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The influence of Cu additions on the microstructure and properties of Al–Fe system alloys produced by casting into electromagnetic crystallizer

Andrey E. Medvedev*[1], PhD (Physics and Mathematics), junior researcher
Olga O. Zhukova[2], postgraduate student
Aigul F. Shaikhulova[3], PhD (Engineering), Associate Professor, senior researcher
Maxim Yu. Murashkin[4], PhD (Engineering), senior researcher
Ufa University of Science and Technology, Ufa (Russia)

***E-mail:** medvedevae@uust.ru,
medvedevandreyrf@gmail.com

[1]ORCID: https://orcid.org/0000-0002-8616-0042
[2]ORCID: https://orcid.org/0000-0002-1879-9389
[3]ORCID: https://orcid.org/0000-0002-3340-3880
[4]ORCID: https://orcid.org/0000-0001-9950-0336

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Abstract: The modern electrical engineering industry requires cheap and easily reproducible aluminum alloys with advanced mechanical strength and electrical conductivity. This work studies the influence of small (up to 0.3 wt. %) copper additions on the microstructure and physical and mechanical properties, as well as phase transformations in the Al–Fe system alloys with an iron content of 0.5 and 1.7 wt. %, produced by continuous casting into electromagnetic crystallizer. Alloys of the above chemical compositions were produced, and subsequently annealed at 450 °C for 2 h. In all states, the microstructure (via SEM), yield strength, ultimate tensile strength, elongation to failure, and electrical conductivity were studied. It has been shown that copper additions lead to an increase in the strength of both alloys and a slight decrease in their ductility compared to similar materials without copper. An increase in strength and a decrease in ductility due to the copper addition is associated with the formation of more dispersed intermetallic particles in copper-containing Al–Fe system alloys. Additional spheroidizing annealing leads to a decrease in the length of the interphase boundary between the aluminum matrix and iron aluminide particles due to a change in their morphology, which leads to an increase in electrical conductivity. In general, copper-containing alloys showed higher mechanical strength with lower electrical conductivity, as well as higher thermal stability.

Keywords: Al; Al–Fe–Cu; casting into electromagnetic crystallizer; phase transformations; mechanical properties; electrical conductivity; thermal stability.

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INTRODUCTION

Today, the major consumers of aluminum alloys are high-tech sectors of the economy, such as locomotive, railcar and shipbuilding, aerospace, automotive, electrical industries, construction, and production of power lines [1]. The current trends in metallurgy and materials science are the need to reduce weight, metal consumption, and increase the efficiency of the materials' use. These trends are largely determined by the development of new materials with the necessary performance characteristics and the introduction of technologies for their production.

Due to their distinctive performance characteristics and technical properties, aluminum alloys stand out from other metallic materials for structural and electrical purposes. Aluminum and its alloys are used in electrical engineering and usually are produced in the form of wire rod/wire obtained by the methods of combined casting and rolling, casting, rolling, and pressing, using subsequent rolling or drawing [2; 3]. However, despite relatively high level of electrical conductivity (52–62 % IACS), their strength and heat resistance are rather low [4], which is further complicated by the fact, that strength and electrical conductivity improvement in Al alloys usually exclude each other [5]. In this regard, modern research is aimed at finding new alloys and production technologies that will allow the use of aluminum more efficiently, both in terms of physical and mechanical properties, as well as from a financial standpoint.

A step towards the wider use of aluminum was the introduction of aluminum alloys of the Al–Fe system of such grades as 8030 and 8176, from which conductors with a cross section of 2 to 10 mm are made[1]. These alloys have greater strength than pure aluminum, such as grade 1350, good ductility and an acceptable level of fire safety. Improvements in physical and mechanical properties in alloys of the Al–Fe system were achieved by introducing Fe (in the range of 0.4–1.0 wt. %) into the composition of aluminum [6; 7], as well as small additions of Cu (up to 0.3 wt. %) [8]. The presence of Fe provided an increase in the strength of the alloy after its heat treatment (annealing). Small additions of Cu also improve the strength characteristics of conductors based on Al–Fe alloys. However, a number of physical and technical-operational indicators limit their application, encouraging researchers to look for further ways to increase the strength and thermal stability of alloys of the Al–Fe system without losing their electrical conductivity.

In recent decades, attention has been paid to the formation of nanostructured, nanophase-containing, and ultrafine-grained structures in semi-finished products and products from aluminum alloys, which can significantly improve the complex of physical and mechanical, as well as functional and operational characteristics [9; 10]. In addition, traditional methods for obtaining and processing aluminum-based alloys are being improved and developed.

One of the promising methods for the production of wire rod and wire from aluminum alloys for electrical purposes is continuous casting into electromagnetic crystallizers (EMC), also known as casting into electromagnetic mold. The use of EMC makes it possible to provide unique physical and mechanical properties of the wire by achieving extremely high cooling rates (10^3–10^4 K/s), providing unique alloy structures and properties (high strength and high electrical conductivity), as it was shown on the example of the Al–Zr [11] and Al–Ca–Fe–Si [12] alloys.

In this paper, the results of studies are carried out, which are a continuation of the work carried out by a group of scientists from Ufa University of Science and Technology, aimed at creating new materials for electrical purposes based on Al alloys obtained by casting in EMC. In [13] the Al–La–Ce alloy was produced and then subjected to high-pressure torsion (HPT). It was demonstrated that HPT does not only result in the grain size refinement, but also in the formation of a solid solution of La and Ce in Al, although this system is considered to have zero solubility of the alloying elements. In [14] studies dedicated to the Al–Fe system were conducted, showing that Al–Fe alloys, produced via EMC, tend to have higher mechanical strength and finer grain size relatively to the alloys produced by conventional methods. Also, EMC resulted in the formation of the metastable Al_2Fe phase, usually not presented in the Al–Fe system alloys [15]. As research materials, Al–0.5Fe and Al–1.7Fe alloys (wt. %), obtained by casting in EMC, additionally alloyed with 0.3 wt. % Cu (hereinafter, Al–0.5Fe–0.3Cu and Al–1.7Fe–0.3Cu, respectively), were used.

Based on the previous research, the annealing for the studied materials was conducted. In [16; 17] it was demonstrated that the annealing in the range of 450–550 °C in the Al alloys with low immiscibility of the alloying elements leads to coagulation and spheroidization process of the intermetallic particles without phase transformations. The spheroidization of lamellar/plate-like intermetallic particles in alloys of the Al–Fe system obtained by casting in EMC is accompanied by a decrease in the area of the interfacial surface and an increase in their electrical conductivity. Such heat treatment also results in the increase of the material's ductility. Since addition of the Cu into Al–Fe alloy decreases the ductility of the alloy, the annealing at 450 °C may be performed as a ductility increasing measure.

The aim of this work is establishing the influence of copper additions and intermetallic particles morphology on the mechanical and electrical properties of the Al–0.5Fe and Al–1.7Fe alloys, produced by electromagnetic casting.

METHODS

Initial bars with a diameter of 11 mm and a length of more than 2 m from alloys of the Al–Fe system with an iron content of 0.5 and 1.7 wt. %, and the addition of copper 0.3 wt. % were made by continuous casting in EMC on the experimental laboratory casting equipment at the LLC "Scientific and Practical Center for Magnetic Hydrodynamics" (Krasnoyarsk, Russia). The chemical composition of the studied alloys is presented in Table 1.

The study samples were prepared from aluminum grade A85 and the addition of Fe80Al20 master alloy in proportions selected to match the required iron concentration. After reaching a melt temperature of more than 800 °C, continuous casting was carried out in an EMC equipment at a rate of 12.4 mm/s. Cast blanks were processed by cold drawing to a diameter of 3 mm in 8 passes.

Heat treatment of samples was carried out in an atmospheric Nabertherm B 180 (Lilienthal, Germany) furnace at 450 °C for 2 h.

Scanning electron microscopy (SEM) was performed on a JEOL JSM-6490LV (Tokyo, Japan) microscope at an accelerating voltage of 15 kV. For image processing and quantitative measurements of microstructural elements (average grain size, average particle size of the second phases), the "ImageJ" software and the "Grain Size" software package were used.

Tensile tests were carried out on an Instron 5982 (Norwood, USA) machine at room temperature and a strain rate of 10^{-3} s^{-1}. At least 3 samples of each test condition were tested to obtain statistically reliable results. Yield strength ($\sigma_{0.2}$), ultimate tensile strength (σ_{UTS}), and elongation to failure (δ) were obtained using flat specimens with dimensions of 2.0×1.0×6.0 mm.

Electrical conductivity (ω) was determined with an error of ±2 % by the eddy current method. The electrical conductivity relative to annealed copper (International Annealed Copper Standard, % IACS) was calculated using the equation:

$$IACS = \frac{\omega_{Al}}{\omega_{Cu}} \cdot 100\,\%, \tag{1}$$

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[1] *GOST R 58019-2017. Rod aluminium wire of 8176 and 8030 alloys. Specifications. M.: Standartinform, 2018. 20 p.*

Table 1. *Chemical composition of Al–Fe alloys, wt. %*
Таблица 1. *Химический состав Al–Fe сплавов, мас. %*

Alloy	Cu	Fe	Si	Σ (Mn, Cr, Zn)	Al
Al–0.5Fe–Cu	0.30	0.50	0.02	<0.01	99.04
Al–1.7Fe–Cu	0.30	1.85	0.00	<0.01	97.71
AA8176 (ASTM B800)	–	0.40–0.50	0.07	<0.03	The rest
AA8030 (ASTM B800)	0.15–0.20	0.35–0.45	0.07	<0.03	The rest

Note. For comparison shows the chemical composition of AA8176 and AA8030 alloys currently used as a material for electrical conductors both in Russia and abroad.

Примечание. Для сравнения приведен химический состав сплавов AA8176 и AA8030, в настоящее время используемых в качестве материала для электропроводников в России и за рубежом.

where ω_{Al} is the measured electrical conductivity of the Al alloy;
ω_{Cu} is the electrical conductivity of annealed chemically pure copper (58 MS/m).

RESULTS

Evolution of the microstructure as a result of heat treatment

Fig. 1 shows the microstructure of billets of Al–0.5Fe–0.3Cu and Al–1.7Fe–0.3Cu alloys, obtained by casting into an electromagnetic mold. Analysis of the images, obtained by SEM, showed that the aluminum matrix contains inclusions of the intermetallic phase formed during crystallization. In the Al–1.7Fe–0.3Cu alloy, particles of the second phase form a continuous net with a cell size of (2.1±0.3) μm (Fig. 1 b), and in the Al–0.5Fe–0.3Cu alloy, the intermetallic network has the average cell size is (5.7±0.9) μm (Fig. 1 a). Judging by the size of the dendritic cells, the cooling rate during crystallization of the billet was at least 1000 °C/s. A detailed examination (Fig. 1 c, 1 d) shows that the intermetallic phase crystallized in the form of plates/needles up to (0.6±1.0) μm thick in Al–0.5Fe–0.3Cu and Al–1.7Fe–0.3Cu alloys. In addition, intermetallic particles in copper-containing alloys are more fragmented than in alloys without copper.

Fig. 2 shows the microstructure of Al–0.5Fe–0.3Cu and Al–1.7Fe–0.3Cu alloys obtained by casting in EMC and additional annealing at 450 °C for 2 h. Quantitative analysis showed that annealing does not lead to a noticeable change in the size of dendritic cells in both studied materials. However, due to annealing, the particles began to spheroidize – in the structure of both alloys, a change in the morphology of thin plates/needles of the intermetallic phase is observed – their spheroidization.

Fig. 3 shows the microstructure of Al–1.7Fe and Al–1.7Fe–0.3Cu alloys after casting in EMC and additional annealing at a temperature of 450 °C for 2 h. The presence of the copper in the alloy reduces the tendency of the alloy to spheroidization after annealing at a temperature of 450 °C – in Al–1.7Fe–0.3Cu alloys particles have sharper and rougher edges.

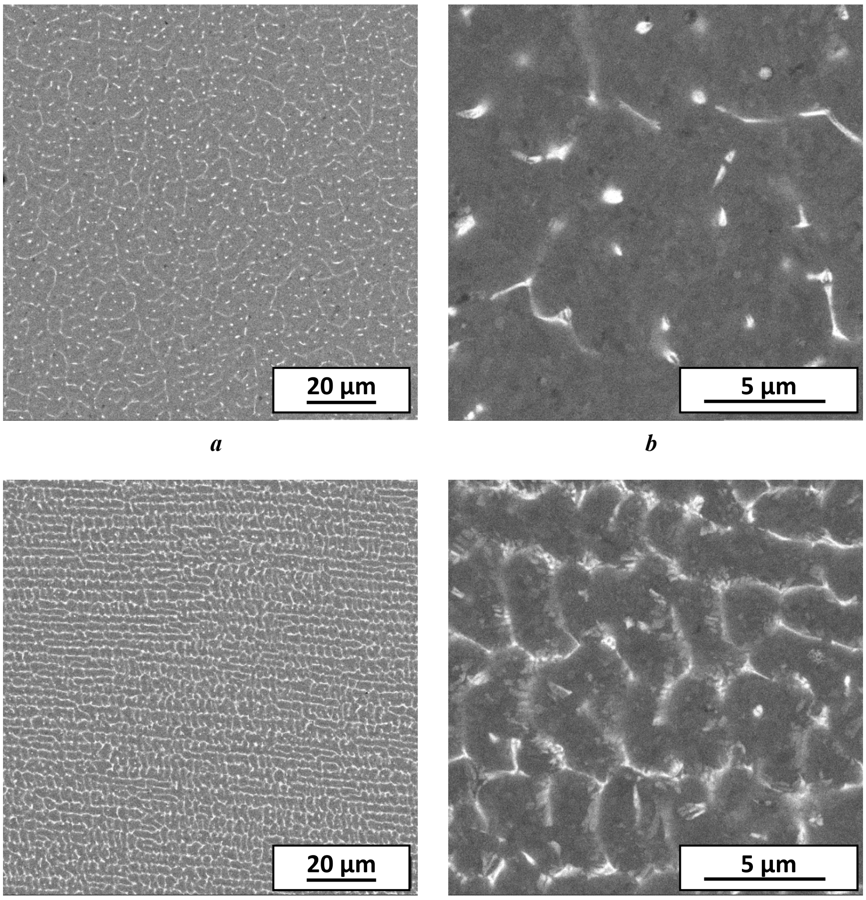
Evolution of mechanical and electrical properties as a result of deformation processing

Table 2 shows the physical and mechanical properties of alloys of the Al–Fe system. In the initial state the ultimate tensile strength of the Al–0.5Fe–0.3Cu alloy is (106±4) MPa, in the Al–1.7Fe–0.3Cu alloy the σ_{UTS} is (174±11) MPa. With the addition of 0.3 wt. % Cu – the electrical conductivity of the Al–0.5Fe alloy is reduced by 1.7 % IACS, while the electrical conductivity of the Al–1.7Fe alloy is reduced by 8.2 % IACS (1). Such a change in electrical conductivity indicates that it is mainly controlled by the content of iron, and, accordingly, the proportion of particles of iron aluminides in alloys.

Spheroidizing annealing, aimed at reducing the length of the interfacial boundary in the alloys, led to a decrease in strength and an increase in plasticity and electrical conductivity in the study materials. Thus, in the Al–0.5Fe–0.3Cu alloy, ductility, and electrical conductivity after annealing at 450 °C for 2 h increased from 33.7 to 37.8 % and from 56.1 to 60.9 % IACS, respectively, while the tensile strength decreased from 106 to 100 MPa (within the error value). At the same time, as a result of similar annealing, it increases the ductility and electrical conductivity in the Al–1.7Fe–0.3Cu alloy from 23.3 to 23.6 %, respectively, and from 41.4 to 55.9 % IACS, and the tensile strength decreases from 175 to 150 MPa.

DISCUSSION

This paper discusses the effect of Cu alloying on the microstructure and physical and mechanical properties of alloys of the Al–Fe system, obtained by casting in EMC. It has been established that the introduction of 0.3 wt. % Cu leads to a change in the morphology of intermetallic particles formed during crystallization at rates higher than 10^3 °C/s. In alloys without Cu, the particles form dendritic cells crystallize in the shape of long plates/needles with evenly rounded edges, and in in copper-containing alloys, such particles have a noticeably shorter length, forming "fragmented" clusters. Most likely, the rough shape of the intermetallic particles forms due to the casting method, since in [18] it is demonstrated, that in additively manufactured



a *b*

c *d*

Fig. 1. *Microstructure of electromagnetically cast alloys:* ***a, b*** *– Al–0.5Fe–0.3Cu;* ***c, d*** *– Al–1.7Fe–0.3Cu, SEM*
Рис. 1. *Микроструктура сплавов, полученных литьем в электромагнитный кристаллизатор:*
a, b *– Al–0,5Fe–0,3Cu;* ***c, d*** *– Al–1,7Fe–0,3Cu, РЭМ*

Al–Cu–Fe alloy intermetallic particles have smooth rounded edges. The other production methods demonstrate similar difference [19; 20].

Addition of the copper also increases the number of intermetallic particles nuclei, decreasing the distance between them, thus shortening the free dislocation path and increasing the strength of the alloy. The addition of 0.3 wt. % Cu in alloys with a selected Fe content leads to an increase in the tensile strength (from 90 to 106 MPa in the Al–0.5Fe alloy and from 150 to 174 MPa in the Al–1.7Fe alloy) and a decrease in electrical conductivity (from 57.8 to 56.1 % IACS in Al–0.5Fe alloy and from 49.6 to 41.4 % IACS in Al–1.7Fe alloy). This change in mechanical strength and electrical conductivity is sensitive to the Fe content – the value of the difference in properties is proportional to the iron content. Thus, it might be assumed that the copper doesn’t have the leading role in the properties’ changes of the studied alloys.

It can also be noted that additional alloying with Cu, along with an increase in strength (which is probably due to the formation of a solid solution in aluminum by copper atoms), led to an insignificant decrease in the plasticity of the study materials.

It is important to note that the addition of the same amount of copper to a commercially available 8030 alloy does not lead to a similar increase in its strength, in comparison with an 8176 alloy in which copper is absent (Table 2). Most likely, the difference in mechanical strength noted in this study is due to the difference in the methods for obtaining semi-finished products. As noted above, in alloys obtained by continuous casting in EMC, the wires/rods/blanks are rapidly cooled, and thus, during the crystallization process, most of the copper remains in the aluminum solid solution. In mass-produced semi-finished products, obtained by the method of continuous casting and rolling [21], the copper content in the solid solution of aluminum is noticeably lower, due to the lower crystallization rate (by ~2 orders of magnitude) and slow cooling during subsequent rolling.

The nature of the intermetallic particles is an open question. It is considered that iron has near-to-zero solid solution concentration in aluminium [22; 23], thus no solid solution of Fe should be presented in the Al–Fe alloys, and all the Fe should be bounded in the Al_xFe_y intermetallic particles. Copper, however, can form the solid solution in aluminium with the concentration up to 0.2 wt. % (~0.1 at. %) at a normal condition. According to the ternary Al–Cu–Fe diagram [24], at a given concentration the intermetallic particles are presented by $Al_{13}Fe_4$ and Al_7Cu_2Fe phases. Since the total amount of Cu in the Al–0.5Fe–0.3Cu alloy is 0.3 wt. % and could even be considered impurity, it would be quite hard to separate the strengthening effect of Cu solid solution in aluminium

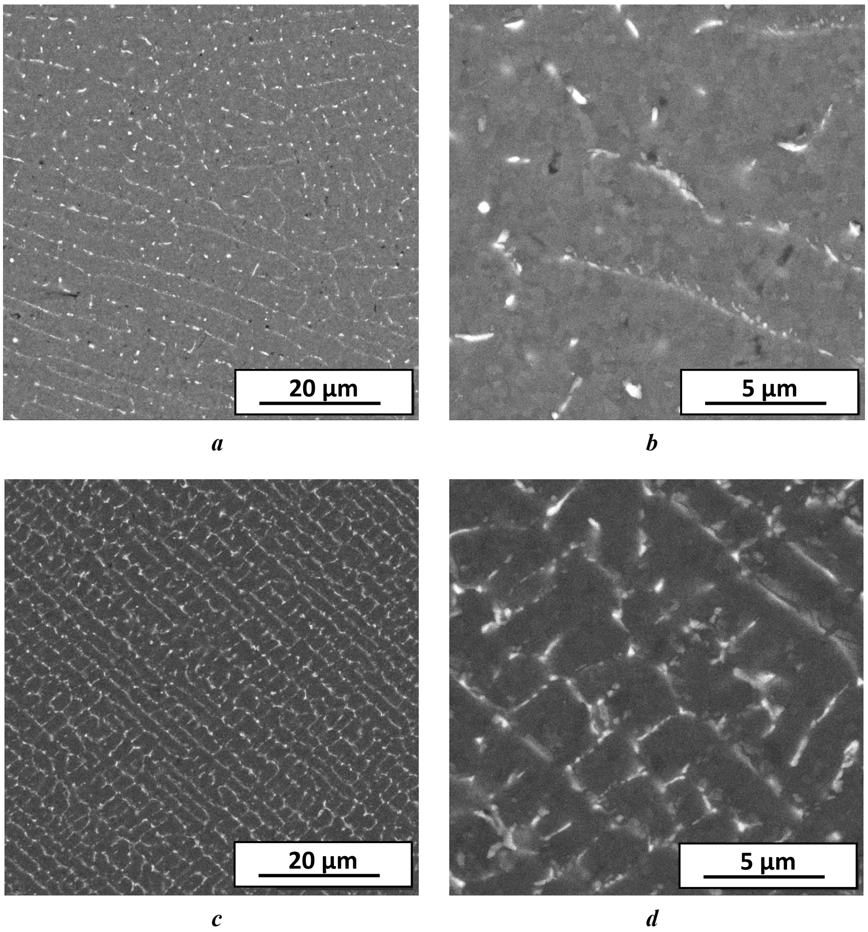


Fig. 2. Microstructure of alloys after casting into electromagnetic crystallizer and additional annealing at 450 °C, 2 h:
***a, b** – Al–0.5Fe–0.3Cu; **c, d** – Al–1.7Fe–0.3Cu, SEM*
***Рис. 2.** Микроструктура сплавов после литья в электромагнитный кристаллизатор*
и дополнительного отжига при 450 °C, 2 ч:
***a, b** – Al–0,5Fe–0,3Cu; **c, d** – Al–1,7Fe–0,3Cu, РЭМ*

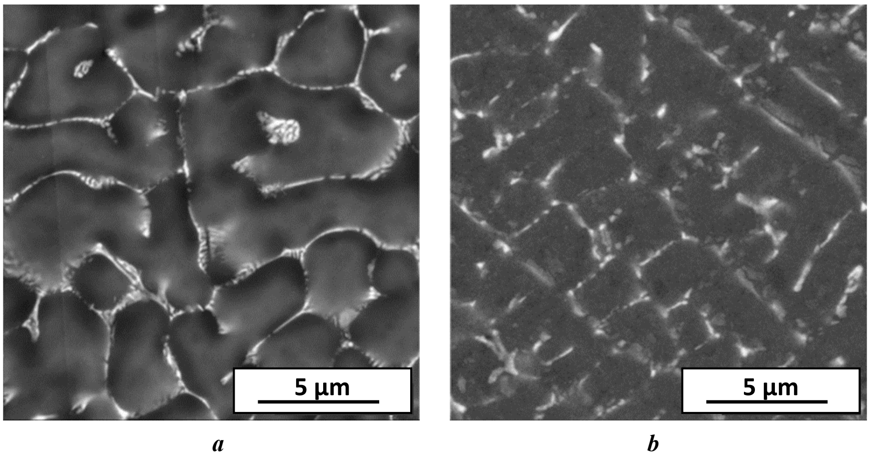


***Fig. 3.** Microstructure of Al–1.7Fe (**a**) and Al–1.7Fe–0.3Cu (**b**) alloys*
after casting in electromagnetic crystallizer and additional annealing at 450 °C, 2 h (SEM)
***Рис. 3.** Микроструктура сплавов Al–1,7Fe (**a**) и Al–1,7Fe–0,3Cu (**b**)*
после литья в электромагнитный кристаллизатор и дополнительного отжига при 450 °C, 2 ч (РЭМ)

Table 2. *Physical and mechanical properties of alloys of the Al–Fe system*
Таблица 2. *Физические и механические свойства сплавов системы Al–Fe*

Alloy	**State**	**Electrical properties**		**Mechanical properties**		
		ω, MS/m	**IACS, %**	**$\sigma_{0.2}$, MPa**	**σ_{UTS}, MPa**	**δ, %**
Al–0.5Fe–0.3Cu	EMC	32.54±0.21	56.1±0.4	72±8	106±4	33.7±6.5
	EMC + 450 °C, 2 h	35.32±0.20	60.9±0.6	65±8	100±13	37.8±2.8
Al–1.7Fe–0.3Cu	EMC	24.01±0.16	41.4±0.3	113±9	174±11	23.6±2.1
	EMC + 450 °C, 2 h	32.42±0.18	55.9±0.5	85±5	149±4	23.9±2.1
Al–0.5Fe [14]	EMC	29.83±0.19	57.8±0.5	35±3	90±7	32.5±3.4
	EMC + 450 °C, 2 h	–	–	–	–	–
Al–1.7Fe [14]	EMC	28.77±0.21	49.6±0.6	60±6	150±11	28.8±2.1
	EMC + 450 °C, 2 h	33.04±0.17	57.0±0.4	68±5	133±3	33.5±2.8
AA8176 (ASTM B800)	–	–	60.6	–	103–152	–
AL2 (EN 50183:2000)	–	–	52.5	–	315	–
AT2 (IEC 62641:2023)	–	–	55.0	–	225–248	–
8030 (GOST R 58019-2017)	–	–	60.0	–	115–140	12
8176 (GOST R 58019-2017)	–	–	60.0	–	115–140	12

and Al_7Cu_2Fe phase with the acceptable tolerance. So, in this study the effect of Cu additions is considered as synergetic of all Cu-containing features.

It would be safe to assume that copper, at least in the cast state, is both presented in the solid solution, intermetallic particles, and grain boundaries segregations. Additional spheroidizing annealing showed that additional alloying with Cu makes alloys of the Al–Fe system obtained by casting in EMC more sensitive to changes in strength and electrical conductivity as a result, and this effect increases with an increase in the Fe content in aluminum. Comparing to the Al–1.7Fe alloy, Al–1.7Fe–0.3Cu alloy demonstrates better thermal stability – it loses mechanical strength to a lesser value. The nature of this effect is yet to be studied.

An annealing at 450 °C for 2 h that was carried out for copper-containing alloys Al–0.5Fe–0.3Cu and Al–1.7Fe–0.3Cu showed result, similar to one observed before [14]. The coagulation of the particles, occurred during the heat treatment, resulted in the smoothing of the particles' sharp edges, making the specimens ess likely to crack during the deformation.

Due to the use of EMC, we can gain the pronounced effect of the influence of copper on the morphology of the phases and the properties of semi-finished products, relative to those obtained by conventional methods. It would be interesting to find out if this effect transfers to the final product, such as wire/stripe. Future studies will be focused on this question as well.

CONCLUSIONS

1. It was established, that addition of 0.3 wt. % copper to the electromagnetically cast Al–0.5Fe and Al–1.7Fe alloys results in smaller size of the intermetallic particles.
2. Addition of the copper into Al–0.5Fe and Al–1.7Fe alloys increases their ultimate tensile strength (by 16 MPa in Al–0.5Fe alloy and by 24 MPa in Al–1.7Fe alloy). It also resulted in the decrease of the electrical conductivity (by 1.7 % IACS in Al–0.5Fe alloy and by 8.2 % IACS in Al–1.7Fe alloy).
3. Iron content in the studied alloys has higher effect on the properties of the alloy that copper content.
4. Annealing at 450 °C for 2 h leads to spheroidizing of the intermetallic particles, smoothing their edges and decreasing particle-matrix interphase area. Such heat treatment, resulting in decrease of the mechanical strength and increase of electrical conductivity, has seemingly no effect on the ductility of the alloys.
5. Alloys, containing additional copper, demonstrate higher thermal stability – they have less value of softening during heat treatment compared to the non-copper alloys. The EMC technique provides the emphasized effect of the Cu presence, that would be negligible in case of traditional cast methods.

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Влияние добавок Cu на микроструктуру и свойства сплавов системы Al–Fe, полученных методом литья в электромагнитный кристаллизатор

Медведев Андрей Евгеньевич*[1], кандидат физико-математических наук, младший научный сотрудник

Жукова Ольга Олеговна[2], аспирант

Шайхулова Айгуль Фазировна[3], кандидат технических наук, доцент, старший научный сотрудник

Мурашкин Максим Юрьевич[4], кандидат технических наук, старший научный сотрудник

Уфимский университет науки и технологий, Уфа (Россия)

***E-mail:** medvedevae@uust.ru,
medvedevandreyrf@gmail.com

[1]ORCID: https://orcid.org/0000-0002-8616-0042
[2]ORCID: https://orcid.org/0000-0002-1879-9389
[3]ORCID: https://orcid.org/0000-0002-3340-3880
[4]ORCID: https://orcid.org/0000-0001-9950-0336

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Аннотация: Современная электротехническая промышленность требует дешевых и легко воспроизводимых алюминиевых сплавов – материалов с повышенной механической прочностью и электропроводностью. В работе исследовано влияние малых (до 0,3 мас. %) добавок меди на микроструктуру и физико-механические свойства, а также фазовые трансформации в сплавах системы Al–Fe с содержанием железа 0,5 и 1,7 мас. %, полученных методом непрерывного литья в электромагнитный кристаллизатор. Были получены сплавы указанных выше химических составов, впоследствии отожженные при 450 °C в течение 2 ч. Во всех состояниях были изучены микроструктура (с помощью РЭМ), предел текучести, предел прочности при растяжении, удлинение до разрушения и электропроводность. Показано, что добавки меди приводят к увеличению прочности обоих сплавов и некоторому снижению их пластичности по сравнению с аналогичными материалами без меди. Повышение прочности и снижение пластичности за счет добавки меди связано с образованием более дисперсных интерметаллидных частиц в медьсодержащих сплавах системы Al–Fe. Дополнительный сфероидизирующий отжиг приводит к уменьшению протяженности межфазной границы между алюминиевой матрицей и частицами алюминида железа за счет изменения их морфологии, что ведет к увеличению электропроводности. В целом медьсодержащие сплавы показали более высокую механическую прочность при меньшей электропроводности, а также повышенную термическую стабильность.

Ключевые слова: Al; Al–Fe–Cu; литье в электромагнитный кристаллизатор; фазовые превращения; механические свойства; электрическая проводимость; термическая стабильность.

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