MATERIALS PHYSICS AND MECHANICS RESEARCH ARTICLE

Submitted: March 02, 2025 Revised: March 19, 2025 Accepted: April 8, 2025

Electromagnetically cast Al-0.5 wt. % Fe alloy as a core material for the co-extruded copper-clad aluminium wire

A.E. Medvedev [1] ✉, O.O. Zhukova [1], A.F. Shaikhulova [1], E.B. Medvedev [1], M.M. Motkov [2], M.Yu. Murashkin [1]

[1] Ufa University of Science and Technology, Ufa, Russia

[2] Siberian Federal University, Krasnoyarsk, Russia

✉ medvedevandreyrf@gmail.com

ABSTRACT

In this study, the electromagnetically cast Al-0.5 wt. % Fe alloy was used as a core material for the copper-clad aluminium wire with the copper grade M2 outer sleeve. The choice of core material decreased the risk of premature copper-clad aluminium wire failure due to higher, compared to pure Al, mechanical strength and thermal stability. The mechanical bonding of the bimetallic wire was conducted via joint cold drawing. The produced copper-clad aluminium wire with the 37 % copper fraction in the cross-section is characterized by good adhesion of the Al and Cu layers. No intermetallic particles were observed on the Al-Cu interface in neither hard-drawn nor annealed state. Hard-drawn copper-clad aluminium wire is characterized by high mechanical strength and electrical conductivity while possessing an acceptable level of ductility. Subsequent to cold drawing annealing at 300 °C for 1h led to decrease of yield strength and ultimate tensile strength, as well as to increase in ductility and electrical conductivity. However, in both hard-drawn and annealed states copper-clad aluminium wire is characterized by the properties that lay within and even exceed the values recommended by international standards. Evaluation of the copper-clad aluminium wire ultimate tensile strength according to the rule of mixtures showed the importance of surface preparation on all the stages of the wire production.

KEYWORDS

copper-clad aluminium • hybrid materials • CCAW • electromagnetic crystallization • mechanical strength electrical conductivity • ductility • rule of mixtures

Funding. *This work has been supported by the grant of the Russian Science Foundation, 20-79-10133.*

Acknowledgements. *The research was carried out using the equipment of the Core Facility Centre "Nanotech" of Ufa University of Science and Technology.*

Citation: Medvedev AE, Zhukova OO, Shaikhulova AF, Medvedev EB, Motkov MM, Murashkin MYu. Electromagnetically cast Al-0.5 wt. % Fe alloy as a core material for the co-extruded copper-clad aluminium wire. *Materials Physics and Mechanics*. 2025;53(2): 25–39.
http://dx.doi.org/10.18149/MPM.5322025_3

Introduction

Copper and its alloys are mainly used as a material for the electrical conductors – wires, cables, busbars etc. due to their high electrical conductivity [1,2]. Since copper and its alloys are relatively expensive material, and its use is limited for economic reasons, the search for more affordable and available alternatives to copper is an urgent task for the modern electrical industry. Conventionally, aluminum and its alloys are the materials of choice for copper substitution due to the relatively low density and low cost. Since modern metallurgy and materials science have effectively reached the limits of further improving the properties of metals and alloys, it is nearly impossible to replace copper and copper materials with other metals and alloys, at least within reasonable prices.

Instead of pushing the limits of single materials, such as metals and alloys, another approach can be taken. Two different metals or alloys can be physically bonded into one hybrid material [3–5]. The variety of materials that this hybrid product may consist of, along with the number of ways of joining them together, provides a wide range of metallic composites [4]. Competently picked materials can supply the combination of desired properties (such as high ductility, high mechanical strength, electrical conductivity etc.) without inheriting undesirable properties (brittleness, low corrosion resistance, low mechanical strength etc.). Since two-component composite already gives a lot of potential with the reaching of desired properties, simultaneously providing challenges of technological nature, usually multi-metal composite only consists of two metals/alloys, on rare occasion – of three or more [6,7]. Thus, the most balanced in terms of profits and complexity are bimetallic materials – a composite material consisting of two different metals or their alloys [4,8–10].

In the electrical industry the most common type of bimetallic conductor is a copper-clad aluminium wire (CCAW) – a composite with an aluminum core and a copper sleeve. Basically, the CCAW is a copper wire, in which the core part of it is substituted with aluminium. Since mechanical properties (especially bending resistance) are mostly determined by the outer part of cylindrical rods and wires, from the mechanical point of view CCAW is virtually a full-copper wire. In case of low-frequency currents the electrical conductivity of CCAW is calculated by the rule of mixture [11,12], but in case of high-frequency currents the electrical current will run along the surface of the conductor. So, in certain applications CCAW will have all the advantages of a full-copper wire, while also having lower density, weight and cost. Thus, CCAW are mostly used in high-frequency applications – audio equipment, high-frequency electrical conductors, and high-precision equipment etc. [13,14].

There are different ways of producing CCAW, although the most simple and widespread is the mechanical cladding, or joint cold drawing, in which copper tape is wound onto aluminum wire, followed by drawing [15]. In some cases, use of combined casting and subsequent drawing/rolling [16,17] is preferable.

The production of bimetallic materials has complications of the technological nature. The most notable effect of the joint cold drawing is the severe drop in the ductility of the CCAW – ductility of less than 1 % in hard-drawn state is considered acceptable according to the international standards [18,19]. The most straightforward way of increasing the CCAW ductility is post-deformation annealing aimed at ant recovery and, sometimes, recrystallization of the aluminium and copper layers [20,21]. Since copper has a notably higher melting point compared to aluminium, thus it requires an annealing temperature of at least 300 °C to initiate recovery, preferably higher [22]. Annealing of the CCAW at this temperature leads to the following complications: (i) severe softening of the aluminium core and (ii) initiation and growth of Al-Cu intermetallic on the Al-Cu interface.

Softening of the aluminium core leads to the overall decrease of the CCAW mechanical strength with the risk of falling out of recommended by the standards interval. While not being the major issue (since mechanical properties of the CCAW are mostly determined by the properties of the Cu layer), this still could affect the performance of the composite wire.

The initiation and growth of intermetallic Al_xCu_y particles on the Al-Cu interface possesses higher risks for the CCAW performance [23]. These particles can form even at room temperature, but temperature increase significantly accelerates these processes. Intermetallic Al_xCu_y particles are brittle in nature and may severely decrease the ductility of the CCAW. Thus, annealing, aimed at ductility increase, may result in opposite result. The issue of the intermetallic particles' presence is even more prominent in CCAW produced via hot deformation or using the liquid phase.

Softening of the aluminium core (and increase of the difference in mechanical strength of the Al and Cu layers) may be avoided by introducing thermally stable aluminium alloys. Conventionally, technically pure aluminium is used as a core material for the CCAW, since core material is usually not expected to demonstrate any performance except for the low density and low cost [24]. Using aluminium alloys, especially thermally stable high-strength aluminium alloys may improve the properties of the CCAW. Alloys of Al-Zr [25], Al-RE (rare earth) [26], Al-Mg-Si [27] systems usually fall into this category, but their price is rather high, and in case of high completion this could be the resulting factor. Recently studied Al-Fe alloys, besides being highly common and inexpensive, also demonstrated the tendency to sustain their mechanical properties at elevated temperatures [28–30]. Thus, using Al-Fe alloys instead of technically pure aluminium may improve the CCAW performance during the annealing without significant increase in cost [31–33].

The issue of the intermetallic particles' presence on the Al-Cu interface can be avoided by choosing the correct temperature and duration of the annealing. Previously it was demonstrated that the temperature interval of 250 °C to 350 °C and duration interval of 30 to 90 min is enough to notably increase the ductility of the CCAW without causing the undesired intermetallic initiation and growth [20,34].

In this study, a potential method of obtaining the bimetallic wire with a copper sleeve and a core made of an aluminum alloy was demonstrated. The core material used was a conductive heat-resistant Al-0.5 wt. % Fe alloy, obtained by casting in electromagnetic crystallizer, due to its increased mechanical characteristics and heat resistance [35,36]. Wires made of such an alloy are characterized by increased strength and thermal stability, while maintaining a relatively high level of electrical conductivity. The presence in the composition of a small amount of accessible material – iron – ensures the low cost of this alloy [37]. In previous study the CCAW with a similar core, made of Al-0.5Fe alloy, was produced via copper electrodeposition [38,39]. This method, while having some advantages, demonstrated its overall ineffectiveness in terms of reaching the desired level of properties. In this study another approach was taken – mechanical bonding of the Al and Cu alloys by cold deformation [9,10].

Material and Methods

The bimetallic wires were fabricated by co-extrusion. Initial rods with a diameter of 11 mm and a length of more than 2 m made from Al-0.5 wt. % Fe alloy were manufactured by continuous casting into an electromagnetic crystallizer (EMC) [36].

The aluminium wire rod was then cold drawn (CD) to diameter of 7 mm and put into hollow tube made of copper grade M2 alloy with the inner diameter of 8 mm and outer diameter of 10 mm. The chemical composition of the alloys is presented in Table 1. Before inserting the aluminium rod into copper tube, the contact surfaces were mechanically cleaned and degreased. The formed billet was then drawn to 3 mm diameter on a laboratory drawing machine with a reduction of ~ 90 % in 10 passes.

Table 1. Chemical composition of the initial materials

Alloy	Cu	Al	Fe	Σ Zn, Si, etc
Al-0.5Fe	≤ 0.04	99.37 min	0.51	≤ 0.13
Cu grade M2	99.87 min	≤ 0.05	≤ 0.05	≤ 0.03

Macrostructure studies were performed on an Olympus Q15OR optical microscope. Scanning electron microscopy (SEM) was performed on a Tescan MIRA microscope. Annealing was performed in an atmosphere furnace Nabertherm B180 at 300 °C for 1 h. Annealing temperature and time were chosen based on the results of study [3]. Samples upon annealing were cooled into water to remove the dross from the surface. The electrical resistivity of the studied material was measured in accordance with the IEC 60468:1974 standard [40]. Straightened samples of at least 1 m long part were taken. Microhardness (HV) was measured using the Vickers method on a Buehler MicroMet 5101 device under a load of 1 N and a holding time under load of 10 s. At least 10 points were made for each composite wire constituent to ensure minimal measuring error. Microhardness was measured on a cross-section of the samples, prior used for the SEM.

To obtain statistically reliable results, tensile tests were carried out on three samples for each state on a universal tensile testing machine Instron 5982 at room temperature and at a speed of 100 mm/min in accordance with government standard GoSt No. 10446-80 "Wires. Tensile testing methods". Based on the test results, the values of the yield strength ($\sigma_{0.2}$), ultimate tensile strength (σ_{UTS}) and elongation to failure (δ) were determined.

Results and Discussion

Choice of the core material

The produced CCAW consists of two notably different materials, with different levels of mechanical strength and ductility. In order to ensure the uniformity and repeatability of the mechanical and functional properties in CCAW it is important to diminish the aforementioned differences. One of the ways to do that is to use aluminium alloys with the level of mechanical strength, as close to that of copper as possible. Since CCAW is also a subject for the annealing at relatively high (for the aluminium) temperature (300 °C) it is also important that the chosen aluminium alloy is characterized by thermal stability.

Both these requirements are met by Al-0.5Fe alloy, cast into electromagnetic mold (Al-0.5Fe EMC). High crystallization rate along with constant stirring provide structural features that in turn ensure increased mechanical strength and thermal stability.

Table 2 contains the results of microhardness tests conducted at the core material and sleeve material of the samples studied after cold drawing and after subsequent annealing at 300 °C for 1 h. The samples designation goes as follows: CCAW MC (copper-clad aluminium wire, mechanical cladding) and CCAW-A MC (copper-clad aluminium wire, mechanical cladding, annealed). Table also contains microhardness data for the aluminium alloy with the similar to Al-0.5Fe chemical composition but produced by continuous casting and rolling (Al-0.5Fe CCR). Samples of the Al-0.5Fe CCR were cold-drawn to the same deformation value as Al-0.5Fe EMC alloy and were subjected to the identical heat treatment. Also, for comparison reasons, the microhardness of the Al-0.4 wt. % Zr alloy is presented, as was used in the similar study [38].

Table 2. CCAW MC and CCAW-A MC microhardness data

	Microhardness, HV	
Alloy	**Hard-drawn state**	**Annealed state**
Cu grade M2 (sleeve)	135 ± 2	130 ± 2
Core material		
Al-0.5Fe EMC	56 ± 2	45 ± 1
Al-0.5Fe CCR	57 ± 2	34 ± 1
Al-Zr CCR	53 ± 3	53 ± 2

Microhardness of the copper layer is seemingly unaffected by the annealing – the temperature is too low to initiate notable recovery process. The Al-0.5Fe EMC alloy undergoes recovery, resulting in the drop of the microhardness from 56 to 45 HV. Samples of the Al-0.5Fe CCR alloy, while having the same level of microhardness in the cold-drawn state (57 HV), demonstrate lower level of microhardness after annealing (34 HV), thus lower thermal stability. Interestingly, Al-Zr alloy is also unaffected by the annealing. However, Al-Zr alloy is more expensive and requires more complex technological treatment, in order to achieve such properties.

While the difference in microhardness of copper and aluminium alloys in CCAW is very significant, it is possible to reduce it both in hard-drawn and annealed states by choosing the right chemical composition and casting conditions of the aluminium alloy. Thus, Al-0.5Fe EMC is a reasonable alternative to similar alloys, produced by the conventional methods, at the same time being cheaper alternative to another Al-based thermally stable alloys.

CCAW structural assessment

Figure 1 shows the results of the optical metallography of CCAW MC and CCAW-A MC samples. According to it the adjacent copper to aluminium appears to be full along the interface (Fig. 1(a)). The Cu-Al interface has small voids about 4 μm width and 10 μm in length (Fig. 1(b)). These voids are formed due to incomplete deformation of the aluminium core surface, that was not polished or prepared in any way specifically after cold drawing. Nevertheless, the number of these voids is small, and they are placed within the interface discontinuously.

Annealing at 300 °C for 1 h seemingly doesn't affect the thickness of the copper layer (Fig. 1(c)), as was the case in CCAW obtained by electrodeposition [39]. Copper layer has notable change in thickness in the lower half of the sample studied, but it is most probably

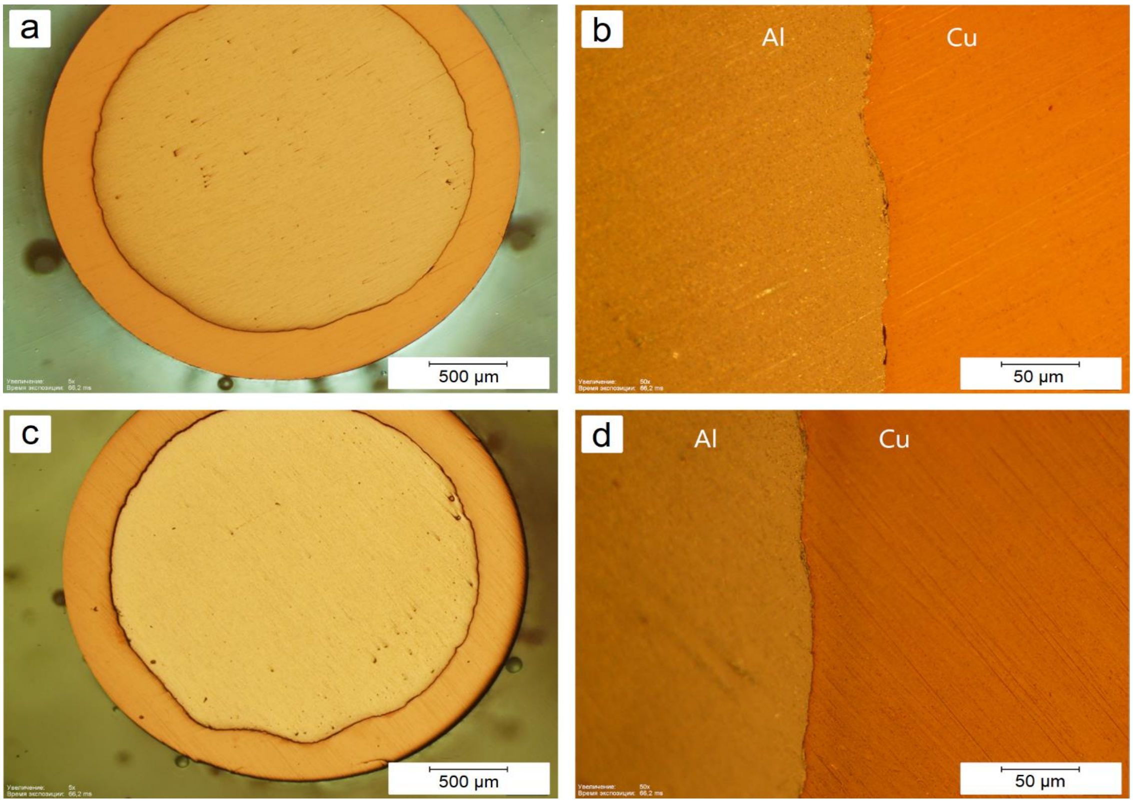

Fig. 1. Optical metallography of the cross section of a CCAW MC (a,b) and CCAW-A MC (c,d). The images show the aluminum core (grey) and copper sleeve (orange)

caused by the uneven surface of the initial Al alloy rod. This suggestion is supported by the smooth and even outer surface of the Cu sleeve. Cu-Al interface in the annealed state demonstrates changes – the voids, presented in the initial sample, were not observed.

The thickness of the copper layer is 308 ± 20 μm in CCAW MC sample and 313 ± 22 μm in CCAW-A MC, which corresponds to 36.2 ± 6 % and 37.6 ± 7 % fraction of the cross-section, respectively (Table 3). The thickness of the copper layer is unaffected by the annealing, no visible evidence of the interdiffusion is presented. The difference in Al layer thickness before and after annealing is minor and most likely caused by the fluctuations of the initial Al-Fe rod diameter, considering the measurements of it were taken from two different samples.

Table 3. Changes in the Cu layer thickness during the annealing

State	Layer thickness, μm		Fraction in the cross-section, %	
	Al	Cu	Al	Cu
CCAW MC	1123 ± 20	308 ± 20	63.8 ± 6.0	36.2 ± 6.0
CCAW-A MC	1177 ± 22	313 ± 22	62.4 ± 7.0	37.6 ± 7.0

Figure 2 shows the cross-section of the CCAW MC and CCAW-A MC samples. Aluminium and copper have a significantly different atomic number so the contrast of these elements in the SEM pictures (especially in backscattered electrons mode) is clearly seen. The Al-Cu interface is continuous, not containing any visible defects. The interdiffusion layers in Al-Cu interfaces have distinct contrasts from both Al and Cu [41], which is not observed in the presented samples, so no Al-Cu interdiffusion evidence was found.

Figure 2(a) shows the interface in CCAW MC sample. The element contrast is clearly distinct, no other than Al or Cu phase particles are observed. The interface in CCAW-A MC sample is wider and contains gaps with the width of up to 10 μm (Fig. 2(b)). The smoothened surface of the Al-Cu interface (Fig. 2(b)), most likely, is due to the heating of the air, remaining in the "pocket" between the copper and aluminum alloy at the Al-Cu. As a result, existing voids could have arisen or developed, initially formed due to incomplete contact between the copper and aluminum layers. In any case, the effect described is local in nature, since these "pockets" or discontinuities have a discrete distribution along contact between the layers.

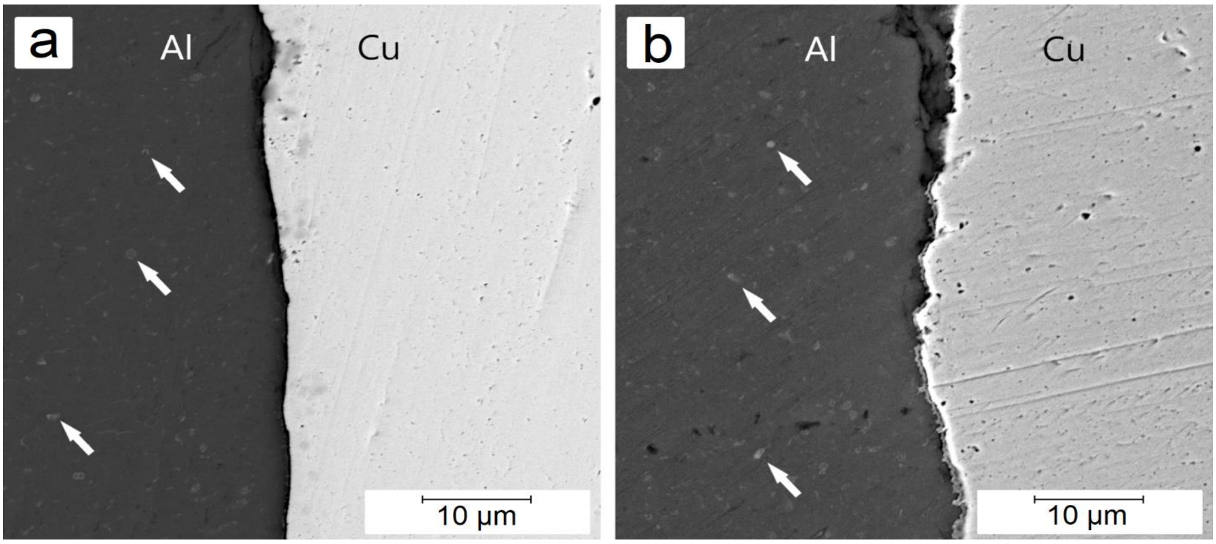

Fig. 2. Microstructure of the CCAW MC (a) and CCAW-A MC (b), cross-section, SEM. The images show the aluminum core (dark gray) and copper outer sleeve (bright gray). White arrows indicate the intermetallic Al_xFe_y particles within the Al-Fe alloy

Figure 3 presents the results of the EDXS analysis of the CCAW MC and CCAW-A MC samples. Line scan across the Cu-Al interface shows no increase of the Al and Cu signals overlap after annealing, once again proving the absence of the Cu-Al interdiffusion.

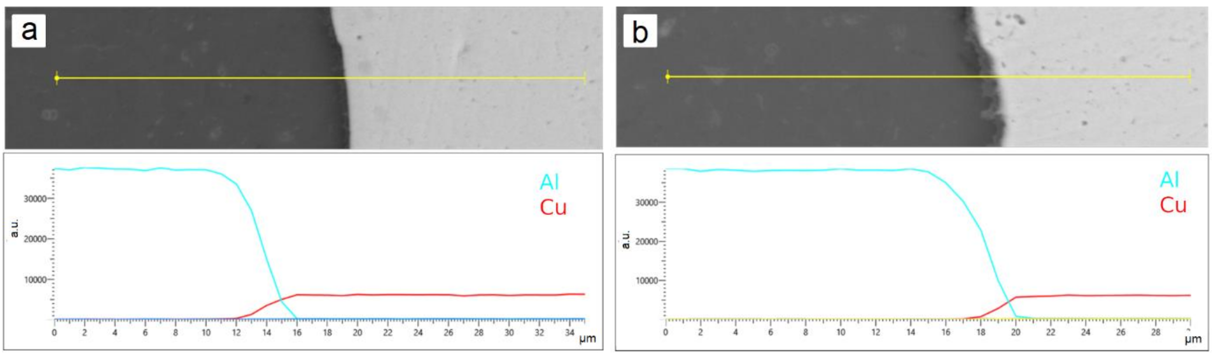

Fig. 3. EDXS results for CCAW MC (a) and CCAW-A MC (b), cross-section, SEM. The direction of line scanning is from left to right

CCAW physical and mechanical properties

Table 4 shows the properties of Al-0.5Fe alloy wire samples without copper cladding – aluminium wire (AW), and with cladding (CCAW MC, CCAW-A MC states). The initial EMC Al-0.5Fe alloy is relatively soft (σ_{UTS} of 90 MPa) alloy, with high value of elongation to failure (32.5 %) and level of electrical conductivity (57.8 % IACS) close to that of pure aluminium (62.0 % IACS) [22]. Cold drawing of the initial AW rod reduces the elongation to failure sixfold, increases the ultimate tensile strength twofold and seemingly has no effect on the electrical conductivity.

Table 4. Physical and mechanical properties of Al-Fe and CCA wires

State	Electrical properties		Mechanical properties		
	ω, MS/m	IACS, %	$\sigma_{0.2}$, MPa	σ_{UTS}, MPa,	δ, %
Al-0.5Fe as-cast [43]	29.83 ± 0.1	57.8 ± 0.5	35 ± 3	90 ± 7	32.5 ± 3.4
Al-0.5Fe hard-drawn (AW) [43]	29.54 ± 0.1	58.4 ± 0.4	170 ± 12	204 ± 14	5.3 ± 0.2
CCAW MC	34.72 ± 1.1	67.2 ± 0.4	260 ± 11	316 ± 16	2.1 ± 0.3
CCAW-A MC	35.12 ± 0.9	68.0 ± 0.4	197 ± 8	225 ± 9	8.0 ± 0.7
Al-10%Cu hard-drawn [18,19]	–	62.9 % min	–	110 – 205	1 % min
Al-10%Cu annealed [18,19]	–	62.9 % min	–	135 – 170	5 – 15 % min
Al-15%Cu hard-drawn [18,19]	–	64.4 % min	–	110 – 205	1 % min
Al-15%Cu annealed [18,19]	–	64.4 % min	–	135 – 170	5 – 15 % min
CCAW ED [39]	29.68 ± 0.9	57.5 ± 0.5	185 ±6	187 ± 7	1.5 ± 0.1
CCAW-A ED [39]	31.43 ± 0.8	60.9 ± 0.3	135 ± 5	184 ± 6	4.3 ± 0.6

The CCAW MC wire with the same 3 mm diameter as AW has both exceeding ultimate strength (316 MPa) and electrical conductivity (67.2 % IACS). Unfortunately, the elongation to failure of CCAW MC is 2.1 %, which is borderline insufficient for the commercial use [42]. As was mentioned in the introduction, the low ductility of copper-clad aluminium wires is improved by annealing. Annealed at 300 °C for 1 h CCAW MC sample demonstrates increased elongation to failure (8.1 %) and electrical conductivity (68.0 % IACS) as well as decreased, but still high for annealed aluminium alloy level of ultimate tensile strength of 225 MPa.

CCAW MC and CCAW-A MC samples notably exceed the commercially available copper-clad samples in terms of mechanical and physical strength in both cold-worked and annealed states (Table 4). It is important to note, however, that the maximum amount of copper in commercial samples is 15 %, while in the samples studied this value is about 35–37 %. Increased amount of copper contributes to high strength and high electrical conductivity in CCAW MC and CCAW-A MC samples.

Table 4 also contains the results of similar tests for the copper-clad Al-Fe wire, obtained by the electrodeposition method (CCAW ED and CCAW-A ED samples, respectively) [39]. Electrical conductivity and mechanical properties are higher for the CCAW MC samples in both deformed and annealed states. Partially this could be attributed to the higher fraction of the copper (there is an average 8 % of copper in CCAW ED samples), and partially to the presence of Ni interlayer in CCAW ED samples.

The engineering stress-strain curves of the CCAW MC and CCAW-A MC samples, as well as CCAW ED and CCAW-A ED samples, are presented in Fig. 4. While the curve for the AW has regular for Al-0.5Fe alloy shape, the curves for the CCAW MC and CCAW-A MC are two-staged having sudden drop of strength with subsequent partial recovery and eventual failure. This drop corresponds to the failure of aluminium alloy core, that fractured first. The rest of the curve corresponds to the failure of the copper sleeve. Similar behavior was demonstrated by CCAW ED and CCAW-A ED samples, although the drop is not so strongly expressed, and the overall fracture of the sample has a more uniform character. Despite having a two-stage stress-strain curve, the CCAW MC and CCAW-A MC samples have uniform plastic deformation stage up until the copper sleeve fracture occurs.

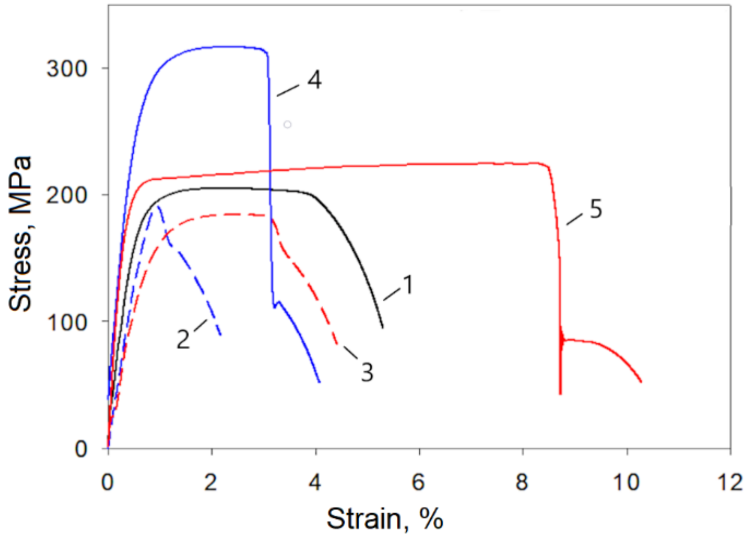

Fig. 4. Engineering stress-strain curves for aluminum wire (1) [43]; copper-clad via electrodeposition aluminum wire in the initial (2) and annealed (3) states [39]; mechanically copper-clad aluminum wire in the hard-drawn (4) and annealed (5) states

Compared to the ED samples, MC samples have significantly higher ductility and ultimate tensile strength for both deformed and annealed states. The character of the two-stage fracture also different – ED samples have smoothed transition between stages, while transition on MC samples, especially in the annealed state, has more abrupt character.

CCAW fracture analysis

The cross-sections of CCAW MC and CCAW-A MC after tensile tests are presented in Fig. 5. CCAW MC and CCAW-A MC samples demonstrate the non-simultaneous fracture of the aluminium alloy core and copper sleeve. The relative narrowing of the aluminium alloy core in CCAW-A MC sample is higher than that of CCAW MC (Fig. 5), correlating to the higher elongation to failure values of this sample (Table 4).

Figure 6 demonstrates the central part of the aluminium alloy core fracture surface in CCAW MC (Fig. 6(a,b)) and CCAW-A MC (Fig. 6(c,d)). Both samples demonstrate a dimpled character of the fracture surface, with dimples being larger in CCAW-A MC sample, which correlates with the four times elongation to failure increase during the annealing.

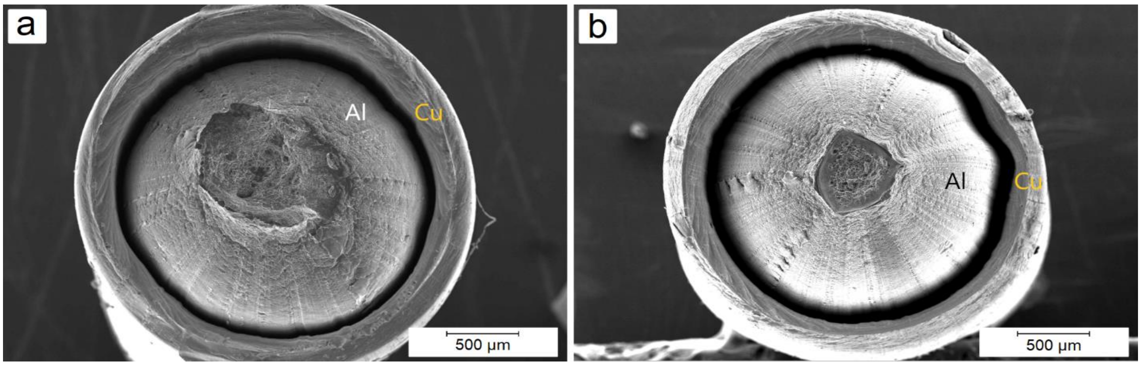

Fig. 5. Results of fractographic analysis of CCAW MC (a) and CCAW-A MC (b) samples, SEM

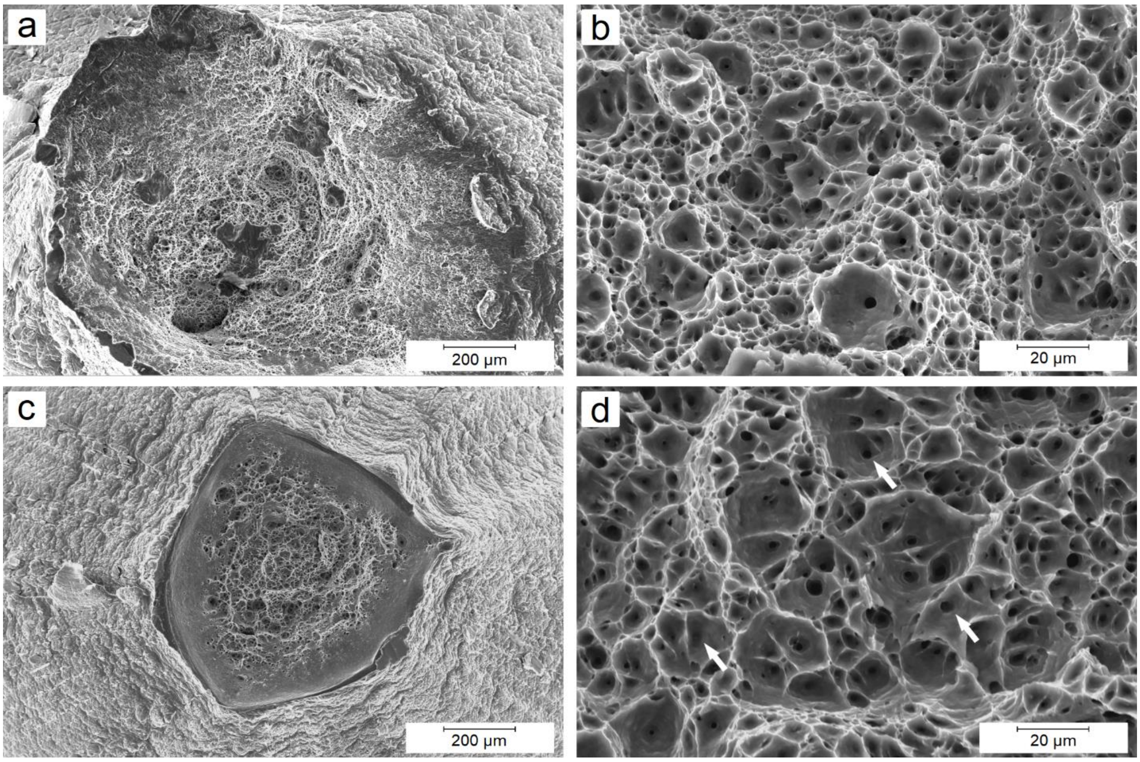

Fig. 6. Results of fractographic analysis of Al-0.5Fe alloy wire core of samples:
(a,b) CCAW MC, (c,d) CCAW-A MC, SEM

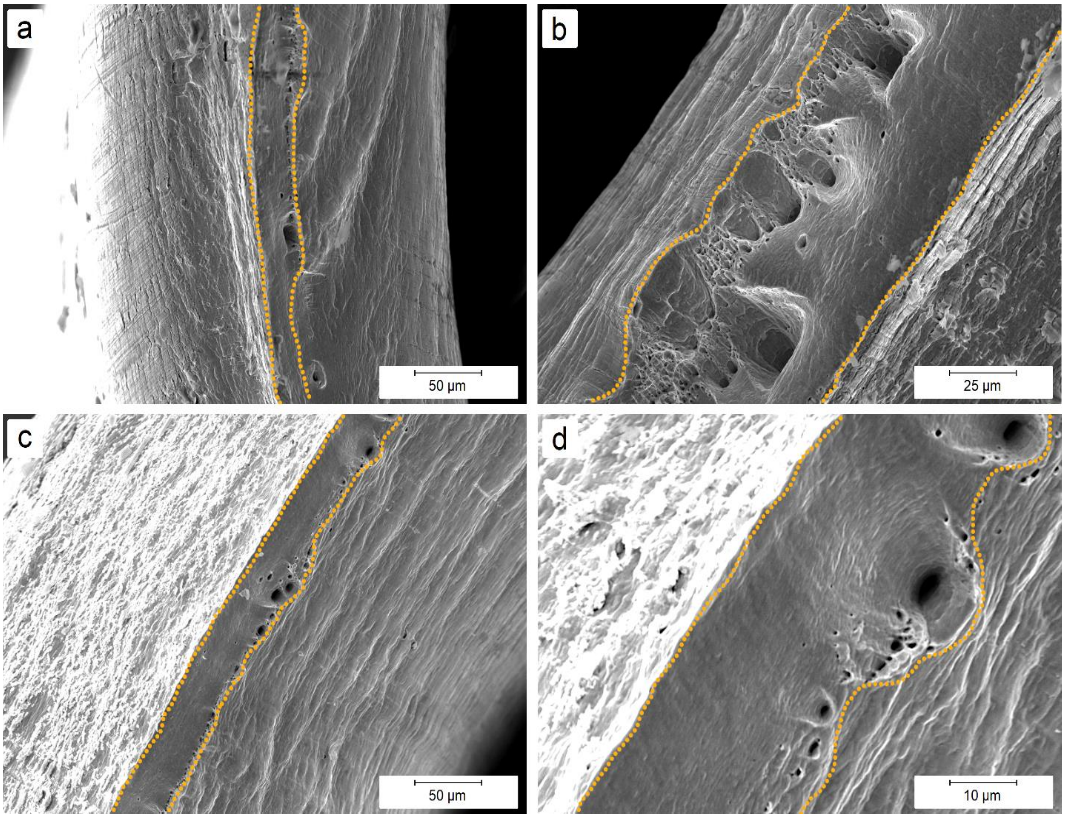

Fig. 7. Results of fractographic analysis of copper sleeve samples: (a,b) CCAW MC, (c,d) CCAW-A MC, SEM. Orange dotted lines outline the borders of the fracture surface

Figure 7 demonstrates the fracture surface of the copper sleeve in CCAW MC (Fig. 7(a,b)) and CCAW-A MC (Fig. 7(c,d)). The fracture has similar character in both states and could be considered semi-brittle, since it has both dimples, typical for the ductile fracture, and so-called "river patterns", typical for the brittle fracture [44]. Annealing at 300 °C for 1 h has seemingly no effect on the character of the copper sleeve fracture.

Discussion

The stress-strain curves analysis (Fig. 4), as well as fracture analysis of the CCAW demonstrated the complex nature of the fracturing behavior. CCAW doesn't behave like a single metal or alloy, and the prediction of the mechanical properties is further complicated by difference in mechanical properties of the constituents, presence of the interface of the core and the sleeve and potential presence of intermetallic particles, oxides and transition layers on it. In the absence of the factors contributing to the premature failure of the bimetallic sample the tensile strength can be evaluated quite accurately.

Generally, tensile strength of the bimetallic metal-metal hybrid materials can be calculated using the rule of mixture with high precision. The rule of mixtures (ROM) [11] is expressed by:

$$\sigma_c = \sigma_1 \times V_1 + \sigma_2 \times V_2, \quad (1)$$

where σ_c is the ultimate tensile strength (σ_{UTS}) of the composite; σ_1 (V_2) and σ_2 (V_2) are the σ_{UTS} and volume fractions of the constituents, respectively. Using the data from Table 2 in Eq. (1), Table 5 can be formed.

Table 5. Experimental and calculated values of σ_{UTS} for CCAW

State	Material	σ_{UTS}, MPa	
		Experimental	**Calculated (ROM)**
Hard-drawn	Al-0.5Fe core	215 ± 10	–
	Grade M2 Cu sleeve	470 ± 22	–
	CCAW	316 ± 16	307
Annealed	Al-0.5Fe core	176 ± 8	–
	Grade M2 Cu sleeve	451 ± 28	–
	CCAW	225 ± 9	279

The calculations of σ_{UTS} presented in Table 5 are made with the assumption that the bimetallic wire is ideal, has no voids or embrittling particles on the constituent's interface. In the hard-drawn state calculated σ_{UTS} is equal to the experimental one, down to the error value, proving relevancy of the ROM implementation concept. Despite the presence of the voids on the Cu-Al interface (Fig. 1(b), Fig. 2(a)), the absence of the coarse third-phase particles allows to predict the ultimate tensile strength level of the hard-drawn CCAW with high accuracy.

In the CCAW-A sample, however, the difference in experimental and calculated σ_{UTS} is relatively high (50 MPa) up to a degree when it cannot be considered as a measuring or calculation error. The evaluated σ_{UTS} in the CCAW-A sample is higher, representing the occurrence of the factors, responsible for the premature failure of the bimetallic wire. Researchers also point out that ROM is very sensitive to the interface [3]. The annealing could affect the surface of the Cu layer, although this effect could be neglected since annealing temperature of 300 °C is not high enough to cause any significant changes (Fig. 1). Most probable cause of the σ_{UTS} difference is the formation of particles, or the growth of the existed ones, on the Cu-Al interface. On Fig. 1(d) the presence of certain formations between Cu and Al layers is clearly visible. As for the nature of these formations, two suggestions can be made. First, these are aluminium oxide particles, formed or grown during the annealing. The annealing was performed in the atmospheric oven, and the interface voids, clearly observed in hard-drawn wire (Fig. 1(b)), could form channels transferring oxygen into the gap between Cu and Al. These interface formations can also be, judging by their smooth appearance, melted Cu-Al particles. Similar effect was observed in [3]. In this study, the melted particles were also observed on the Cu-Al interface in bimetallic strips after annealing, although at notably higher temperatures (350 °C and higher). The SEM and EDXS data, however, testify against this suggestion, since no irregularities were found on the Cu-Al interface, making the oxide presence suggestion the most probable one.

Conclusions

This paper presents the results of the production of the copper-clad aluminium wire (CCAW) in both hard-drawn and annealed states. The core of the bimetallic wire consists of the electromagnetically cast thermally stable Al-0.5 wt. % Fe alloy, and the sleeve is made of grade M2 copper alloy. The following conclusions were drawn:

1. For the first time samples of a bimetallic wire based on electromagnetically cast Al-0.5 wt. % Fe alloy wire with grade M2 copper were obtained by cold co-extrusion. The fraction of copper

in the cross-section is about 37 %, no visible defects or intermetallic particles are observed at the Al-Cu interface. The production method resulted in a strong mechanical bond between aluminium and copper layers both in hard-drawn and annealed states.
2. The ultimate tensile strength (316 MPa), electrical conductivity (67.2 % IACS) and ductility (2.1 %) of produced CCAW notably exceeds those of commercially produced CCAW with the core made of technically pure aluminium. Annealing of the CCAW at 300 °C for 1 hour led to an increase in electrical conductivity to 68.0 % IACS and ductility to 8.0 %, while maintaining high level of ultimate tensile strength (225 MPa).
3. Produced CCAW, both in hard-drawn and annealed states, satisfies and exceeds the requirements for the CCAW according to ASTM B566. "Standard Specification for Copper-Clad Aluminium Wire, 2002" and SJ/T 11223-2000. "Copper-clad aluminum wire, 2000" commercial standards for CCAW.
4. It was demonstrated that implementation of different Al-based alloys as a core material for the CCAW has potential to not only improve the physical and mechanical properties of these products, but also potentially their functional properties, widening the area of their application. The thermal stability of the electromagnetically cast Al-0.5 Fe alloy, diminishing the difference in core's and sleeve's strength of the CCAW, contributed to the high mechanical properties and overall performance of the annealed CCAW.
5. The calculated with the rule of mixtures level of ultimate tensile strength is in good accordance with the experimental results for hard-drawn CCAW and higher for the annealed CCAW, signifying the occurrence of the processes on the Cu-Al, leading to a decrease in UTS of the annealed wire. Improved surface quality control on all stages of CCAW production is a mean of improving the mechanical properties of the product.

CRediT authorship contribution statement

Andrey E. Medvedev: writing – original draft; **Olga O. Zhukova**: data curation; **Aygul F. Shaikhulova**: investigation; **Evgenii B. Medvedev**: conceptualization; **Mikhail M. Motkov**: writing – review & editing; **Maxim Yu. Murashkin**: supervision.

Conflict of interest

The authors declare that they have no conflict of interest.

References

1. An Z, Yan J, An H, Tan J, Han Y, Li H, et al. Resource, environmental and economics research for primary and secondary copper: A bibliometric and systematic review. *Journal of Cleaner Production.* 2023;425: 138671.
2. Huang W, Yu H, Wang L, Wu X, Ouyang C, Zhang Y, He J. State of the art and prospects in sliver- and copper-matrix composite electrical contact materials. *Materials Today Communications.* 2023;37: 107256.
3. Fu X, Wang R, Zhu Q, Wang P, Zuo Y. Effect of Annealing on the Interface and Mechanical Properties of Cu-Al-Cu Laminated Composite Prepared with Cold Rolling. *Materials.* 2020;13(2): 369.
4. Pambhar AC, Valaki JB. Experimental studies of formability in single point incremental forming of Cu-Al bimetallic sheets. *Materials Today: Proceedings.* 2023.
5. Pawlicki M, Drenger T, Pieszak M, Borowski J. Cold upset forging joining of ultra-fine-grained aluminium and copper. *Journal of Materials Processing Technology.* 2015;223: 193–202.

6. Lapovok R, Ng HP, Tomus D, Estrin Y. Bimetallic copper-aluminium tube by severe plastic deformation. *Scripta Materialia.* 2012;66: 1081–1084.
7. Qi Y, Lapovok R, Estrin Y. Microstructure and electrical conductivity of aluminium/steel bimetallic rods processed by severe plastic deformation. *Journal of Materials Science.* 2016;51: 6860–6875.
8. Kocich R. Effects of twist channel angular pressing on structure and properties of bimetallic Al/Cu clad composites. *Materials & Design.* 2020;196: 109255.
9. Zhukova OO, Medvedev AE, Shaykhulova AF, Medvedev EB, Murashkin MY, Motkov MM. Production of bimetallic wire with a core of Al-1.7 wt. % Fe alloy obtained by electromagnetic crystallization and a shell of copper alloy grade M2. *Materials. Technologies. Design.* 2024;6(4(19)): 5–12.
10. Zhukova OO, Medvedev AE, Kiryanova KE, Medvedev EB, Motkov MM. Properties of bimetallic wire with copper sheath and Al-0.5Fe-0.3Cu alloy core obtained by casting in an electromagnetic crystallizer. *Materials. Technologies. Design.* 2024;6(3(18)): 27–33.
11. Feng B, Xin Y, Sun Z, Yu H, Wang J, Liu Q. On the rule of mixtures for bimetal composites. *Materials Science and Engineering A-structural Materials Properties Microstructure and Processing.* 2017;704: 173–180.
12. Tian L, Anderson I, Riedemann T, Russell A. Modeling the electrical resistivity of deformation processed metal-metal composites. *Acta Materialia.* 2014;77: 151–161.
13. Barrett C, Tetelman A, Nix W. *The Principles of Engineering Materials.* Hoboken, NJ, USA: Prentice-Hall; 1973.
14. Dowling M, Al-Hamaoy AR, A. Obeidi M. Laser surface cladding of metal parts. *Results in Surfaces and Interfaces.* 2023;12: 100142.
15. Gueydan A, Hug E. Secondary creep stage behavior of copper-clad aluminum thin wires submitted to a moderate temperature level. *Materials Science and Engineering: A.* 2018;709: 134–138.
16. Li K, Liu X, Zhao Y. Research status and prospect of friction stir processing technology. *Coatings.* 2019;9(2), 129.
17. Chen Y, Wang A, Tian H, Xie J, Wang X. Study on optimization of nozzle for copper-aluminium clad plate twin-roll cast-rolling. *Journal of Materials Research and Technology.* 2021;10: 1075–1085.
18. ASTM B566-93. *Standard Specification for Copper-Clad Aluminium Wire*. 2002.
19. SJ/T 11223-2000. *Copper-clad aluminum wire.* 2000.
20. Song JW, Hong JP, An YJ, Son SH, Park JS, Kim SH, Kang SH, Kang JH. Evaluation of the Mechanical and Electrical Properties of Multistage Drawn Copper-Clad Aluminum Wire After Annealing Process. *Metals.* 2024;14(2): 1386.
21. Sharifian Amiri F, Hosseinipour SJ, Jamshidi Aval H, Jamaati R. Evaluation of strength and electrical conductivity of copper clad-AA6063 bimetallic composite wire after annealing treatment. *Materials Chemistry and Physics.* 2024;312: 128660.
22. Mondolfo LF. *Aluminum Alloys: Structure and Properties.* London: Butterworths; 1976.
23. Lee JE, Bae DH, Chung WS, Kim KH, Lee JH, Cho YR. Effects of annealing on the mechanical and interface properties of stainless steel/aluminum/copper clad-metal sheets. *Journal of Materials Processing Technology.* 2007;187–188: 546–549.
24. Cho Y-R. Clad Metals: Fabrication, Properties, and Applications. *Metals.* 2021;11(8): 1186.
25. International Electrotechnical Commission. IEC 62004:2007. *Thermal-resistant aluminium alloy wire for overhead line conductor.* 2007.
26. Medvedev AE, Murashkin MY, Enikeev NA, Valiev RZ, Hodgson PD, Lapovok R. Enhancement of mechanical and electrical properties of Al-RE alloys by optimizing rare-earth concentration and thermo-mechanical treatment. *Journal of Alloys and Compounds.* 2018;745: 696–704.
27. EN 50183:2002. *Conductors for overhead lines – Aluminium-magnesium-silicon alloy wires*. 2002.
28. Tcherdyntsev VV, Kaloshkin SD, Afonina EA, Tomilin IA, Baldokhin Y V, Shelekhov E V, et al. Effect of Deformation by High Pressure Torsion on the Phase Composition and Microhardness of Mechanically Alloyed and Rapidly Quenched Al-Fe alloys. *Defect and Diffusion Forum.* 2003;216–217: 313–322.
29. Sasaki TT, Ohkubo T, Hono K. Microstructure and mechanical properties of bulk nanocrystalline Al-Fe alloy processed by mechanical alloying and spark plasma sintering. *Acta Materialia.* 2009;57: 3529–3538.
30. Nayak SS, Pabi SK. Structure of nanocomposites of Al-Fe alloys prepared by mechanical alloying and rapid solidification processing. *Bulletin of Materials Science.* 2008;31: 449–454.
31. Bian Z, Dai S, Wu L, Chen Z, Wang M, Chen D, et al. Thermal stability of Al-Fe-Ni alloy at high temperatures. *Journal of Materials Research and Technology.* 2019;8(3): 2538–2548.
32. Chen JK, Hung HY, Wang CF, Tang NK. Thermal and electrical conductivity in Al-Si/Cu/Fe/Mg binary and ternary Al alloys. *Journal of Materials Science.* 2015;50: 5630–5639.

33. Medvedev A, Zhukova O, Enikeev N, Kazykhanov V, Timofeev V, Murashkin M. The Effect of Casting Technique and Severe Straining on the Microstructure, Electrical Conductivity, Mechanical Properties and Thermal Stability of the Al-1.7 wt. % Fe Alloy. *Materials.* 2023;16(8): 3067.
34. Amiri FS, Hosseinipour SJ, Aval HJ, Jamaati R. Fabrication of a novel high-strength and high-conductivity copper-clad aluminum composite wire. *CIRP Journal of Manufacturing Science and Technology.* 2023;41: 144–159.
35. Belov N, Murashkin M, Korotkova N, Akopyan T, Timofeev V. Structure and properties of Al-0.6 wt. % Zr wire alloy manufactured by direct drawing of electromagnetically cast wire rod. *Metals.* 2020;10(6): 769.
36. Li J, Nian Y, Liu X, Zong Y, Tang X, Zhang C, Zhang L. Application of electromagnetic metallurgy in continuous casting: A review. *Progress in Natural Science: Materials International.* 2024;34(1): 1–11.
37. Zhao Q, Qian Z, Cui X, Wu Y, Liu X. Optimizing microstructures of dilute Al-Fe-Si alloys designed with enhanced electrical conductivity and tensile strength. *Journal of Alloys and Compounds.* 2015;650: 768–776.
38. Medvedev AE, Kiryanova KE, Medvedev EB, Gorbatkov MV, Zhukova OO, Murashkin MYu. Copper-clad thermally stable Al-Zr wire, produced via copper electrodeposition. *Materials Physics and Mechanics.* 2024;52(5): 29–39.
39. Medvedev AE, Kiryanova KE, Medvedev EB, Gorbatkov M V, Motkov MM. Microstructure and properties of the Al-0,5 wt.% Fe alloy wire, copper-clad by electrochemical deposition. *International Journal of Lightweight Materials and Manufacture.* 2025;8(1): 28–37.
40. IEC 62641:2023. *Conductors for overhead lines – Aluminium and aluminium alloy wires for concentric lay stranded conductors.* 2023.
41. Zheng H, Zhang R, Xu Q, Kong X, Sun W, Fu Y, Wu M, Kiu K. Fabrication of Cu/Al/Cu Laminated Composites Reinforced with Graphene by Hot Pressing and Evaluation of Their Electrical Conductivity. *Materials.* 2023;16(2): 622.
42. ASTM B800-05. *Standard Specification for 8000 Series Aluminum Alloy Wire for Electrical Purposes—Annealed and Intermediate Tempers.* 2021.
43. Medvedev AE, Zhukova OO, Fedotova DD, Murashkin MYu. The mechanical properties, electrical conductivity, and thermal stability of a wire made of Al-Fe alloys produced by casting into an electromagnetic crystallizer. *Frontier Materials & Technologies.* 2022;3(1): 96–105.
44. François D. 2.4 – Fracture mechanisms of metals. In: Herrmann HJ, Roux S. (eds.) *Random Materials and Processes. Statistical Models for the Fracture of Disordered Media.* North-Holland: Elsevier; 1990. p. 59–65.