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Unique properties of the Al-0.5Fe-0.3Cu alloy, obtained by casting into an electromagnetic crystallizer, after equal-channel angular pressing and cold drawing

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ABSTRACT

The effect of equal-channel angular pressing (ECAP) and subsequent cold drawing (CD) on the microstructure and properties of the Al-0.5Fe-0.3Cu (wt. %) alloy produced by electromagnetic casting (EMC) is examined. The high rate of crystallization of the alloy ensured the formation of a solid solution of copper in the aluminum matrix, while iron was completely bound in intermetallic particles of the Al-Fe and Al-Fe-Cu types. A distinctive feature of ECAP processing followed by CD is the presence of signs of both ECAP and CD in the structure of the processed alloy. Moreover, the syncretic effect of two deformation methods, implementing different deformation schemes, led to the appearance of features that were absent in the alloy structures after ECAP or after CD. Presence of the unique ultra-fine grained (UFG) microstructure, formed as a result of the combined ECAP+CD treatment, led to an increase in the tensile strength of wires made of the Al-0.5Fe-0.3Cu alloy to 342 MPa while maintaining a relatively high electrical conductivity of 55.5 % IACS. Compared to the commercial scale alloys, the wire (with a UFG structure) from the Al-0.5Fe-0.3Cu alloy demonstrates either equal (6000 series alloys) or improved (8000 series alloys) mechanical strength and electrical conductivity. Introduction of copper into Al-0.5Fe alloy, obtained using the EMC method, allows to even further improve the strength-conductivity combination of this alloy.

KEYWORDS

aluminum alloy • Al-Fe-Cu • electromagnetic crystallization • equal-channel angular pressing cold drawing • UFG microstructure • electrical conductivity • strength • thermal stability

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Introduction

The development of the industrial and technical complex requires new materials, while traditionally used aluminum alloys are close to exhausting the resource for further improving their characteristics [1]. Nevertheless, aluminum remains, due to its availability and a combination of attractive properties, one of the most popular materials, and the task of modern metal science is to find new ways of producing and processing aluminum alloys [2,3].

Improvement of mechanical performance of aluminum alloys can be achieved in several ways - by alloying, by thermal and deformation treatment, as well as by modification of casting methods [4–6]. However, with almost any method of increasing the strength of aluminum alloys, their electrical conductivity is inevitably lost [5–7]. This is due to the fact that the same structural mechanisms that lead to increased strength (increased dislocation density, increased density of grain boundaries, the presence of strengthening particles, the presence of a solid solution of alloying elements in aluminum) simultaneously negatively affect electrical conductivity. An important point is that the absolute values of the contributions of the above mechanisms are different, and by selecting them in a special way, it is possible to ensure an increase in mechanical strength without a significant loss of electrical conductivity [8].

In this regard, the creation of low-alloyed alloys is of particular importance, since the influence of alloying elements on the structures is more significant, the higher the concentration of these elements [9,10]. Maximum reduction in the concentration of alloying elements and a competent approach to structural mechanisms can provide the required level of physical and mechanical properties.

Relatively recently, alloys of the Al-Fe system have gained a significant interest [11]. New methods for producing these alloys, as well as their maximum availability due to the low cost of components, have led to the fact that their use is permitted as materials for household electrical wiring [12,13]. In addition to being cheap, such materials are also subject to requirements for mechanical strength, electrical conductivity, and thermal stability. This set of properties is achievable by creating certain structures in the material, namely, a relatively small grain size, the presence of strengthening intermetallic particles and the absence of a solid solution. Alloys of this system are also attractive because the solubility of iron in aluminum at room temperature is no more than 0.005 wt. %, which transforms these alloys into the category of an alloy with no solubility of alloying elements in the solid state, which means that the contribution of the solid solution to the increase in electrical resistance will be minimal or equal to zero [14].

In addition to Al-Fe alloys, the advancement of this system with the addition of copper is also of interest. Al-Fe alloys are already quite well studied, which prompts the search for new materials and combinations of alloying elements. Copper additions have a positive effect on the strength of alloys without significantly affecting their electrical conductivity. Copper, unlike iron, forms a solid solution with aluminum, which allows a more flexible approach to the issue of heat treatment and decomposition of the solid solution/formation of intermetallic precipitates [15,16].

In addition to the selected chemical composition, the structure of the material in its initial state also plays an important role. If the cast billet is subsequently subjected to deformation processing, then to obtain a relatively small average grain size in the original billet, conditions must be created for this [17]. In addition, the initial workpiece should not contain large gradients in the chemical composition and inhomogeneities in the distribution of structural elements, since such features may not be eliminated by deformation treatment and remain in the final product.

A relatively new method for producing aluminum alloys is casting in an electromagnetic crystallizer [18,19]. The main advantage of this method is the high (10^3-10^4K/s) cooling rate of the melt, which ensures nonequilibrium crystallization conditions. In addition, the method itself makes it possible to obtain a workpiece that is uniform in chemical composition and size and distribution of structural elements. Thus, it becomes possible to form highly dispersed particles of the second phases and a supersaturated solid solution already in cast workpieces, homogeneously distributed in the aluminum matrix [20].

The third way to obtain outstanding properties is the currently widely known methods of severe plastic deformation [21,22]. Techniques such as high-pressure torsion [23], equal-channel angular pressing [24,25] and their variations make it possible to achieve large degrees of deformation in materials and obtain nonequilibrium structures (minimum grain size, supersaturated solid solution), which would be impossible to obtain using classical methods. Such alloy microstructures, in combination with subsequent heat treatment, make it possible to realize the best balance of physical and mechanical properties in semifinished products and products [26,27].

In the previous study, authors have stablished that combined deformation treatment including SPD methods positively affects the mechanical properties of the Al-Fe-Cu system alloys [28]. Particularly, stripes of the Al-0.5Fe-0.3Cu produced by EMC and subjected to the ECAP with the subsequent cold rolling demonstrated formed UFG microstructure providing the UTS of 300 MPa along with the electrical conductivity of the 56 % IACS. Since the form of a wire is preferable for the materials in the electrical industry, the combination of the ECAP and cold drawing was studied in the current work.

In this work, three approaches are used to create a conductive aluminum alloy with unique properties. The workpieces of economically alloyed Al-0.5Fe-0.3Cu alloy (wt. %) obtained by frontier technique of casting in an electromagnetic crystallizer were subjected to two-stage deformation processing, including equal-channel angular pressing and cold drawing. Samples of wire with a diameter of 3 mm obtained by this treatment were subjected to annealing at 230 °C for 1 hour to test its thermal stability. The physical and mechanical properties of the wire samples produced in this work are compared with the properties of conductive wires made from commercial alloys for electrical purposes, as well as from Al-Fe system alloys produced by casting in EMC, which do not contain copper.

Materials and Methods

In order to study the effect of electromagnetic casting and subsequent deformation treatment the experimental Al-0.5Fe-0.3Cu wt. % alloy was produced. Its samples in the form of thin rods of a diameter of 10 mm were obtained by continuous casting in an electromagnetic mold. The chemical composition of the alloy samples is presented in Table 1. In terms of the content of alloying elements and impurities, it is close to the AA8030 alloy [29], widely used in electrical engineering. Conventionally, wire rod of such alloys is produced by the method of continuous casting and rolling (CCR) [30].

Table 1. Chemical composition of alloys of the Al-Fe system (wt. %)

Alloy	Cu	Fe	Si	Σ (Mn, Cr, Zn)	Al
Al-0.5Fe-0.3Cu	0.30	0.50	0.02	< 0.01	Res.
AA8030 [29]	0.15 – 0.20	0.35 – 0.45	0.07	< 0.03	Res.

Samples of wire rod of the Al-Fe-Cu alloy were made on the basis of primary aluminum grade A85 (not less than 99.85 wt. % Al), copper grade M00k (not less than 99.9 wt. % Cu), as well as Fe80Al20 alloy in proportions selected to match the required Fe and Cu concentrations. After the melt temperature reached more than 800 °C, continuous casting was carried out in an EMC installation at a speed of 12.4 mm/s.

Some of the obtained wire rod samples were subjected to two-stage deformation treatment, including SPD by equal-channel angular pressing (ECAP) and subsequent cold drawing (CD), and the other part was subjected to deformation only by cold drawing.

Using an ARTA-120 wire-cutting machine, square samples measuring 10 × 10 × 100 mm were made from cast semifinished products and subjected to two-stage deformation processing.

At the first stage, the samples were deformed using the ECAP method in equipment with a channel coupling angle of 120º, in the B_C mode, at room temperature. The number of processing cycles was 4. Similar processing conditions are used to form the UFG structure in low-alloy aluminum alloys [31–33]. As a result of SPD processing, samples with a cross-section of 10 × 10 mm and a length of up to 80 mm were obtained.

At the second stage, the samples were subjected to cold deformation on a laboratory drawing machine with a draw ratio of 13.5 (relative compression ~ 75 %). As a result of CD, wire samples with a diameter of 3 mm were obtained. Samples of the original wire rod were also subjected to CD using similar conditions.

The heat resistance of wire samples was assessed in accordance with the requirements of the IEC 62641:2023 standard [34]. To do this, after cold treatment, some of the samples were annealed at a temperature of 230 °C for 1 hour, followed by cooling in air. Annealing was carried out in a Nabertherm B180 furnace.

The microstructure was studied using scanning electron microscopy (SEM) on a Tescan Mira microscope at an accelerating voltage of 10-20 kV in back-scattered (BSE) and secondary electrons (SE) modes.

The microstructure was studied using transmission electron microscopy (TEM) on a JEOL JEM 2100 microscope at an accelerating voltage of 200 kV. Before the study, the samples were subjected to electropolishing by double-jet polishing of thin foils on a Struers Tenupol-5 unit using a solution of 20 % nitric acid and 80 % methanol. Polishing was carried out at a solution temperature of -20 °C and a voltage of 20 kV. The studies were carried out on three foils per condition to obtain statistically reliable data. Images were obtained in bright field (BF) and dark field (DF) modes.

To obtain statistically reliable results, tensile tests were carried out on three samples for each state, on a universal dynamometer Instron 5982 at room temperature and a strain rate of 10^{-3} s^{-1} (for initial samples and after deformation by the ECAP method) in accordance with GOST 1487-94 and at a speed of 100 mm/min (for wire samples after cold drawing) in accordance with GOST 10446-80. Based on the test results, the values of the yield strength (σ_{YS}), ultimate tensile strength (σ_{UTS}) and elongation to failure (δ) were determined. Tensile test samples after ECAP had the dimensions of 1 × 1 × 4 mm, after cold drawing – the shape of cylinders of 3 mm diameter and 100 mm length.

X-ray diffraction (XRD) analysis was conducted with a Bruker D2 Phaser diffractometer using CuKα radiation. Values of lattice parameter were calculated via the Rietveld refinement method using MAUD software [31].

Electrical conductivity (ω) was determined with an error of ± 2 % by the eddy current method on samples after ECAP and by the four-point bridge method on samples after drawing [35]. The electrical conductivity relative to annealed copper (International Annealed Copper Standard, % IACS) was calculated using Eq. (1):

$$IACS = \frac{\omega_{\mathrm{Al}}}{\omega_{\mathrm{Cu}}} \times 100\% \quad (1)$$

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 and Discussion

Microstructural assessment

Figure 1 shows images of the microstructure of the Al-0.5Fe-0.3Cu alloy formed in the original wire rod after EMC casting. The dark gray phase is the aluminum matrix, the light phase is intermetallic particles. The structure is very similar to one observed before in Al-Fe [36], Al-La-Ce [17] and Al-Fe-Cu [28] system alloys produced by casting into electromagnetic mold.

The average size of a dendritic cell is 5.7 ± 0.9 μm. Based on the previous research it means that the crystallization rate was not less than 10^3 K\s [18]. It is known from the literature that in alloys of the Al-Fe system, during nonequilibrium crystallization, both metastable phases such as Al_2Fe and Al_6Fe and a stable phase $Al_{13}Fe_4$ can be formed [36–38]. However, the studied alloy also contains copper, which can form a solid solution in aluminum with a maximum equilibrium concentration at room temperature of about 0.3 wt. % and form double phases like Al_2Cu and/or ternary Al-Fe-Cu phases, the most prevalent of which is Al_7Cu_2Fe [39–41].

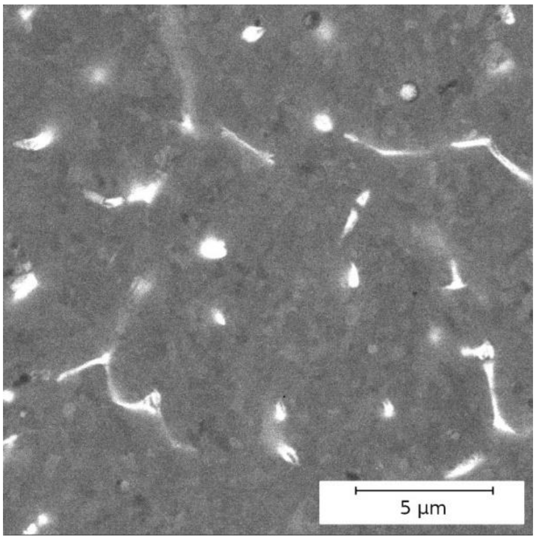

Fig. 1. Microstructure of the Al-0.5Fe-0.3Cu alloy in the initial state, SEM, BSE [41]

According to previous studies, almost all Fe is concentrated in intermetallic particles, which is expected, given its low solubility in aluminum [8,14]. Due to the high rate of crystallization of the alloy, part of the Cu is in the solid solution of aluminum and can also be part of some intermetallic particles [42].

Judging by the results of XRD analysis, which were previously carried out by authors on alloys of the Al-Fe system, obtained by a similar casting method [37,38], it can be assumed that the particles of the double phase of iron aluminide belong to the metastable Al_2Fe phase. While the lattice parameter of the Al-0.5Fe alloy practically does not change due to ECAP (from 4.0507±0.0001 Å to 4.0503±0.0001 Å) [37], the lattice parameter of the Al-0.5Fe-0.3Cu alloy due to ECAP decreases from 4.0522 ± 0.0001 to 4.0498 ± 0.0001 Å. The data obtained indicate the retention of a solid solution of copper in aluminum in the alloy after casting in the EMC, as well as the presence in the composition, in addition to the double phase of iron aluminide, of a ternary phase, presumably Al_7Cu_2Fe [43]. Copper, when dissolved in a solid solution of aluminum, reduces its lattice parameter, which can be seen in the material under study. According to literature data [8,14], the maximum concentration of a solid solution of copper in aluminum at room temperature is about 0.3 wt. %, so theoretically all the copper could dissolve in aluminum. According to the literature data, the ECAP has a rather weak effect on the formation of a solid solution, so it could be safely assumed that not all copper is dissolved in the solid solution after ECAP [44].

Figure 2 shows the microstructure of a sample of the Al-0.5Fe-0.3Cu alloy after deformation by ECAP. The intermetallic network formed by the plates of intermetallic phases is deformed and becomes curved due to deformation and loses its continuity. Fragmentation of intermetallic particles also occurs. The average grain/structural element size is 1350 ± 70 nm in length and 700 ± 40 nm in width, the average size of intermetallic particles is 650 ± 50 nm. Despite the fact that ECAP belongs to SPD methods, it usually does not lead to phase transformations in aluminum alloys of this or similar alloying systems [31,45], suggesting their absence in this case. Figure 2(b) shows black voids in the middle of intermetallic particles. This could be attributed either to fragmentation of the particles during the ECAP and formation of the micropores (similar effect was observed in [46]), or to the effect of the particles "falling out" from the sample during the electropolishing. Since this effect was previously observed on samples prepared by mechanical polishing, authors are inclined to the state that these voids are the result of the deformation of the relatively soft aluminium matrix by the fragmented intermetallic particles.

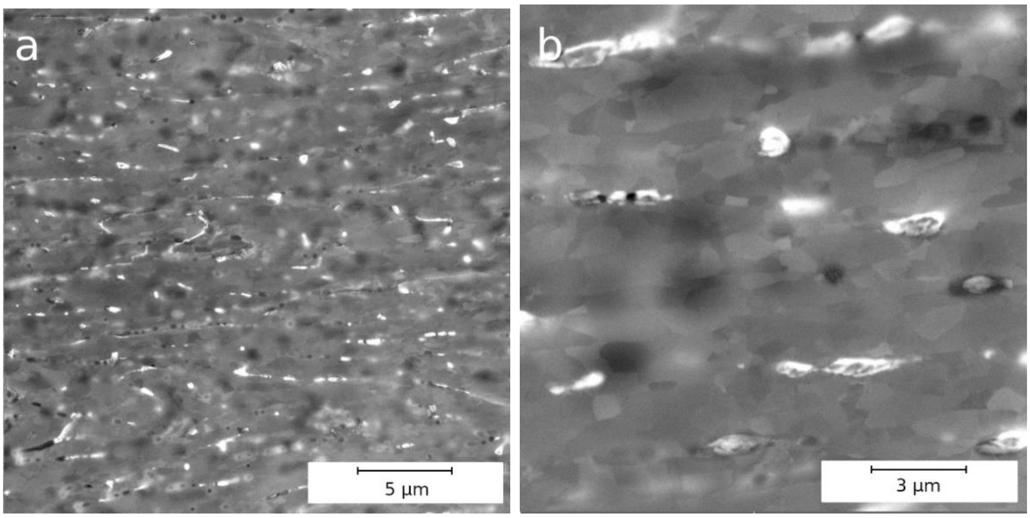

Fig. 2. Microstructure of the Al-0.5Fe-0.3Cu alloy in the state after ECAP: (a) 2kx, (b) 5kx, SEM, BSE

After ECAP, the consequent deformation treatment of the alloy in the form of cold drawing took place. Figure 3 shows the microstructure of the Al-0.5Fe-0.3Cu alloy after combined ECAP and CD. The material in this state was successively subjected to deformation with tangential (ECAP) and normal (CD) stresses, affecting its microstructure. Both grains and intermetallic particles experience the fragmentation during CD. Thus, according to SEM data, the average size of intermetallic particles after ECAP and CD in decreased to 380 ± 45 nm, the average grain width - to 350 ± 15 nm with the simultaneous average grain length increase up to 2850 ± 290 nm. The decrease in size of the major structural features, such as average grain size and average particle size, was facilitated by both the deformation accumulated during ECAP and the preliminary fragmentation of intermetallic particles and their denser distribution in the volume of the material.

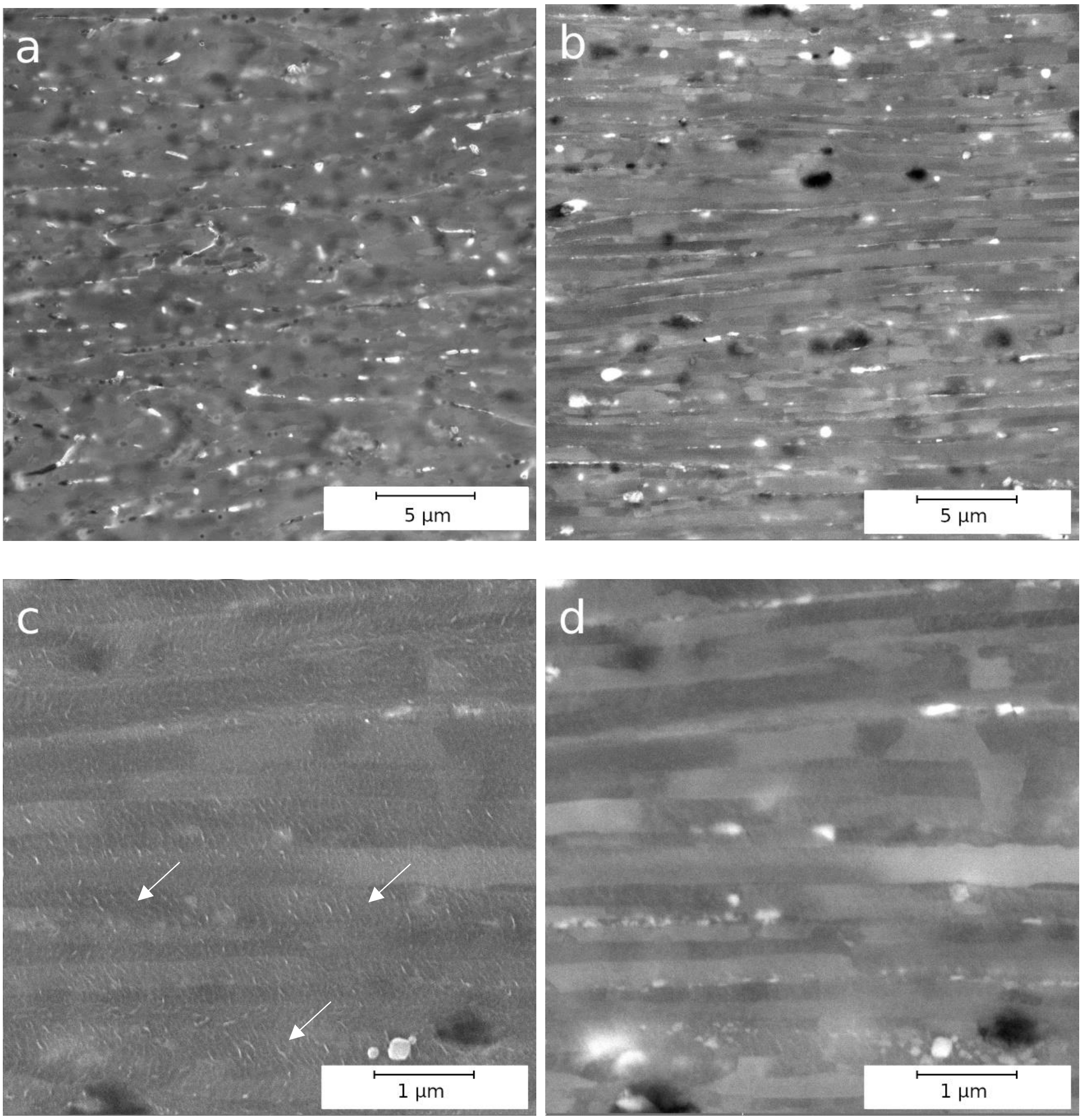

Fig. 3. Microstructure of the Al-0.5Fe-0.3Cu alloy after ECAP+CD, obtained in different SEM modes: (a,c) backscattered electrons, 2kx, (b,d) secondary electrons, 10kx. Secondary electrons mode allows to highlight the surface relief of the sample. White arrows indicate the deformation bands

Another effect introduced by the combined ECAP+CD treatment is a characteristic relief on the surface of samples for microscopy. It consists of the presence of bright stripes located within the grain boundaries and oriented at an angle of 45° relative to the direction of deformation (Fig. 3(c)). These structural elements are visible only in secondary electrons and are not visible in back-scattered electrons, from which two conclusions can be drawn: first, these bands are not particles of a different phase relative to the grains, and second, they appear on the surface of the sample. Most likely, these are shear bands formed during the localization of deformation in the aluminum matrix as a result of combined deformation treatment according to schemes that implement shear (ECAP) and normal (CD) deformation [25].

Figure 4 shows the microstructure of the Al-0.5Fe-0.3Cu alloy after cold drawing. The structure is qualitatively similar to that observed in the ECAP+CD state (Fig. 3).

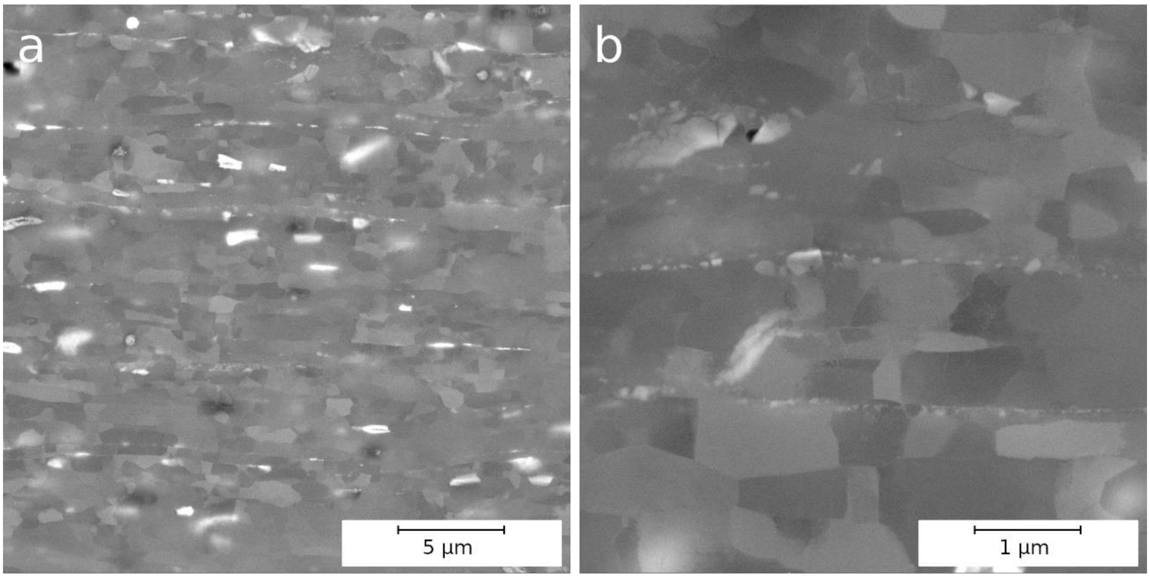

Fig. 4. Microstructure of the Al-0.5Fe-0.3Cu alloy after CD: (a) 2kx, (b) 10kx, BSE, SEM

The arrangement of layers of intermetallic particles along the grain boundaries is noticeably less dense than after ECAP +CD (Fig. 3). This effect is facilitated by the absence of the preliminary fragmentation of clusters of intermetallic particles during ECAP (like in the case of ECAP+CD), providing fewer barriers for the grain boundary migration and resulting in wider grain - due to CD of the materials in the initial state the grains acquired an elongated shape with an average length of 2750 ± 400 nm and an average width of 650 ± 20 nm, while grains after ECAP, having roughly the same length, are about 2 times narrower. The fragmentation of the intermetallic particles occurs during the CD, resulting in the formation of the linear particles clusters oriented in the direction of deformation (Fig. 4(b)). The average size of intermetallic particles in CD state is 390 ± 80 nm.

It should also be noted that the segregations/clusters of intermetallic particles, although they acted as barriers to the migration of grain boundaries, were not the only obstacle to their migration - the grain boundaries of the aluminum matrix also line up in lines parallel to the direction of deformation (Fig. 4(b)).

The abovementioned observations are confirmed by the TEM results. Figure 5 shows the microstructure of the Al-0.5Fe-0.3Cu alloy after cold drawing in longitudinal (Fig. 5(a,b)) and cross-sections (Fig. 5(c,d)). Images of a longitudinal section show segregations of intermetallic particles along grain boundaries elongated in the direction of deformation. These segregations act as obstacles to the migration of grain boundaries. Segregation of particles along grain boundaries are also observed in the cross-section.

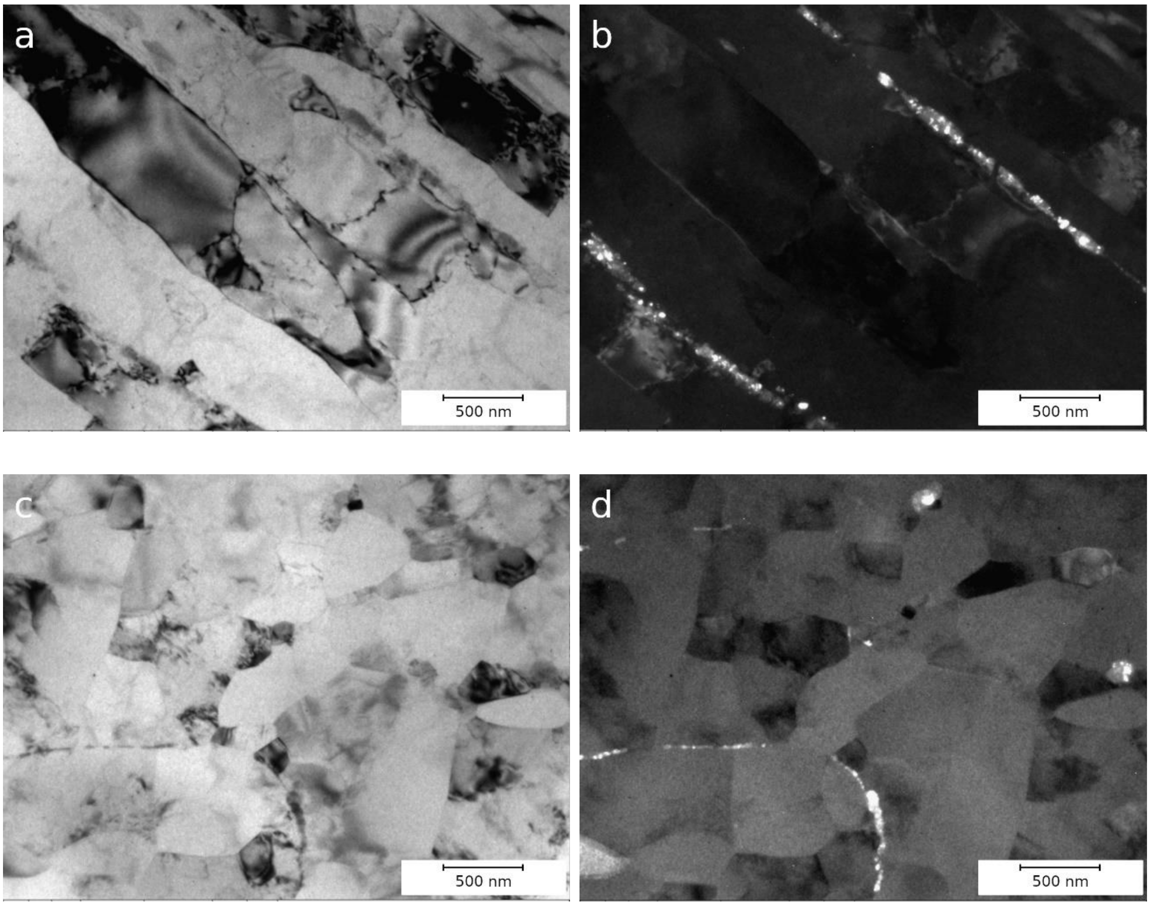

Fig. 5. Microstructure of Al-0.5Fe-0.3Cu alloy in cold drawing state, longitudinal ((a) - BF, (b) - DF) and cross section ((c) - BF, (d) - DF), TEM

Overall, the implementation of the ECAP before the CD results in the qualitatively and quantitively different microstructure in comparison to the single CD treatment. ECAP+CD provides narrower grain with more even distribution of the intermetallic particles within the material, although the size of the particle remains the same.

According to previously published studies, the smaller grain should provide the higher level of the yield stress since it shortens the free path of the dislocations [26]. Rough estimation of the grain size impact on the mechanical strength of the material shows that ECAP + CD state should have 25 MPa higher yield stress than CD state, which is confirmed, considering the error value, in the Table 2.

Physical and mechanical properties of Al-0.5Fe-0.3Cu alloy

The mechanical properties and electrical conductivity of the Al-0.5Fe-0.3Cu alloy are presented in Table 2. According to the data given below, in the initial state the Al-0.5Fe-0.3Cu alloy is characterized by low strength indicators (ultimate strength 106 MPa) with a fairly high level of electrical conductivity (about 56%IACS) and elongation to failure (about 34 %).

Table 2. Physical and mechanical properties of the Al-0.5Fe-0.3Cu alloy

State	Electrical properties	Mechanical properties		
	IACS, %	σ_{YS}, MPa	σ_{UTS}, MPa	δ, %
Before and after ECAP				
Initial (cast)	56.1±0.4	72.0±8.0	106.0±4.0	33.7±6.5
ECAP	54.8±0.2	181.0±12.0	214.0±15.0	13.7±2.8
ECAP+CD	55.5±0.3	234.0±19.0	342.0±6.0	2.7±0.5
CD	55.8±0.4	230.0±7.0	260.0±5.0	2.5±0.2
After CD and annealing at 230°C for 1h				
ECAP+CD+230 °C	58.5±0.3	146.0±16.0	163.0±15.0	7.2±3.7
CD+230 °C	58.0±0.1	174.0±3.0	200.0±3.0	3.2±0.3
Wire made from Al-0.5Fe and 6101 Al-Mg-Si alloys				
8000 series alloys [29]	60.6	-	103.0-152.0	-
Al-0.5Fe EMC + CD [37]	58.4	170.0±12.0	204.0±14.0	5.3±0.2
Al-0.5Fe EMC + CD+230°C [37]	59.2	175.0±11.0	200.0±16.0	4.0±0.4
6000 series alloys [47]	57.4-52.5	-	245.0-342.0	3.0-3.5
6101 ECAP-C +AA+CD [31]	56.4	-	364.0	3.5
Stripes				
Al-0.5Fe-0.3Cu EMC + ECAP + Cold rolling [28]	55.9±0.7	267.0±6.0	309.0±4.0	13.8±0.9

In case of the studied materials, ECAP generally leads to a lower level of structural defects than cold drawing resulting in a lower level of ultimate tensile strength (214 MPa). The electrical conductivity value, however, is higher in the cold-drawn state, which can be explained by the possible formation of a solid solution of copper in aluminum during ECAP due to the diffusion of copper into the aluminum matrix under the influence of large stress fields and shear deformation. As a result of the combined processing of ECAP + CD, a wire was obtained that is characterized by a high (as after drawing) level of electrical conductivity and a significantly increased (even more than after ECAP) level of tensile strength. The relative elongation to failure, however, is at the level of the wire after cold drawing and is very small (Table 2).

Table 2 also shows the strength and electrical conductivity values of some commercial alloys for comparison. Thus, wire from the Al-0.5Fe-0.3Cu alloy after combined ECAP + CD treatment in terms of strength and electrical conductivity is at the level of heat-resistant wire made from 6101 alloy by the same deformation scheme, making it affordable alternative to the Al-Mg-Si alloys. Commercially produced wires from 6000 and 8000 series alloys, as well as wires made from electromagnetically cast Al-0.5Fe alloy, while having slightly higher level of electrical conductivity, demonstrate notably (about 1.5 times) lower mechanical strength compared to the wires produced from electromagnetically cast Al-0.5Fe-0.3Cu alloy with use of ECAP+CD.

Alloys made from these systems are subject to thermal stability requirements. Thermal stability is tested by annealing at 230 °C for 1 hour, which is equivalent to operating at 150 °C for 40 years [34].

Engineering stress-strain curves of the alloy in deformed states and after annealing are presented in Fig. 6. It would be fair to say that every studied state has ductile character of the deformation and failure. This is surprising considering that the presence of the Cu in aluminium alloy may result in the embrittlement of the latter.

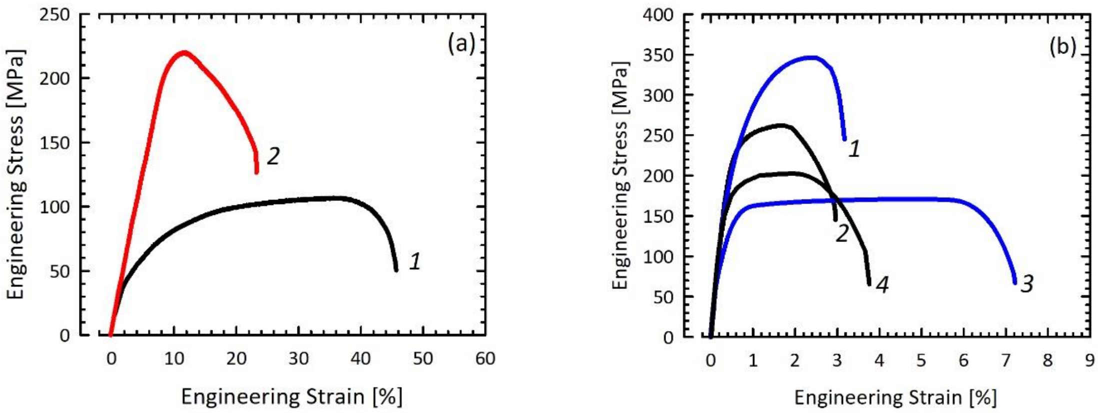

Fig. 6. Engineering stress-strain curves of alloy samples in the EMC and ECAP states (a): 1 – EMC, 2 – ECAP; as well as samples in the form of a wires (b): 1 – ECAP+CD, 2 – CD, 3 – ECAP+CD+230°C, 4 – CD+230 °C

The mechanical properties and electrical conductivity of the alloy after annealing at 230 °C for 1 hour are also presented in Table 2. Annealing leads to softening of alloys both after cold drawing and after a combination of equal-channel angular pressing and cold drawing [48]. The drop in the level of ultimate strength in the alloy after drawing was 23 %, in the alloy after combined processing – 52 %. None of these states can be considered thermally stable, since the drop of the UTS was more than 10 %. As for absolute values, the alloy after combined processing softened significantly more than after drawing. At the same time, there was an increase in the relative elongation to failure and electrical conductivity. Similar processes occurred in the alloy after cold drawing, but the decrease in strength and increase in ductility are much less pronounced. The electrical conductivity in both states is comparable and amounts to 58–58.5 % IACS, exceeding the electrical conductivity of the starting material.

Conclusions

In this work, a two-stage deformation treatment was carried out, including equal-channel angular pressing and cold drawing, of an Al-0.5Fe-0.3Cu alloy produced by casting in an electromagnetic crystallizer. During the work, the following conclusions were drawn:

1. The method of casting in an electromagnetic crystallizer makes it possible to form the microstructure of the alloy at a high crystallization rate. The resulting microstructure is characteristic of aluminum alloys with limited solubility of components in the solid state after casting in an EMC.

2. During the ECAP a solid solution of copper in aluminum is formed. Iron is bound in intermetallic Al_2Fe, Al_6Fe and $Al_{13}Fe_4$ phases. Copper atoms are also bound in either double (Al_2Cu) or triple (Al_7Cu_2Fe) intermetallic phases.

3. The combined treatment of ECAP + CD leads to the formation of a structure in the Al-0.5Fe-0.3Cu alloy that is different from one formed as a result of CD. The main difference is the decreased grain width and the presence of the shear bands within them in the ECAP+CD state. This structural difference resulted in the 25 % increased UTS of the wire in the ECAP+CD state relative to the CD sate with the similar values of the electrical conductivity and elongation to failure.

4. The strength level of wire made from the Al-0.5Fe-0.3Cu alloy after ECAP + CD exceeds that of thermally resistant alloys of the 6000 and 8000 series, as well as the Al-0.5Fe alloy produced by casting in an electromagnetic crystallizer. As a result of the combined ECAP + CD processing, a tensile strength level of 342 MPa and an electrical conductivity level of 55.5 % IACS are achieved, which is comparable to the similar characteristics of the commercial alloy 6101 subjected to ECAP-Conform processing followed by cold drawing.

5. According to the standards for conductive wires made of aluminum alloys, wire made of Al-0.5Fe-0.3Cu alloy after heat treatment and ECAP + CD cannot be considered thermally stable, since the loss of strength after heat treatment is more than 10 % in both cases. However, after annealing equivalent to operating at 150 °C for 40 years, both wires have an electrical conductivity of at least 58 % IACS and a strength of at least 160 MPa.

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