosphere with simultaneous multiple circulation of the current-carrying liquid metal through a ceramic foam filter installed on one of the outfalls of the induction channel [12, 22, 23]. By implementing this scheme on silumins, the hydrogen content in the processed alloy was significantly reduced to a level of $0.05\ \mathrm{cm}^3/100\ \mathrm{g}$ of alloy, which corresponds to the levels achieved during vacuum processing, and it was possible to remove up to 80% of non-metallic inclusions from the alloy.

2.2. Study of the Structure and Mechanical Properties of the Experimental Alloy

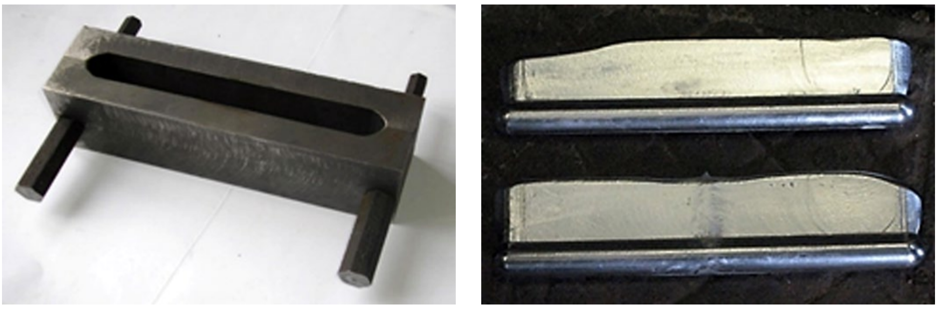
After the preparation of the alloy in the MDI, samples were cast from it to investigate the structure and key mechanical properties. These investigations were carried out using standard techniques. From the obtained alloy, samples were cast into a cast iron mould for mechanical testing and metallographic analysis (Fig. 3, *a*). The cast samples (Fig. 3, *b*) after machining took the form of rods, 230 mm in length and 25 mm in diameter, after removing the excess material. The cooling rate of the solidifying melt did not exceed 10^2 K/s.

A portion of the obtained cast samples underwent mechanical testing using break strength testing method. The remaining samples underwent standard heat treatment, typical for high-strength casting Al–Cu alloys, specifically the T6 heat treatment mode. This process involves quenching (heating up to 545 °C, holding for 10–14 hours, and water cooling at 20–100 °C) followed by complete artificial aging (heating up to 170 °C, holding for 6–10 hours). After the heat treatment, the samples were subjected to mechanical testing and metallographic analysis of their structure using standard accepted methods for such alloys.

2.3. Investigation of the Main Casting Properties of the Experimental Alloy

2.3.1. Study of the Fluidity of the Experimental Alloy

During the development of an experimental analogue of a high-strength casting Al–Cu alloy, it was necessary to achieve the required mechanical properties and a level of technological characteristics for the alloy that would allow the production of cast products. Special attention was given to the study of fluidity and susceptibility to hot cracking in the conducted research. These are the main indicators that directly affect the feasibility and quality of the castings produced.



a *b*

Fig. 3. Casting chill mould (*a*) and the cast samples of the alloy with excess material obtained in it (*b*).

a *b*

Fig. 4. Scheme of the U-shaped fluidity test sample (*a*) and the casting chill mould (*b*) for its production.

The study of fluidity utilized a standard U-shaped sample, as shown in Fig. 4, *a*, with the corresponding mould for its production depicted in Fig. 4, *b*. The sample has a channel of constant cross-section with a curved shape, which allows for the evaluation of the alloy's fluidity. Due to the complex configuration of the sample cavity, it is possible to assess qualitatively the alloys' susceptibility to hot cracking.

To determine the fluidity using such test samples, the length of the channel and the cross-sectional area of the mould are selected in a way that the metal, upon solidification, does not completely fill the entire cavity. The fluidity is measured by the length of the obtained rod under specified casting and cooling conditions. During the casting process, the following parameters need to be observed in accordance with the standard:

the temperature of the mould before casting should be $(100 \pm 10)^\circ$C;

the temperature of the melt should exceed the liquidus temperature of the alloy by $(10 \pm 0.5)\%$;

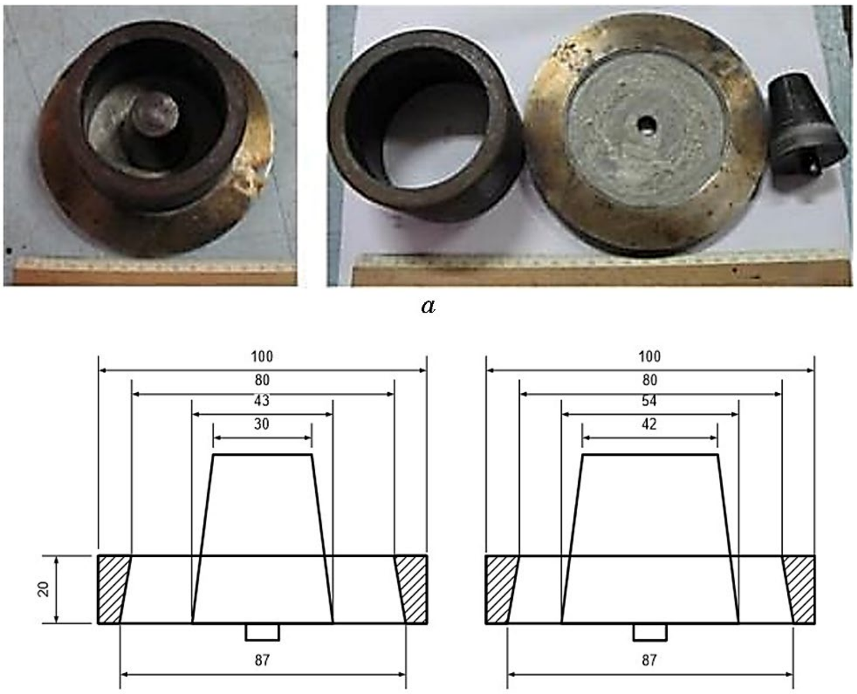
the same hydraulic parameters for casting should be maintained when collecting the entire series of samples.

2.3.2. Study of the Susceptibility of the Experimental Alloy to Hot Cracking during Solidification

The susceptibility of alloys to hot cracking during solidification is a complex property influenced by various parameters, including linear shrinkage and its onset temperature, mechanical properties (strength, ductility and elasticity) of the alloy at high temperatures, rate and nature of solidification, mould compliance, *etc*.

To obtain quantitative assessments of the occurrence of hot cracks in castings, special samples are used. In the study, a ring-shaped sample (Fig. 5, *a*) was employed. It is a disassembled structure consisting of a bottom plate, a ring for forming the outer part of the cast sample, and a cone that shapes the inner diameter. The plate has a hole for the installation of an internal cone, and has a groove made around it, the diameter of which corresponds to the outer diameter of the ring. Therefore, all the components have a precise positioning on the plate relative to each other, enabling the production of castings with consistent dimensions and the creation of identical conditions for braking linear shrinkage.

However, since identifying the primary cause of hot crack formation is challenging for each specific alloy, the tendency to form defects is determined through a comparative method. For this purpose, another ring-shaped sample was manufactured, having the same outer ring dimensions but an increased cone diameter. By reducing the cross-section of the solid sample, it imposes an additional restriction on linear shrinkage and allows the more accurate detection of defects during casting. Figure 5, *b* illustrates the schematics of the two forms used in



a

b

Fig. 5. The ring-shaped samples for assessing hot cracking susceptibility (*a*). Schematics of the two forms of the ring-shaped samples used in the experiments (*b*).

the experiments. The ratio of the cross-sectional areas of the obtained samples is approximately 1:1.5. Figure 5, *b* illustrates the schematics of the two forms used in the experiments. The ratio of the cross-sectional areas of the obtained samples is approximately 1:1.5.

3. RESULTS AND DISCUSSION

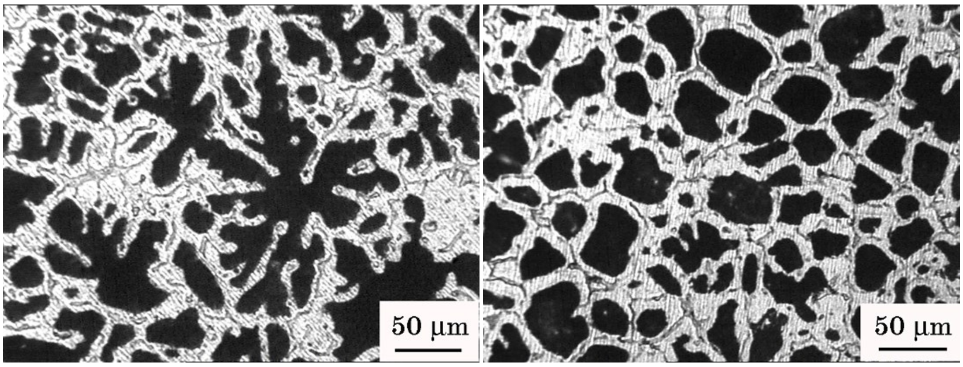
Using the MDI, an experimental alloy was prepared, the composition of which, as well as the compositions of analogues alloys, are given in Table 1. The base aluminium melt was initially obtained in a resistance furnace, and then the necessary alloying components, primarily copper and manganese, were introduced into the MDI.

Immediately after the preparation of the initial alloy, samples were poured for the investigation of the structure, basic mechanical, and casting properties (see Figs. 3, 4, 5). Then, the alloy underwent MHD processing in the MDI according to the previously developed regimes for 30 minutes, and corresponding samples were again selected [12]. Subsequently, a comprehensive refining processing of the liquid alloy was carried out for 20 minutes, including argon blowing with simultaneous filtration through a foam ceramic filter under MHD influence, and experimental samples were cast again.

Metallographic examinations and mechanical tests of the produced samples were conducted at the G. V. Kurdyumov Institute for Metal Physics (IMP) of the National Academy of Sciences of Ukraine. It was found that MHD processing of the experimental Al–Cu alloy, which does not contain cadmium and silver, had an effective modifying effect

TABLE 1. Chemical composition of the experimental alloy and its analogues [6].

Alloy	The chemical composition (Al–base), mass %:													
	Cu	Mn	Ti	Cd	Ag	Mg	Ni	Fe	Zn	Si	Zr	Pb	Sn	Cr
Experimental	4.65	0.43	0.19	–	–	0.01	<0.01	0.06	<0.01	0.18	–	–	–	–
AM4.5Kd (GOST 1583-93)	4.50–5.10	0.35–0.80	0.15–0.35	0.07–0.25	–	0.05	–	0.15	0.10	0.20	0.15	–	–	–
A201 (USA)	4.60	0.35	0.15–0.35	–	0.70	0.35	–	<0.15	–	<0.10	–	0.70	–	–
AC1B (Japan)	4.00–5.00	0.10	0.05–0.30	–	–	0.15–0.35	–	0.35	0.10	0.20	–	0.05	0.05	0.05
A-U5GT (France)	4.20–5.00	0.10	0.05–0.30	–	–	0.15–0.35	0.05	0.35	0.10	0.20	–	0.05	0.05	–



a *b*

Fig. 6. Microstructure of the experimental Al–Cu alloy in the as-cast state: without external processing (*a*); after MHD processing in the MDI (*b*).

on its structure (Fig. 6). In the absence of processing, the alloy exhibits a dendritic structure (Fig. 6, *a*). After MHD processing, the dendrites acquire a cellular structure, almost globular (Fig. 6, *b*).

The research revealed the presence of $CuAl_2$ phase inclusions along the boundaries of globular dendrites, which negatively affect the strength properties. After the conducted heat treatment, these formations transformed into an oversaturated solid solution.

Tests were conducted to determine the main mechanical properties of the experimental alloy and compare them with the values of the alloy analogues (Table 2). It was found that the experimental alloy exhibited higher values of elongation compared to the considered analogues, including those containing toxic and expensive strengthening additives. At the same time, the strength characteristics of the experimental alloy were lower than those characteristics of standard alloys containing cadmium and silver are, but exceeded the properties of analog alloys without these additives.

Further, using the obtained technological samples, the casting

TABLE 2. Key mechanical properties of the experimental Al–Cu alloy and standard analogue alloys after T6 heat treatment.

Alloy	Tensile strength σ_B, MPa	Elongation δ, %
Experimental alloy	400	10.5
AM4.5Kd (GOST 1583-93)	490	4.0
A201 (USA)	448	8.0
AC1B (Japan)	304	3.0
A-U5GT (France)	340–360	8.0–11.0

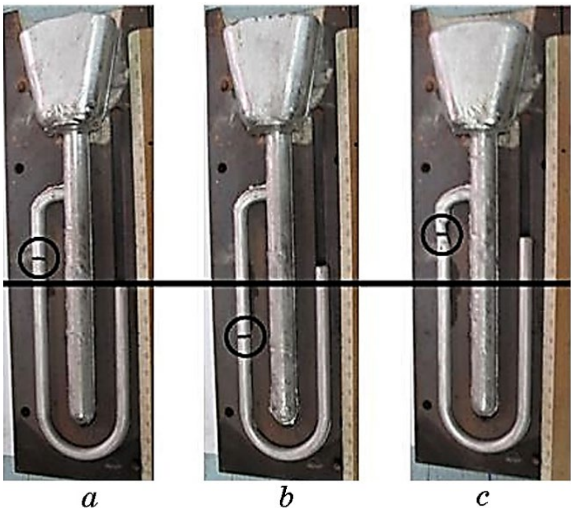


Fig. 7. Fluidity samples of the experimental Al–Cu alloy: in the as-cast state (*a*); after MHD processing in the MDI (*b*); after complex refining and MHD processing in the MDI (*c*).

TABLE 3. Fluidity of the experimental and standard Al–Cu alloys.

Alloy		Fluidity, mm	Density, kg/m^3
Experimental alloy	In the as-cast condition	287	2691
	After MHD processing in the MDI	299	2693
	After complex refining and MHD processing in the MDI	316	2750
AM4.5Kd (GOST 1583-93)		245	2800

properties of the experimental Al–Cu alloy were studied in comparison with the standard AM4.5Kd alloy.

The results of fluidity tests are presented in Fig. 7 and Table 3. It can be observed that the comprehensive and refining MHD processing of the experimental alloy in the MDI allows for improved density and tightness, as well as an increase in fluidity by 10% compared to the initial value (and by 30% compared to the standard AM4.5Kd alloy, which contains toxic cadmium).

As for the investigation of the experimental alloys' susceptibility to hot cracking during solidification, the results of such studies are presented in Fig. 8 and Table 4. It can be seen that the experimental alloy has a narrower solidification range (by 13 °C) compared to the standard alloy containing cadmium. This leads to a slight increase in the samples' section before the occurrence of cracks.

a *b*

Fig. 8. Samples for studying the susceptibility of Al–Cu alloys to hot cracking during solidification: experimental alloy (*a*); standard A201 alloy (USA) (*b*).

TABLE 4. Study of the susceptibility of the experimental and standard Al–Cu alloy to hot cracking during solidification.

Alloy	Solidification range, °C	Hot cracking susceptibility (Ring width), mm
Experimental alloy after complex refining and MHD processing in the MDI	642–551	28
AM4.5Kd (GOST 1583-93)	650–548	27.5

4. CONCLUSIONS

In conclusion, the conducted research has established the following.

1. In order to enhance the properties of high-strength casting Al–Cu alloys, expand their applications, reduce production costs, and ensure environmental safety, there is a need for the development of new scientific approaches and technical solutions. This includes the exclusion of toxic (cadmium) and expensive (silver) components from the alloy composition, as well as the utilization of efficient equipment and technologies.

2. The utilization of complex refining processing, electromagnetic field energy, and magnetohydrodynamic effects implemented in magnetodynamic casting installations has facilitated the production of the experimental Al–Cu alloy with increased ductility compared to standard alloys in the same group. The strength characteristics of the experimental alloy only lag behind alloys additionally reinforced with cadmium or silver.

3. The investigation of the casting properties of the experimental alloy has confirmed the potential for manufacturing critical compo-

nents, including thin-walled and complex configuration, from this material. Further research is intended to be carried out in the following directions:
to improve the basic mechanical properties of the alloy to the level of standard high-strength casting Al–Cu alloys, the selection of alloying components that promote the formation of the desired alloy structure needs to be conducted;
due to potential changes in the chemical composition of high-strength alloys, attention should be given to some changing the heat treatment modes of cast products to achieve maximum strengthening effects;
the characteristics of introducing alloying and modifying components into the melt (both in pure form and as part of master alloys) need to be studied, particularly under the impact of electromagnetic effects; if necessary, solutions for obtaining special master alloys should be proposed.

In order to explore the possibility of expanding the application range of the experimental alloy, in-depth investigations into its special, physical, and operational properties are required.

The work is being carried out within the framework of competitive research programs of the National Academy of Sciences of Ukraine.

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