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EFFECT OF ECAP PROCESS ON DEFORMABILITY, MICROSTRUCTURE AND CONDUCTIVITY OF CuCoNi ALLOY

B. Grzegorczyk [a], S. Rusz [b], P. Snopinski [a], O. Hilšer [b], A. Skowronek [a], A. Grajcar [a,*]

[a] Silesian University of Technology, Faculty of Mechanical Engineering, Department of Engineering Materials and Biomaterials, Gliwice, Poland
[b] VSB – Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Mechanical Technology, Ostrava – Poruba, Czech Republic

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Abstract

The study deals with the influence of various variants of severe plastic deformation in the Equal Channel Angular Pressing (ECAP) process on the microstructure, microhardness, and conductivity of CuCoNi alloy. The microstructure evolution was studied by microscopic observations and electron back-scattered diffraction (EBSD) in a scanning electron microscope (SEM). The Vickers method was used to test the microhardness of the samples after various variants of the ECAP process. The conductivity was measured with an eddy current electrical conductivity meter based on the complex impedance of the probe. The results indicated the possibility of deformation of CuCoNi alloys in the process of pressing through the ECAP angular channel and developing their microstructure and properties. The method is an effective tool for strengthening the tested copper alloy by refining its microstructure. After the first pass, the grain size was reduced by 80%. Increasing the plastic deformation temperature did not significantly affect the obtained level of microstructure fragmentation - the average grain size is approx. 1.4-1.5 µm. The fragmentation of the microstructure had a negligible effect on the conductivity of the CuCoNi alloy, which oscillated at the value of 13 MS/m after the ECAP process.

Keywords: *ECAP; Copper alloy; Severe plastic deformation; Microstructure; Microhardness; Conductivity*

1. Introduction

Modern technologies in the electrical and electronic industry require the use of metals with high plasticity, electrical conductivity, good thermal conductivity, as well as low chemical affinity to oxygen. Such properties are characterized by copper, which contributed to the wide application of this metal in various fields of technology. The role of copper may increase even more, as the technologies based on it help building a low-carbon economy focused on reducing CO_2 emissions in both the power industry and construction. It is estimated [1, 2] that by taking advantage of the excellent electrical conductivity of copper in the next 10-20 years, it will be possible to reduce CO_2 emissions by 100 million tons per year.

The improvement of the mechanical properties of copper occurs most often through the addition of alloying elements such as beryllium, silver, titanium, and niobium. However, the electrical conductivity of these copper alloys is typically lower than 20% of IACS (International Association of Classification Societies) [3]. One of the ways to increase the electrical conductivity and mechanical properties of copper alloys is to refine the microstructure. The interest in the production of ultra-fine-grained materials (UFG with a grain size of 100-1000 nm) by methods of severe plastic deformation has significantly increased over the last few decades, which is confirmed by the growing number of publications on this subject [4-7].

One of the basic methods of producing this type of structures are plastic deformation processes allowing to obtain high plastic deformation: Severe Plastic Deformation (SPD) processes. The main assumption of SPD processes is the fragmentation of the microstructure of coarse-grained materials, which occurs as a result of the reorganization of the dislocation structure during plastic deformation [4, 5]. At low values of plastic deformation, the dislocations generated in the material are distributed randomly [6-8]. These defects regroup with an increase in the value of plastic deformation. Only after reaching a critical value of strain, they form specific systems called dislocation cells and shear bands. During the SPD process, when the value of accumulated plastic deformation increases, the distance between the grain boundaries decreases and the misorientation angle increases. The process of such grouping of

Corresponding author: adam.grajcar@polsl.pl

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dislocations in the material is called polygonization [5, 8, 9]. For the fragmentation of the structure to occur, it is necessary to accumulate much higher deformation amount than in the case of conventional methods of plastic working.

In the last decade, most of the research in the field of intensive plastic deformation has focused mainly on the use of several methods, which can be classified as follows: ARB - (Accumulative Roll Bonding) - packet rolling, CEC - (Cyclic Extrusion Compression) method of cyclic compression extrusion, ECAP (Equal Channel Angular Pressing - a method of pressing through an angular channel, HPT (High Pressure Torsion) - tightening under high pressure [4, 5].

One of the most frequently used methods of intensive plastic deformation is pressing through the angular channel (ECAP). In this process, the material is subjected to very high stress as a result of the action of shear forces in the area of intersecting channels [10, 11]. Most of the materials produced by SPD methods have unique properties compared to their coarse-grained counterparts. This is because during the ECAP process grains are ground to the nano- or sub-micrometric scale, which results in a significant increase in the strength of the material, often allowing for sufficient plasticity.

The methods of intensive plastic deformation, unlike conventional plastic deformation technologies, are not used to shape the starting material, but to transform the coarse-grained microstructure into the ultra-fine or nanometric microstructure [4, 12]. The obtained grain size and the nature of the produced nanostructures mainly depend on conditions of the SPD process, the phase composition, and the initial grain size of the starting material. Compared to conventional coarse-grained materials, those treated with SPD have better mechanical and physical properties [13-15]. In the case of pure metals (such as copper), the improvement in mechanical properties is up to eight times and 30–50% for alloys [15-17].

For each material, there is a characteristic minimum grain size that can be achieved by refining the structure with SPD methods. This value depends on the material's tendency to annihilate defects generated during deformation (mainly dislocation) and a rate of the recovery and recrystallization processes. It should be mentioned that in Cu alloys, significant strengthening due to intense plastic deformation is not accompanied by a noticeable decrease in electrical conductivity [15-17]. The ECAP method is most often used for refinement of Al alloys [6, 12, 13, 18-23], Mg alloys [7, 14, 24], copper alloys [3, 6, 15-17, 25-30], titanium alloys [31, 32], as well as mild steels [33, 34]. In the case of copper alloys, this method is most often used for alloys containing such elements as Zn, Al, Mg and Co [15, 27-29].

Due to the unique magnetic properties (very high magnetoresistance) and the possibility of using them as a catalyst (e.g. in the synthesis of higher alcohols), CuCo alloys are of considerable interest. In order to improve / change the magnetic properties of Cu-Co alloys, various alloying additions are used, e.g. Cr, Fe, Mn and Ni. Among the above-mentioned alloying elements, nickel contributes to the greatest extent to the improvement of magnetoresistance. The improvement of the magnetoresistance is noticeable in particular in Cu-Co alloys with a low Ni content [28, 29]. Nickel has the significant influence on the physical and mechanical properties of Cu-Ni alloys. While tensile strength, yield stress, hot-temperature resistance, solidus and liquidus temperatures, and corrosion resistance increase with increasing nickel content, thermal and electrical conductivity decreases. That is why it is worth to be investigated.

Cu alloys with a small addition of Co are plastically deformable, which was confirmed by Bursik et al. [28]. They proved that intensive plastic deformation using the ECAP method results in the significant fragmentation of the microstructure characterized by a relatively high quantitative proportion of high-angle boundaries (> 55%) after 12 ECAP cycles. Intense plastic deformation also allows to control the magnetic properties of these alloys and promotes an even distribution of precipitates in the Cu matrix [27-29]. The minimum grain size obtained for the Cu-Co alloy after intensive plastic deformation by HPT is ~ 100 nm [30].

Wang et al. [35] investigated the evolution of the microstructure and mechanical properties of Cu-Ti-Cr-Mg alloy deformed by ECAP at different temperatures. The cryogenic-temperature-deformed samples exhibited improved hardness than room-temperature-deformed samples. ECAP deformation significantly refined the grain size of the alloy due to the dislocation subdivision and twin fragmentation. It was reported that the average grain sizes after 8 passes may be reduced to about 0.32 µm. Caldatto Dalan et al. [36] investigated the effect of ECAP at room temperature and 300 °C on the distribution of the second phase particles and its influence on hardness and electrical conductivity in the commercial Cu−0.81Cr−0.07Zr alloy. Microstructural characterization indicated that the area fraction of coarse Cr-rich particles decreased after ECAP processing. Kim et al. [37] evaluated the grain refinement and mechanical properties of Cu–40Zn brass alloy processed by ECAP. Increased pass number led to notable grain refinement, from 13 µm in the initial sample (350 °C/180 min heat-treated material) to 300 nm after 4 passes. Naser Radhi et al. [38] investigated a commercial Cu-30Zn brass alloy after the ECAP process. The results showed that a significant grain refinement was also achieved in the microstructure. The microhardness, ultimate tensile strength, and the wear resistance were also increased remarkably after the ECAP compared to the initial microstructure.

The aim of this study is to assess the influence of various variants of severe plastic deformation in the modified torsion-channel ECAP process on the deformability, microstructure, microhardness, and conductivity of the CuCoNi alloy.

2. Experimental

The investigations concern low-alloy copper, CuCoNi, cast under laboratory conditions with the use of an induction furnace. The obtained alloy was poured into graphite ingot molds with a diameter of 30 mm, and then forged into bars on a compressor hammer with a beater weight of 200 t. From the obtained rods, 5 samples with dimensions: 16x16x62 mm were cut and used for the experiments. The chemical composition of the alloy is presented in Table 1.

Table 1. *Chemical composition of investigated material*

Alloy designation	Chemical elements, wt.%					
	Cu+Ag	Co	Ni	P	Si	Fe
CuCoNi	97.7	1.187	1.026	0.055	0.013	0.009

After forging, the supersaturation at 900 °C followed by water quenching was performed.

The supersaturation temperature of the tested CuCoNi alloy was selected on the basis of the analysis of the three-component phase equilibrium system of copper with nickel and cobalt. Heating to the supersaturation temperature was carried out in an electric chamber furnace equipped with a controller enabling temperature registration with an accuracy of ± 5 °C. After supersaturation, the formed scale and unevenness were removed obtaining a sample size of 14.5 x 14.5 x 60 mm. The samples of this size were subjected to severe plastic deformation using the ECAP method. Based on the literature data and preliminary tests [27, 29, 39], different process conditions were established, which are summarized in Table 2. The samples before deformation were preheated to the process temperature (T). The samples' annealing time at temperature T was 10 minutes.

The process of intensive plastic deformation was performed using a die with the channel intersection angle of 90º with the modified geometry of the outlet channel - a 30º torsion channel (Fig. 1a) and a hydraulic press with a total allowable pressure of 1600 kN. Modification of the die allows to obtain back pressure, which directly translates into an increase in the squeezing force [10]. The deformation by this modified matrix causes an equivalent deformation of ε = 1.23 per one pass. The use of a modified exit channel in the ECAP die also causes turbulent material flow and enables greater accumulation of plastic strain in one process cycle [11]. The samples were deformed with a constant deformation rate of 2 mm/s by way A (the sample was pressed without rotation). The hydraulic press used in the ECAP process was equipped with a heating device, which allowed the samples to be heated by the tool frame. The entire arrangement of the tool is shown in Fig. 1b. The annealing time of the samples was 10 minutes.

In order to assess the influence of various variants of intensive plastic deformation in the ECAP process on the microstructure of the CuCoNi alloy, microscopic observations were made using the Axio Observer light microscope by Zeiss. The microstructures revealed on the electro-polished specimens were observed using the SUPRA scanning microscope by Zeiss. Secondary electrons (SE) and backscattered electrons (BSE) analyses were used. Using the EBSD (Electron Backscatter Diffraction) technique, the misorientation angle of individual areas were determined on selected surfaces and along the scanning line. The scanning was carried out with a step of 0.1 μm, and data processing was performed using the TSL OIM software [40]. With respect to the angular resolution of the EBSD equipment, a threshold angle of 3° was used in determining the boundaries to minimize the effects of orientation noise. To perform grain size analysis, grains below a threshold size of four pixels were first removed. Then, the average grain size was analyzed using a misorientation threshold angle of 5°, i.e., two adjacent scan points were considered to belong to two different grains if the misorientation between them exceeded 5°.

Measurement of microhardness using the Vickers method was performed on the cross-section of the samples before and after the ECAP process, with the

Table 2. *ECAP process parameters for CuCoNi alloy*

Sample	1	2	3	4
Channel rotation angle, °	30	30	30	30
Number of ECAP cycles	1	1	1	1
Temperature, T °C	20 / 200	100	200	250

Figure 1. *ECAP die with a modified output channel: a) construction diagram, image of the die, b) the entire arrangement of the tool*

load of 9.81 N. The duration of the loading force was 15 s. 15 measurements were made on each sample in a line from the center to the edge of the sample.

Conductivity tests were performed using the Sigmatest 2.069 from Foerster. It uses the eddy currents to measure the electrical conductivity. The measurement was carried out by applying the measuring probe to the tested material. The result obtained is expressed in the MegaSimens per meter (MS/m) unit.

3. Results and discussion

After the ECAP process, the shape of the CuCoNi alloy samples changed; they are clearly twisted, while the ends of the samples become elongated (Figs. 2-5). According to the established test plan, sample no. 1 should be pressed in the ECAP at the temperature of 20 ºC. However, during the test, the maximum allowable pressure of the press was reached - 1000 MPa (Fig. 2a). Due to the limited plasticity of the sample at 20 ºC, in order not to damage the ECAP matrix, it was necessary to heat the sample to 200 ºC, which allowed to complete one ECAP cycle. The heated sample was present in the ECAP matrix during heating. Fig. 2a shows the forces registered during the deformation of sample no. 1 at 20 ºC and 200 ºC. After heating, the maximum pressure decreased to approx. 700 MPa (Fig. 2b). In this way it was possible to assess how the temperature change affects the plasticity of the alloy. In conclusion, full extrusion of the CuCoNi alloy sample at room temperature was impossible due to the squeezing force and reaching the stress of approx. 1000 MPa, forcing the process to be interrupted. Therefore, it was a reference sample for further variants. Sample no. 2 was heated to 100 °C before being forced through the channel. Stress values of about 800 MPa were obtained during the process. Before the process, samples no. 3 and 4 were successively heated to the temperatures of 200 ºC and 250 ºC. The increase in the process temperature was clearly accompanied by a decrease in the stress value, which can be observed in Figs. 4 and 5. The stress value of the sample deformed at 250 ºC is ~ 400 MPa, which is 50% of the stress recorded at 100 ºC.

After the ECAP process, the CuCoNi alloy shows the characteristics of deformed material on a microstructural scale. Examination of the microstructure revealed a gradual fragmentation of grains as a result of the shear bands formed, where the

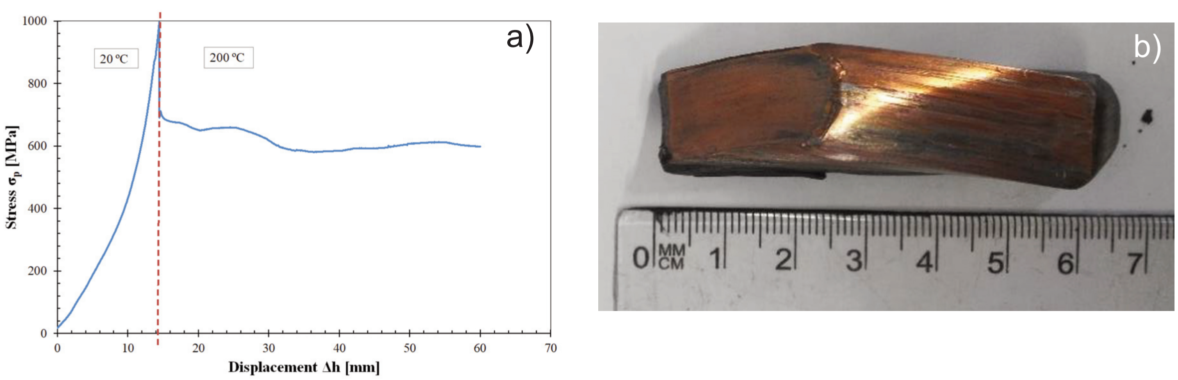

Figure 2. *a) The forces registered in the ECAP process for sample no. 1 at 20 ° C / 200 ° C, b) sample after the completed ECAP process*

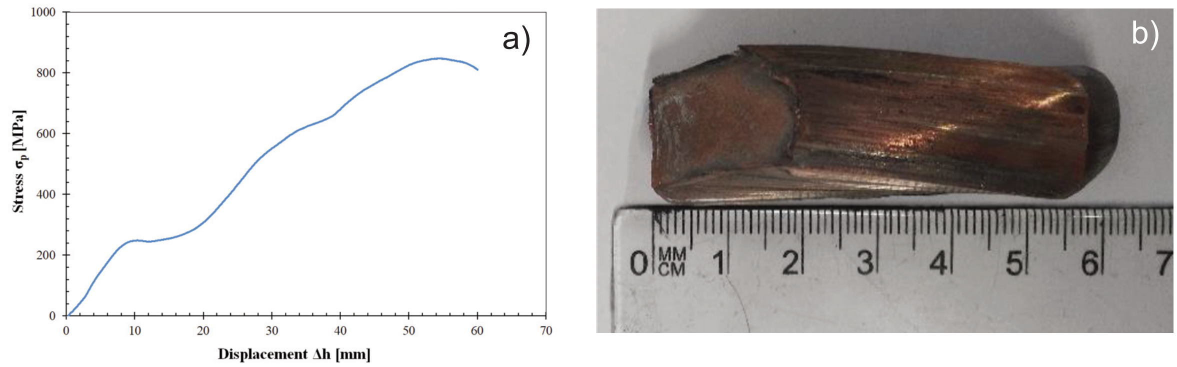

Figure 3. a) The forces registered in the ECAP process for sample no. 2 at 100 ° C; b) sample after the completed ECAP process

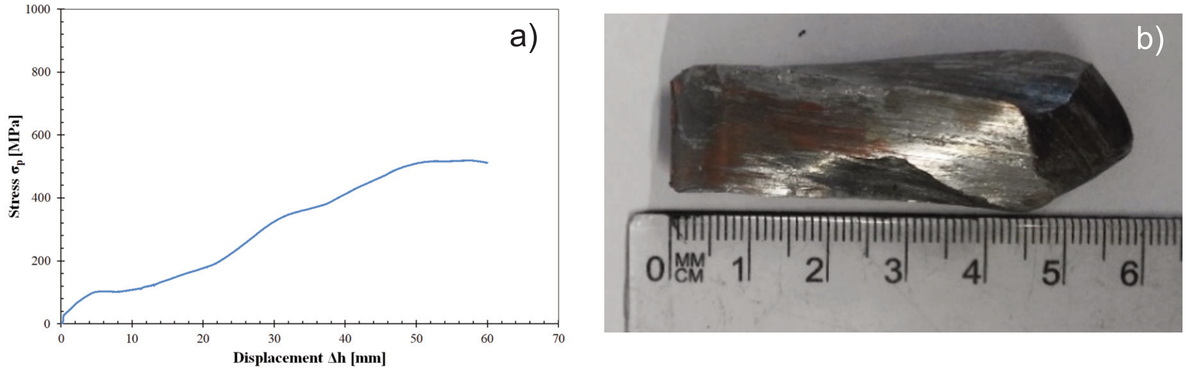

Figure 4. a) The forces registered in the ECAP process for sample no. 3 at 200 ° C; b) the sample after the completed ECAP process

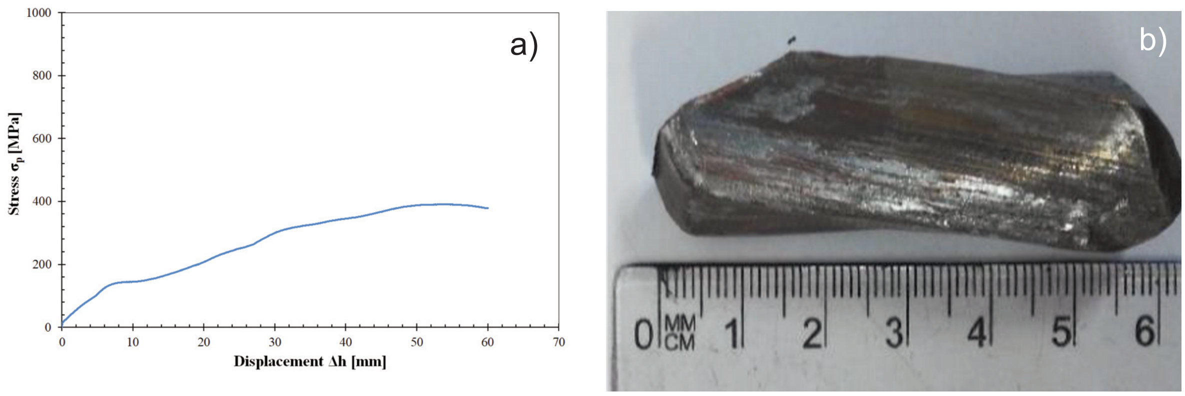

Figure 5. a) The forces registered in the ECAP process for sample 4 at 250 ° C; b) sample after the completed ECAP process

intense plastic deformation is located. It can also be observed that the alloy grains have been elongated as a result of the shear forces acting on the sample in the area of the matrix channels intersection. The dynamic recrystallization also cannot be excluded locally in the area of shear bands. However, it requires further research. It can also be observed that the grains have been elongated as a result of the shear forces acting on the sample in the area of the matrix channels intersection. It was found that the temperature at which plastic deformation was carried out influences the refinement of the microstructure. In the case of the sample deformed at the temperature of 250 ºC, the average grain size is ~ 21 μm, while the average grain size for the samples deformed at the temperatures of 100ºC and 200 ºC is ~ 17 μm and 19 μm, respectively.

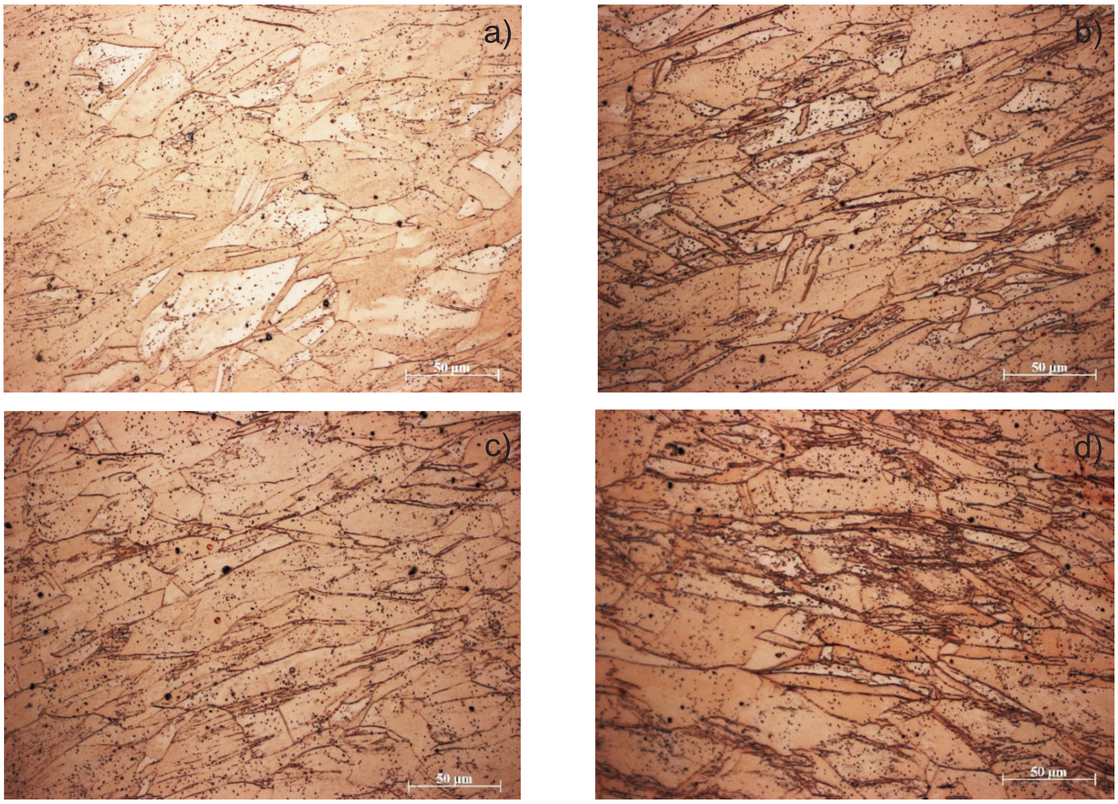

Figure 6. *Microstructure of the CuCoNi alloy after the ECAP process at the temperature: a) 20/200 °C, b) 100 °C, c) 200 °C, d) 250 °C*

Fig. 7a-d shows IPF-Z maps of the samples after supersaturation and plastic deformation. The analysis of the obtained EBSD maps shows that after supersaturation (Fig. 7a), large equiaxial grains dominate in the structure. These grains are characterized by irregular boundaries and annealing twins can be observed inside them (Fig. 7a). This is confirmed by the analysis of the histogram of the distribution of the grain boundary misorientation angle (Fig. 8a), where a large share of high-angle boundaries can be observed. A strong extreme at Θ = 60º according to the literature [22, 23] confirms the presence of twin boundaries Σ3 (60º <111 >). The average grain size of the sample after supersaturation is 7.1 µm (Table 3).

The crystallographic orientation measurements performed by the backscattered electron diffraction method confirm the significant influence of plastic deformation on the microstructure of the CuCoNi alloy (Fig. 7b-d). The obtained images show the differentiation of grain size, which proves the structural heterogeneity of the material. After the ECAP process, the microstructure is dominated by elongated grains, in which deformation bands and low-energy configurations of low-angle boundaries are visible, as shown by the maps of grain boundary disorientation distribution (Fig. 8b-d). An increase in deformation temperature does not significantly affect the degree of microstructure fragmentation achieved - the average grain size is in the range of 1.4 - 1.5 µm. Plastic deformation, on the other hand, leads to an increase in the percentage of low-angle boundaries, which is confirmed by the histograms of the distribution of grain boundary misorientation in Figs. 9b-d and the quantitative data presented in Table 3. They show that at 100 ºC, the fraction of low-angle boundaries is about 72%. Increasing the plastic deformation temperature from 100 to 200 ºC is accompanied by an increase in the fraction of low-angle boundaries from 72% to 77%, and when the deformation temperature is further increased to 250 ºC the fraction of low-angle grain boundaries slightly decreases to 73%.

The obtained results are in agreement with those of Shaeri et al. [20, 21], who also found that increasing the temperature of the ECAP process was accompanied by an increase in the fraction of low-angle boundaries. This can be explained by the fact that in the ECAP process, as the deformation temperature increases, the recovery rate increases, which causes dislocation extinction; the probability of dislocation absorption by the grain boundaries is lower at the higher process temperature. It can be concluded that the evolution of the microstructure to

Table 3. *Summary of EBSD results*

	Grain size (diameter) [µm]	Fraction of low angle grain boundaries, %	Fraction of high angle grain boundaries, %	Average -misorientation angle, θ_{AV} [º]
Solution treated	7.1	5	95	48
ECAP at 100 ºC	1.42	71.3	28.7	17.9
ECAP at 200 ºC	1.46	77.4	22.6	14.9
ECAP at 250 ºC	1.41	72.8	27.2	16

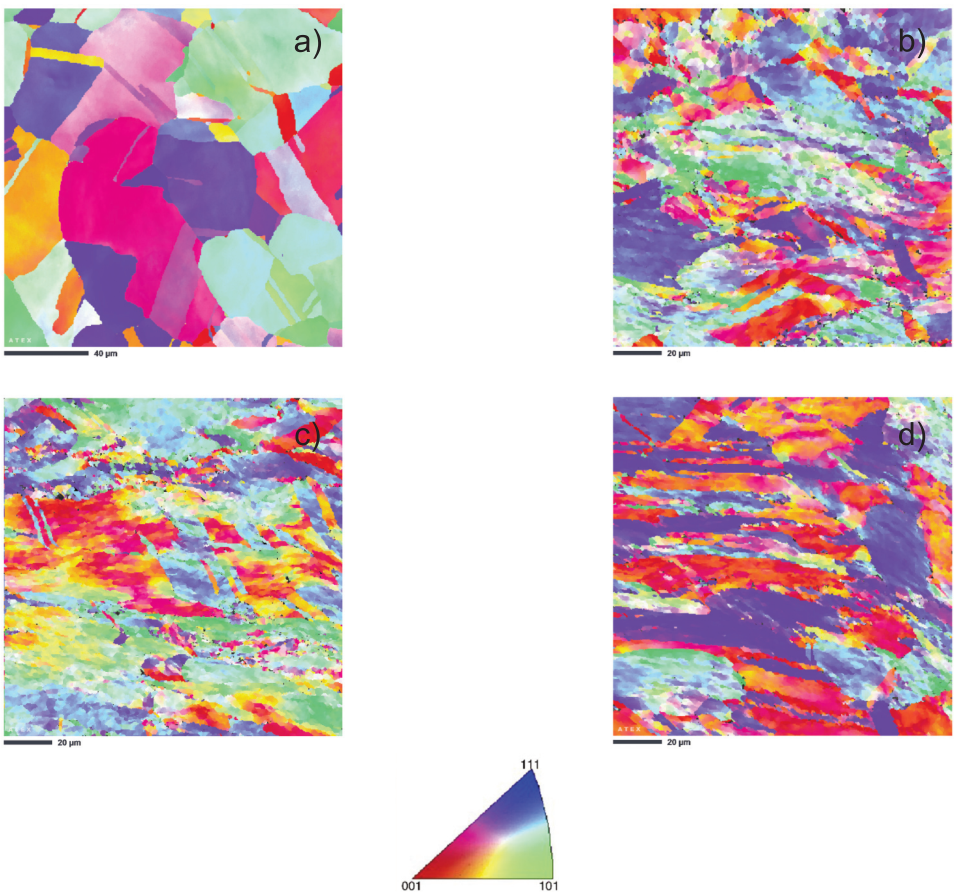

Figure 7. *IPF-Z maps of the CuCoNi alloy: a) after supersaturation, b) ECAP 100 ℃, c) ECAP 200 ℃, d) ECAP 250 ℃*

ultrafine-grained microstructure with a large share of high-angle boundaries is slower at the higher temperature of the ECAP process, which is confirmed by the current research results and literature data [41, 42].

The results of the microhardness measurements presented in Fig. 10 clearly show that changes in the microstructure and the associated grain refinement led to an improvement in mechanical properties. The experimental data show that the highest hardness is achieved in the sample after the ECAP cycle at a temperature of 100 ºC - 127 HV. The hardness increase compared to the undeformed sample is ~ 205%. With the increase in deformation temperature, some decrease in hardness to 124 and 118 HV is observed for samples deformed at temperatures of 200 and 250 ºC, respectively. Regardless of the temperature applied in the ECAP process, a large heterogeneity was observed in the hardness distribution at the cross-section level. The relatively large hardness spread is due to inhomogeneous deformation and the formation of shear bands in the microstructure of the material. The presence of heterogeneity after a single pass is similar to measurements in Al alloys [17, 20], where a similar hardness distribution was observed after one ECAP cycle.

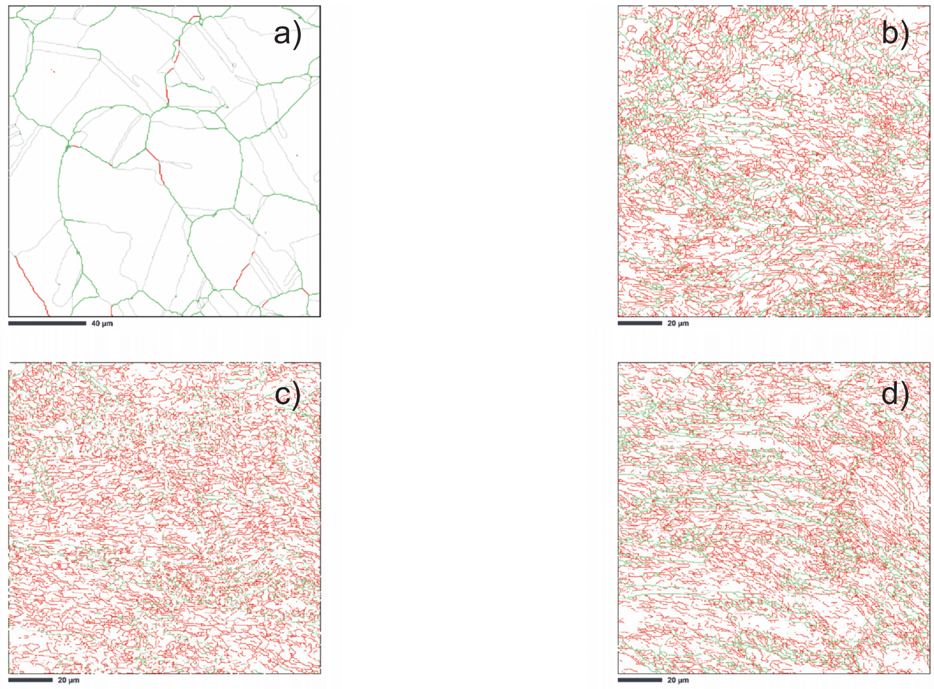

Figure 8. *Maps of the grain boundary misorientation: a) after supersaturation, b) ECAP 100 ºC, c) ECAP 200 ºC, d) ECAP 250 ºC (red - low-angle boundaries 3-15º, green - high-angle boundaries 15-58º, grey - twin boundaries 58-63.5º)*

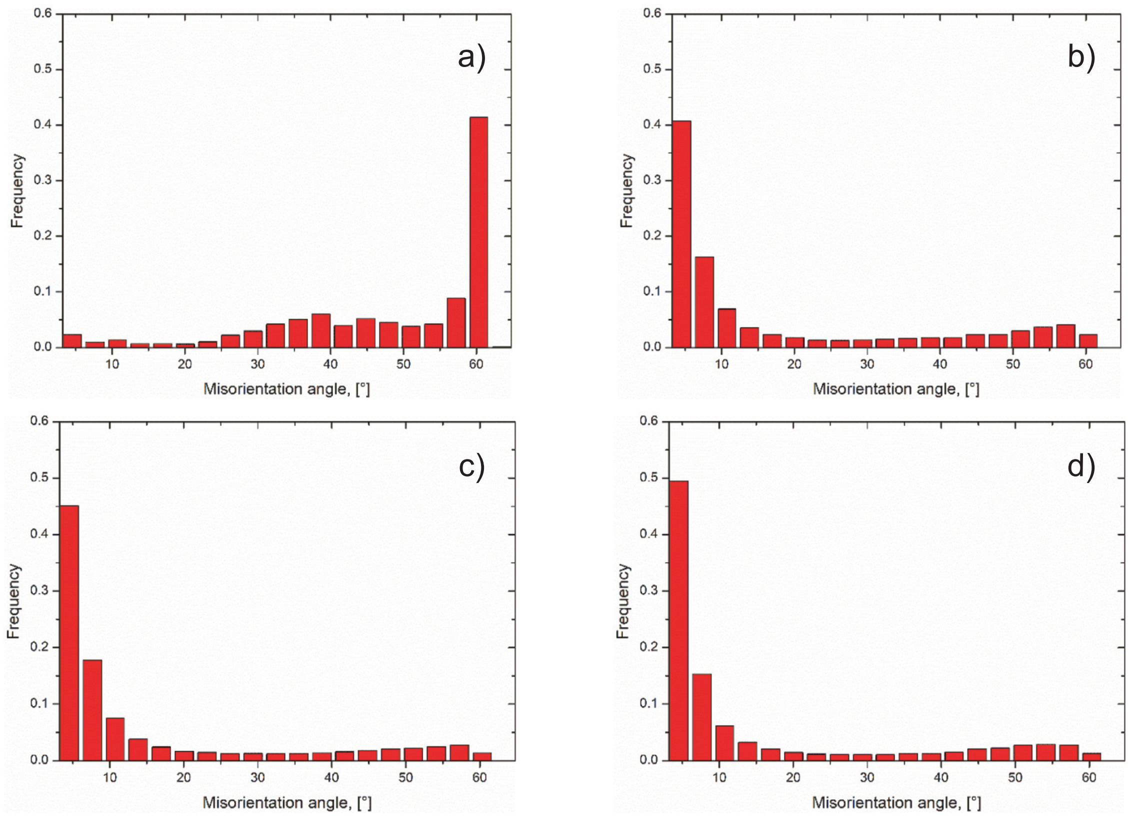

Figure 9. *Misorientation angle distributions for the CuCoNi samples a) after supersaturation, b) ECAP 100 ºC, c) ECAP 200 ºC, d) ECAP 250 ºC*

The observed increase in hardness is caused by the simultaneous influence of several strengthening mechanisms, the most important of which is dislocation strengthening and strengthening from the substructure. The results presented above (Fig. 7-10, Table 3) show that regardless of the deformation temperature used, similar grain sizes were obtained (a similar level of microstructure refinement) from ~ 7 µm in the supersaturated state to ~ 1.5 µm after 1 cycle of the ECAP process, which resulted in an increase in hardness of ~ 205% for the sample deformed at 100 ºC. Such a significant increase in hardness after the first pass can be explained by the equilibrium between the generation and annihilation of dislocations in the ECAP process at low temperatures [24, 42]. Increasing the temperature of the ECAP process reduces the amount of strain hardening, which is related to the intense dislocation annihilation through thermally activated processes. For this reason, as the deformation temperature increases, the dislocation density decreases, which is confirmed by the works [22, 23], as well as the GNDs density analysis shown in Fig. 11. Using the ATEX software we calculated the average GNDs density of 7.51·1013 m^{-1} for the supersaturated sample, 2.59·1013 m^{-1} for the sample deformed at 100 ºC, 2.79·1013 m^{-1} for the sample deformed at 200 ºC, and 2.73·1014 m^{-1} for the sample deformed at 250 ºC. The red 'hot spots' correspond to the highest GNDs density in the maps. Similar values of an increase in

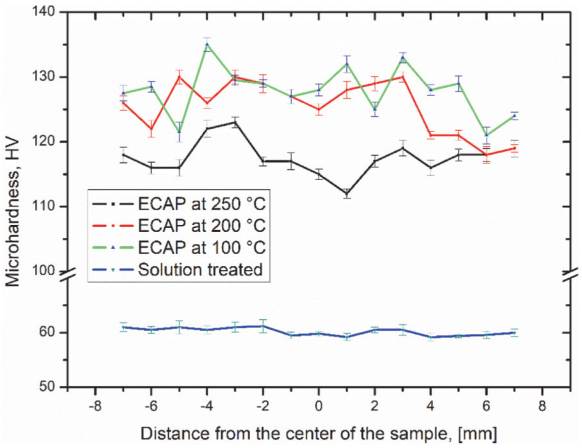

Figure 10. *Hardness distribution over cross-sectional plane of the samples*

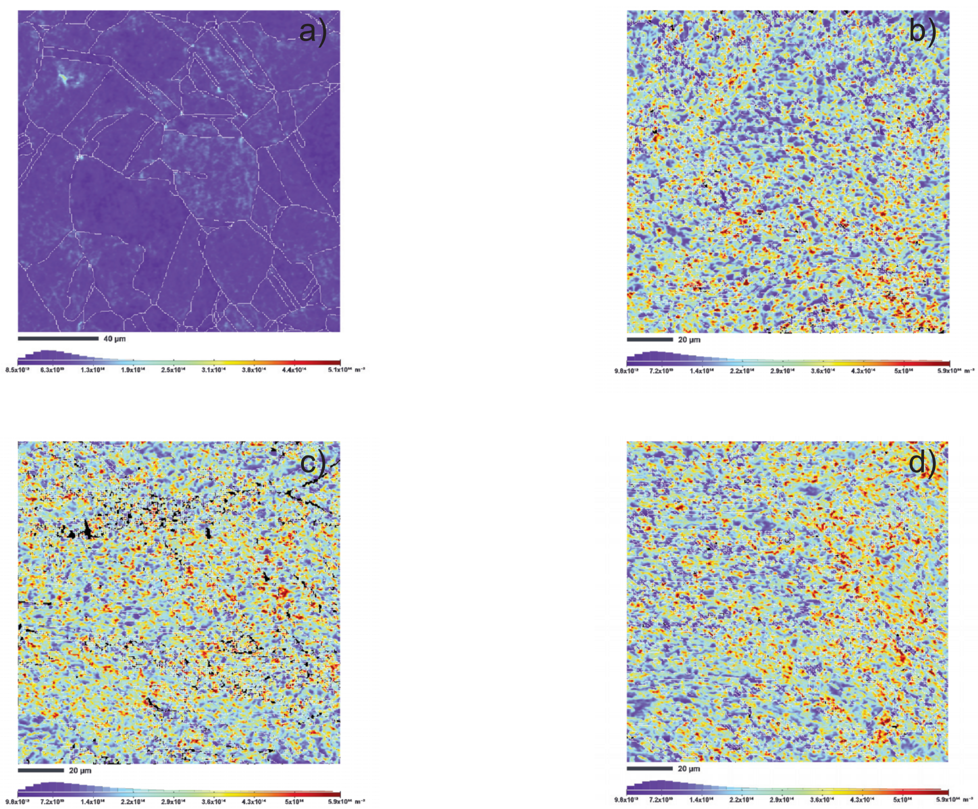

Figure 11. *Geometrically necessary dislocation (GND) distribution maps of CuCoNi alloy: a) after supersaturation, b) ECAP 100 ºC, c) ECAP 200 ºC, d) ECAP 250 ºC. Using the atex software we calculated the average GNDs density of 7.51·1013 m^{-1} for the sample after supersaturation, 2.59·1013 m^{-1} for the sample deformed at 100 ºC, 2.79·1013 m^{-1} for the sample deformed at 200 ºC and 2.73·1014 m^{-1} for the sample deformed at 250 ºC. The red 'hot spots' correspond to highest GNDs density in the maps*

microhardness were reported for both alloys and pure copper after one cycle of the ECAP process [27, 41].

The results of the conductivity measurements of the CuCoNi alloy before and after the ECAP process are presented in Table 4. The obtained results can be compared with the literature data for the conductivity of pure copper (58.6 MS / m), which is four times higher than the CuCoNi samples tested. From the data presented in Table 4, it can be concluded that the fragmentation of the microstructure caused by plastic deformation by the ECAP method had little effect on the conductivity of the tested alloy. The conductivity of copper is closely related to its mechanical properties. The conductivity increases as hardness decreases. Greater strengthening is observed for the alloy pressed at a lower temperature. The increase in temperature was accompanied by a decrease in hardness, and a small increase in conductivity which can be explained by the thermally activated processes of microstructure renewal [43, 44]. Compared to the sample after supersaturation, the highest increase in conductivity was observed for the sample deformed at the highest temperature.

Table 4. *Results of measurements of the conductivity of the CuCoNi alloy*

	Sample				
	Supersaturated	20 / 200	100	200	250
Conductivity MS/m	12.47	12.54	12.6	12.97	13.12
	12.48	12.54	12.46	12.68	13.18
	12.7	12.57	12.43	12.68	12.89
	12.84	12.55	12.52	12.82	12.98
	12.6	12.43	12.4	12.8	12.89
Average value	12.62	12.53	12.48	12.79	13.01
Standard deviation	0.16	0.05	0.08	0.12	0.16

The investigated CuCoNi alloy is a model alloy. The CuCoNiBe alloy is commonly used in the industry. Due to the toxicity of beryllium, this element was omitted during smelting. So far, no research results have been reported for CoCoNi alloys. The refinement of the microstructure obtained in the ECAP process and the increase in the hardness of the CuCoNi alloy are consistent with the results presented in [46] for the similar CuCoNiBe alloy. Moreover, little changes in conductivity after the ECAP process are consistent with the literature data for the CuCoNiBe alloy [46]. The authors of the article will conduct further research on the mechanical and tribological properties of the CuCoNi alloy after the ECAP process and after heat treatment.

4. Conclusions

The presented research indicates the possibility of CuCoNi alloy deformation in the process of pressing through the modified torsion ECAP channel and tailoring their structure and properties. This method is an effective tool for grain refinement of the tested copper alloy. Based on the research, it was found that:

- The deformation of CuCoNi alloy at room temperature is difficult due to the large extrusion force required and reaching the stress of approx. 1000 MPa. As the process temperature increased from 100 to 250 °C, a significant decrease in the pressing force was observed at the stress level from 800 to 400 MPa.
- The increasing temperature of the ECAP process contributes to the homogenization of the structure and intensifies the grain refinement from ~ 7 μm in the supersaturated state to ~ 1.4 μm after 1 cycle of the ECAP process in the temperature range of 100-250 °C.
- Stronger hardening is observed for the alloy pressed at a lower temperature. The increase in temperature was accompanied by a decrease in hardness, which can be explained by the thermally activated process of microstructure recovery. The hardness of the pressed sample at 250 °C is lower by approx. 7% (10 HV) in relation to the sample deformed at 100 °C and by 200% higher in relation to the supersaturated sample.
- The temperature of the ECAP process in a range of 20-250°C and the corresponding microstructure fragmentation did not affect significantly the conductivity of the tested copper alloy, which oscillated at the value of 13 MS/m.

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Author Contributions

B. Grzegorczyk: conceptualization, data curation, investigation, methodology, writing-original draft; S. Rusz: conceptualization, data curation, methodology, recources, writing-original draft; P. Snopinski: investigation, validation, visualization, writing-original draft; O. Hilšer: data curation, investigation, validation, vizualization; A. Skowronek: resources, validation, vizualization, writing-review and editing; A. Grajcar: formal analysis, project administration, supervision, writing-review and editing.

Data Availability

The data are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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UTICAJ ECAP PROCESA NA DEFORMABILNOST, MIKROSTRUKTURU I PROVODLJIVOST CuCoNi LEGURE

B. Grzegorczyk [a], S. Rusz [b], P. Snopinski [a], O. Hilšer [b], A. Skowronek [a], A. Grajcar [a,*]

[a] Šleski tehnološki univerzitet, Mašinski fakultet, Odsek za inženjerstvo materijala i biomaterijala, Gljivice, Poljska

[b] VSB –Tehnički univerzitet u Ostravi, Mašinski fakultet, Odsek za mašinsku tehnologiju, Ostrava – Poruba, Republika Češka

Apstrakt

Studija se bavi uticajem različitih varijanti intenzivne plastične deformacije pri ECAP procesu na mikrostrukturu, mikrotvrdoću i provodljivost CuCoNi legure. Evolucija mikrostrukture proučavana je mikroskopskim posmatranjima i difrakcijom elektrona povratnog rasejanja (EBSD) primenom skenirajućeg elektronskog mikroskopa (SEM). Vikersov metod je korišćen za ispitivanje mikrotvrdoće uzoraka nakon različitih varijanti ECAP procesa. Provodljivost je merena pomoću uređaja za merenje električne provodljivosti vrtložne struje na osnovu kompleksne impedanse sonde. Rezultati su ukazali na mogućnost deformacije CuCoNi legura tokom presovanja kroz ECAP ugaoni kanal i razvoja njihove mikrostrukture i svojstava. Metoda je efikasan alat za ojačavanje ispitivane legure bakra usitnjavanjem njene mikrostrukture. Nakon prvog prolaza, veličina zrna je smanjena za 80%. Povećanje temperature za plastičnu deformaciju nije značajno uticalo na postignuti stepen fragmentacije mikrostrukture – prosečna veličina zrna je oko 1,4-1,5 mm. Fragmentacija mikrostrukture je imala zanemarljiv uticaj na provodljivost CuCoNi legure, koja je posle ECAP procesa oscilovala na vrednosti od 13 MS/m.