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Influence of Heat Treatment and Plastic Deformation on the Mechanical and Electrical Properties of Cu-Sc Alloys Prepared by Continuous Casting Process

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Abstract

Paper presents analysis and results of studies on scandium addition to copper from 0.1 wt. % up to 0.4 wt. % and influence of heat treatment and forging process on alloys mechanical and electrical properties. The studies included the production of CuSc0.1, CuSc0.2, CuSc0.3 and CuSc0.4 alloys with the use of metallurgical synthesis and horizontal continuous casting processes. The continuous casting process is a commonly used method for producing rods from various materials for further processing. The research involved the selection of heat treatment for the produced materials in various states of hardening, i.e. immediately after the casting process, after the cold and hot forging process. The research aimed to obtain the highest possible mechanical and electrical properties of Cu-Sc alloys. The studies showed that for CuSc0.4 alloy hardness was at the level of 216 HV (after cold forging and artificial ageing). In case of electrical conductivity, all Cu-Sc alloys were in the range of 27 - 51 MS/m.

Keywords: Heat treatment, Copper alloys, Copper-scandium, Continuous casting, Metallurgical synthesis

1. Introduction

Over the centuries, continuous development of materials production methods with increasingly higher exploitational properties has been observed. This also applies to one of the most popular metals - copper, which is characterized by very high electrical properties and is therefore mainly used for electrical applications. However, in its pure form, copper is mainly characterized by very high plasticity and low strength, which significantly reduces its application possibilities. In order to increase the mechanical properties, numerous alloy additions are used allowing to produce alloys, which have much higher operational properties compared to pure copper [1-3].

One of the interesting solutions observed in recent years relates to the addition of scandium to copper in order to increase the mechanical properties of base material. As it results from [4, 5], scandium significantly affects the pure ETP copper properties in the annealed state. The Cu-Sc phase diagram shows that scandium has limited solubility in copper in the solid state at the level of about 0.5% by weight. Therefore, this alloy is susceptible to the precipitation strengthening treatment, by precipitation of the Cu_4Sc phase [6,7]. As it results from the literature analysis of the Cu-Sc alloy, depending on the amount of Sc and strain hardening level, this material exhibit different properties in terms ultimate tensile strength (up to 700 MPa), hardness (up to 200HV) and electrical conductivity (up to 52 MS/m) [8-12]. Due to the possibility to obtain high mechanical and electrical properties by Cu-Sc alloys produced with the use of heat treatment and metal forming processes, these materials can be used in a wide range of electrical power engineering systems applications. Cu-Sc alloys can become substitutes for the currently most popular materials such as Cu-Ni-Si or Cu-Ag alloys [13-18].

A commonly used industrial production method of copper alloys semi products is the continuous casting process, which thanks to the possibility casting speed control, enables to shape initial functional properties and microstructure of the base material [19-21]. This process can be carried out by upwards, downwards and horizontal casting systems. There are also many varieties of the continuous casting process, one of which enables to cast metal between rolls (Twin Roll Casting), where after crystallization, additional hot rolling occurs simultaneously [22]. So far, no studies on the production of Cu-Sc alloys with the use of continuous casting method have been presented in the literature. Only results of scandium micro-addition to the CuCrZr copper alloy has been presented [23].

This article presents studies on heat treatment and forging process of Cu-Sc alloys produced in the continuous casting process in various states of strain hardening in order to determine the changes in mechanical and electrical properties. The aim of the research is to investigate the potential use of Cu-Sc alloys for power engineering applications, where materials are required to have high mechanical properties combined with high specific electrical conductivity.

2. Materials and methods

In order to conduct studies on heat treatment and metal forming processing effect on mechanical and electrical properties of Cu-Sc alloys, following materials were selected, i.e. CuSc0.1, CuSc0.2, CuSc0.3 and CuSc0.4 (all within the solubility limit of scandium in copper). In accordance to the scheme presented in Fig. 1, these alloys were selected based on the data provided in the introduction of the article, which indicated a maximum solubility of scandium in copper at the level of 0.5 wt.%. Consequently, the specific scandium contents in the selected materials have a technological nature and are feasible for industrial application.

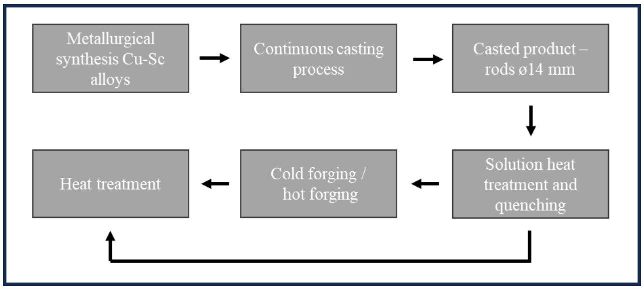

Fig. 1.Schematic diagram of research program

These alloys were produced by continuous casting method with the use of horizontal laboratory casting line (TERMETAL laboratory line, Poland) (fig. 2 - 3). Laboratory line was equipped with induction furnace and graphite crucible (HLM grade) which was filled with commercial copper granulate (CuETP grade) and scandium in pure metallic form (purity of > 99.99%). Metallurgical synthesis was carried out at a temperature of 1250°C for 20 minutes under a graphite coating. The continuous casting process was carried out using a graphite crystallizer with a diameter of 14 mm (R4450 type). The individual parameters of the continuous casting process are presented in Table 1.

Table. 1.
Continuous casting parameters

Liquid metal temperature	Casting speed		Cooling medium flowrate	
	Feed	Standstill	Primary	Secondary
[°C]	[mm]	[s]	[l/min]	[l/min]
1250°C (±15°C)	4	2	0,42 - 0,48	0,1 - 0,15

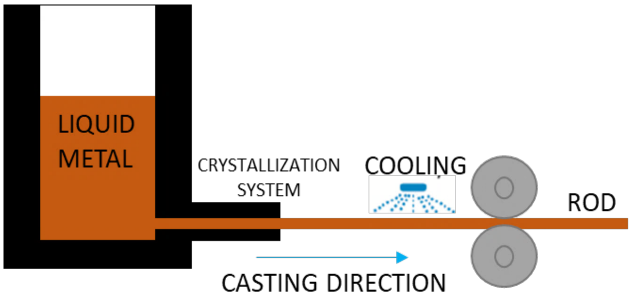

Fig. 2. Schematic diagram of used horizontal continuous casting process

Fig. 3. View of laboratory horizontal continuous casting line (TERMETAL)

With the use of continuous casting set-up, rods for further tests were produced from CuSc0.1, CuSc0.2, CuSc0.3 and CuSc0.4 (fig. 4), the chemical composition of which was analyzed and verified using a Spectro Spectrotest TX03 (Germany) spark spectrometer (tab. 2).

Fig. 4. View of rods obtained via the continuous casting process (a) CuSc0,1, (b) CuSc0,2, (c) CuSc0,3, (d) CuSc0,4

Table. 2.
Chemical composition analysis of the Cu-Sc alloys after continuous casting process

Material	Elements [wt. %] *								
	Sn	P	Fe	Ni	Si	Mg	Ag	Sc	Cr
CuSc0,1	<0,002	0,007	<0,008	0,008	0,045	0,001	0,002	0,11	<0,003
CuSc0,2	<0,002	0,007	<0,008	0,008	0,049	0,001	0,002	0,23	<0,003
CuSc0,3	<0,002	0,004	<0,008	0,008	0,045	0,001	0,002	0,29	<0,003
CuSc0,4	<0,002	0,006	<0,008	0,008	0,018	0,001	0,002	0,37	<0,003

*Cu – rest

In order conduct heat treatment analysis, samples cut from the casted bars were subjected to the cold and hot open die forging processes. For both variants, the actual deformations were set at εt=0.2 and εt=1. The forging process was performed with the use of eccentric press with nominal pressure of 40 kN on samples in the form of cylinders with a diameter of 14 mm and a height of 10 mm (fig. 5-6).

Fig. 5. View of eccentric press (max. force 40kN) with flat die

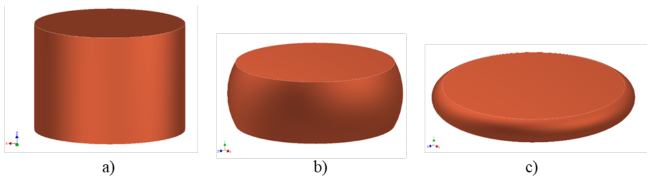

Fig. 6. Scheme of samples subjected to heat treatment (a) cast, (b) after forging ε_t=0,2, (c) after forging ε_t=1

Forging tests were conducted for cold variant at ambient temperature and for hot variant at 850°C. During forging, a separator in the form of boron nitride (aerosol) was used, which was applied each time to the upper and lower die in order to limit the adhesion of forged samples to the tools. Cold forged samples were previously homogenized at 850°C for 3 hours and then supersaturated with water. The same procedure was followed for hot forged samples, but supersaturation was performed with the use of water immediately after forging. A resistance CZYLOK furnace (Poland) was used to heat the samples for the forging process and for the heat treatment. Artificial ageing was carried out in the following temperatures: 450°C, 500°C and 550°C for as-cast samples and at temperatures of 400°C and 450°C for samples after hot and cold forging variants. Material hardness tests were carried out using a Tukon2500 (USA) hardness tester in the Vickers scale. All hardness tests were carried out in accordance with a HV10 indenter load for 10s. Electrical conductivity tests were carried out using a SigmaTest2.069 (USA) measuring device. For all obtained research results a statistical average value was calculated according to the scheme presented in Table 3.

Table 3.
Research statistics admitted for different properties' analysis

Research Type	Test stand	Number of Measurements/Samples	Final Result
Electrical conductivity	SigmaTest 2.069	5	Arithmetic average (x) / standard deviation (s)
Hardness	Tukon2500	10	
Chemical composition	Spectro SpectroTest TX3	5	

3. Results

Obtained test results of mechanical and electrical properties of CuSc0.1, CuSc0.2, CuSc0.3 and CuSc0.4 alloys after heat treatment in different material hardening states, which were presented below in Fig. 7–12 and Table 4.

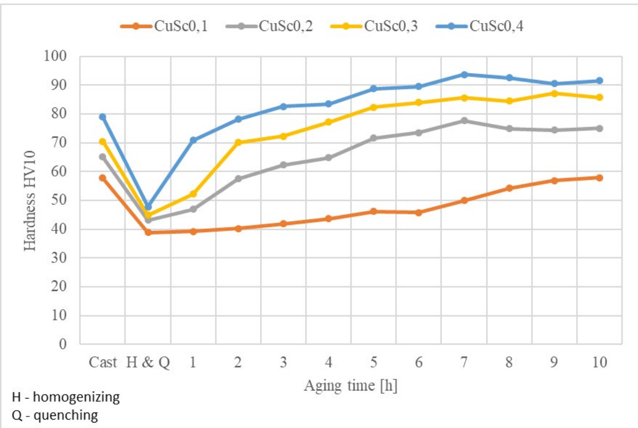

Fig. 7. Characteristics of hardness for the Cu-Sc alloys during artificial aging at 450°C – after casting

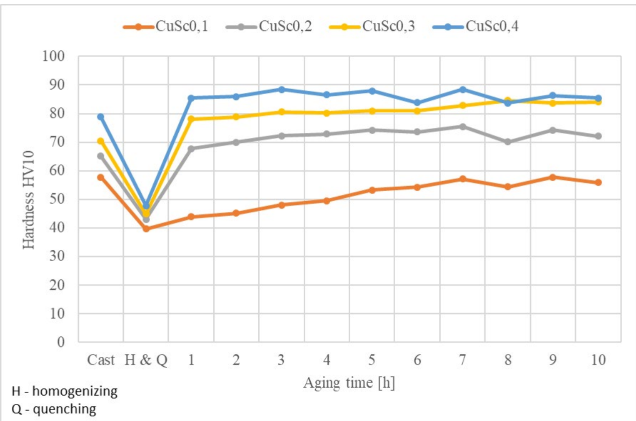

Fig. 8. Characteristics of hardness for the Cu-Sc alloys during artificial aging at 500°C – after casting

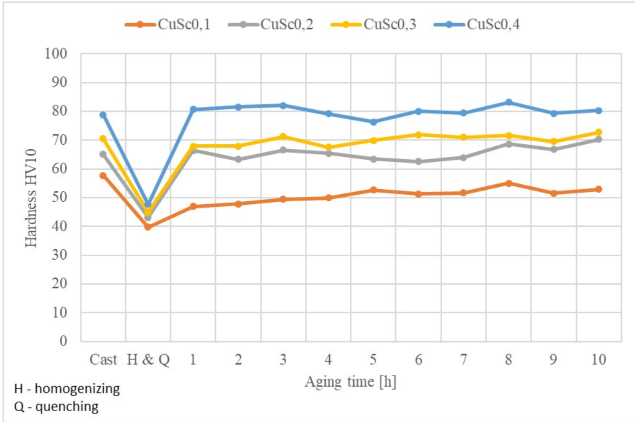

Fig. 9. Characteristics of hardness for the Cu-Sc alloys during artificial aging at 550°C – after casting

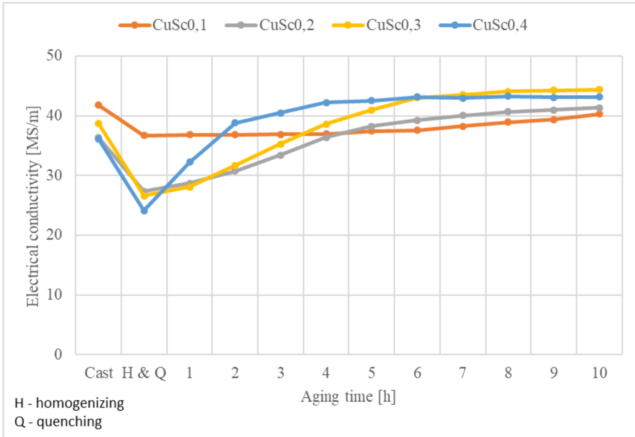

Fig. 10. Characteristics of electrical conductivity for the Cu-Sc alloys during artificial aging at 450°C – after casting

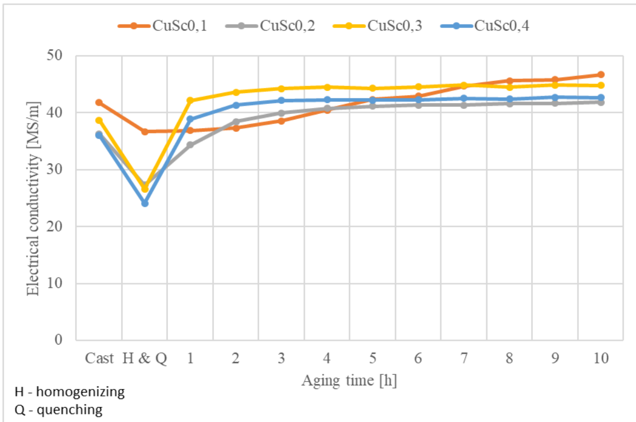

Fig. 11. Characteristics of electrical conductivity for the Cu-Sc alloys during artificial aging at 500°C – after casting

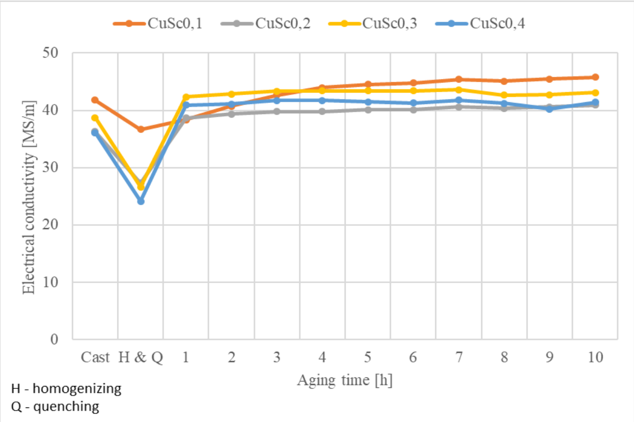

Fig. 12. Characteristics of electrical conductivity for the Cu-Sc alloys during artificial aging at 550°C – after casting

Table. 4.
Comprehensive hardness and electrical conductivity data in the best artificial aging times after casting for the Cu-Sc alloys

Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
Aging at 450°C					
		x	s	x	s
CuSc0,1	10	58	2,11	40,32	0,16
CuSc0,2	10	84	4,64	41,37	0,10
CuSc0,3	9	87	3,04	44,25	0,01
CuSc0,4	7	94	3,75	42,93	0,06
Aging at 500°C					
		x	s	x	s
CuSc0,1	9h	59	1,79	45,85	0,14
CuSc0,2	7h	76	1,20	41,34	0,02
CuSc0,3	8h	85	3,33	44,50	0,11
CuSc0,4	7h	88	1,40	42,56	0,06
Aging at 550°C					
		x	s	x	s
CuSc0,1	8h	55	1,70	45,07	0,06
CuSc0,2	10h	70	1,36	40,91	0,09
CuSc0,3	10h	73	1,68	43,10	0,07
CuSc0,4	8h	83	8,71	41,22	0,11

From the conducted heat treatment analysis of previously casted materials, which were next subjected to homogenization and supersaturation processes, it can be concluded that alloys from the Cu-Sc group are susceptible to the precipitation hardening process (for casted only variants). Additionally, it can be inferred, that during the cooling process (immediately after crystallization in the cooling system), the properties of casts, in their as-cast state, may indicate effect of aging phenomena. This is indicated by the hardness properties observed in the as-cast state, which are significantly higher than those after annealing and solution heat treatment. Furthermore, when comparing the properties of the materials in the as-cast state with those after 1 hour of aging, it becomes apparent that partial precipitation hardening occurs in the as-cast state. The characteristics presented in Fig. 5-10 show that these materials, at a temperature of 450°C, achieve their maximum properties (mainly hardness), in a longer exposure time of ageing process, than in the case of 500°C and 550°C temperature conditions. At the aging temperature of 450°C, the CuSc0.1 alloy exhibits the highest hardness of 58 HV10 (after 10 hours), the CuSc0.2 alloy achieves hardness of 84 HV10 (after 10 hours), the CuSc0.3 alloy reaches hardness of 87 HV10 (after 8 hours), and the CuSc0.4 alloy shows hardness of 94 HV10 (after 7 hours). From the heat treatment analysis of the as-cast materials, it can be concluded that the best properties in terms of hardness (with the resulting electrical conductivity) are achieved by the materials at different ageing times, which are presented for the individual Cu-Sc alloys in Table 4.

In the second stage of research aimed to analyze properties of selected materials after heat treatment process, research were carried out on the influence of deformation and ageing temperature on the evaluation of Cu-Sc copper alloys properties. The research covered analysis of forgings obtained as a result of the cold and hot process variants with εt=0.2 and εt=1 deformations. Based on the previously conducted heat treatment research of castings, it was found that the favorable temperatures for tested materials are 400°C and 450°C and these temperatures were selected for the forgings analysis. Figures 13-20 present hardness and electrical conductivity characteristics as a result of the ageing process of forgings.

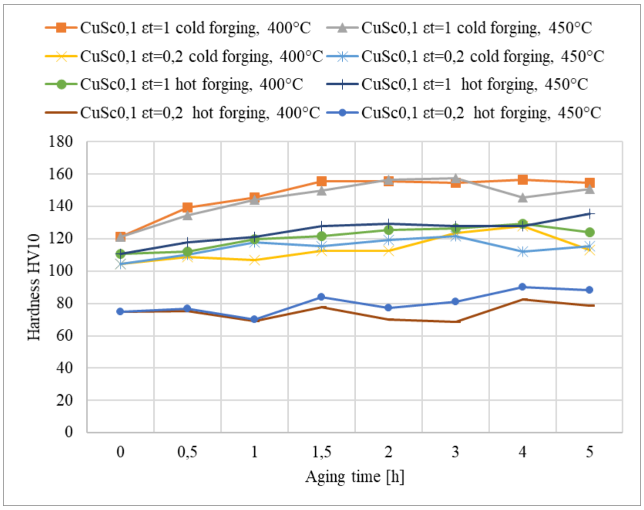

Fig. 13. Characteristics of hardness for the CuSc0,1 alloys during artificial aging – strain hardened samples after cold and hot forging processes

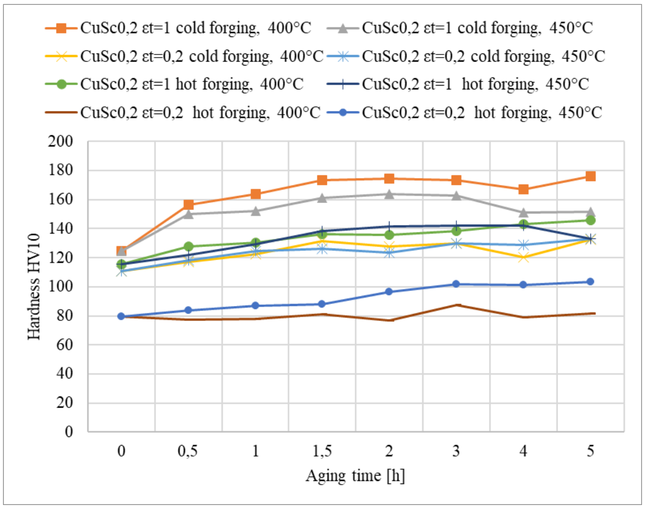

Fig. 14. Characteristics of hardness for the CuSc0,2 alloys during artificial aging – strain hardened samples after cold and hot forging processes

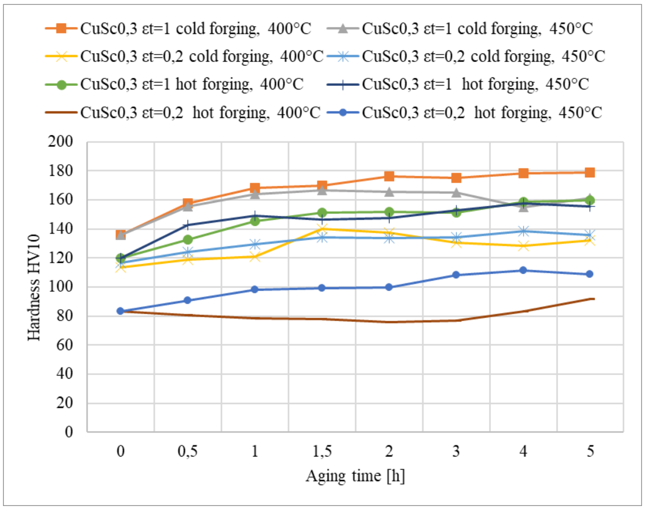

Fig. 15. Characteristics of hardness for the CuSc0,3 alloys during artificial aging – strain hardened samples after cold and hot forging processes

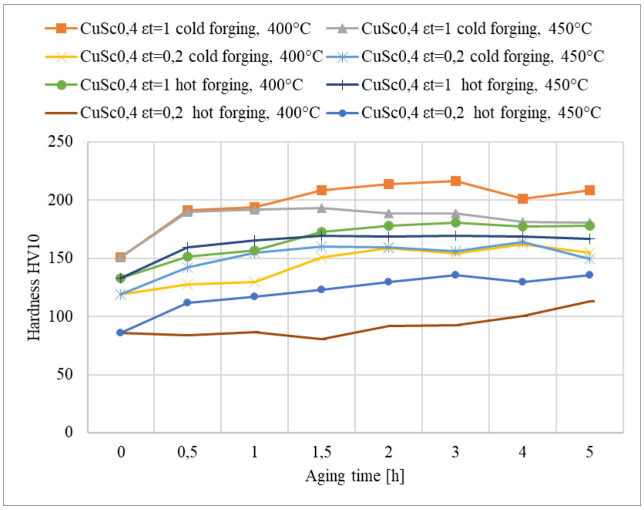

Fig. 16. Characteristics of hardness for the CuSc0,4 alloys during artificial aging – strain hardened samples after cold and hot forging processes

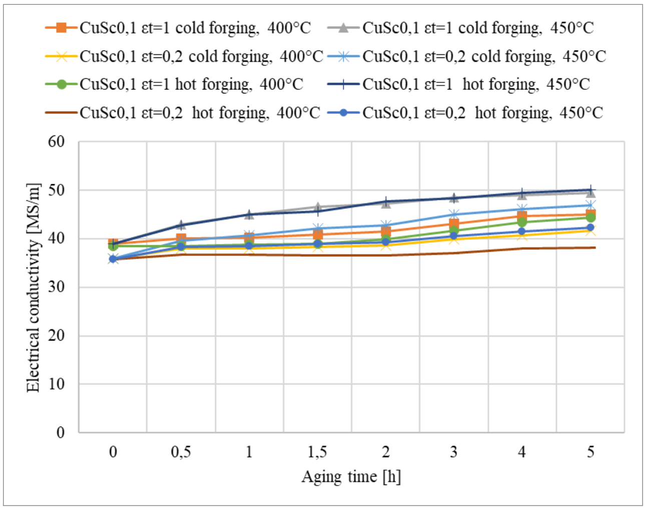

Fig. 17. Characteristics of electrical conductivity for the CuSc0,1 alloys during artificial aging – strain hardened samples after cold and hot forging processes

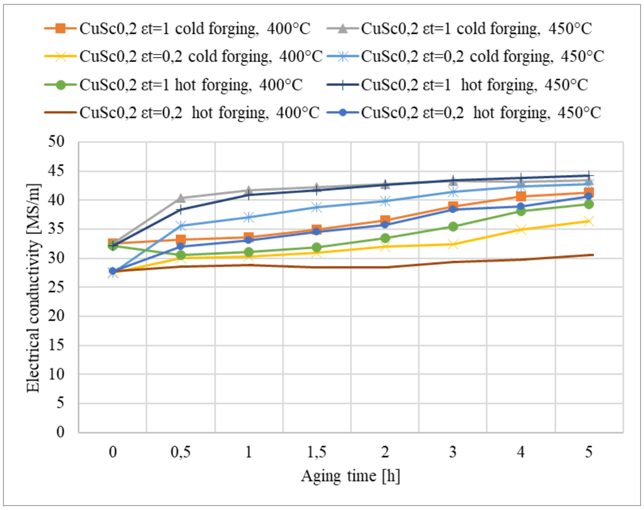

Fig. 18. Characteristics of electrical conductivity for the CuSc0,2 alloys during artificial aging – strain hardened samples after cold and hot forging processes

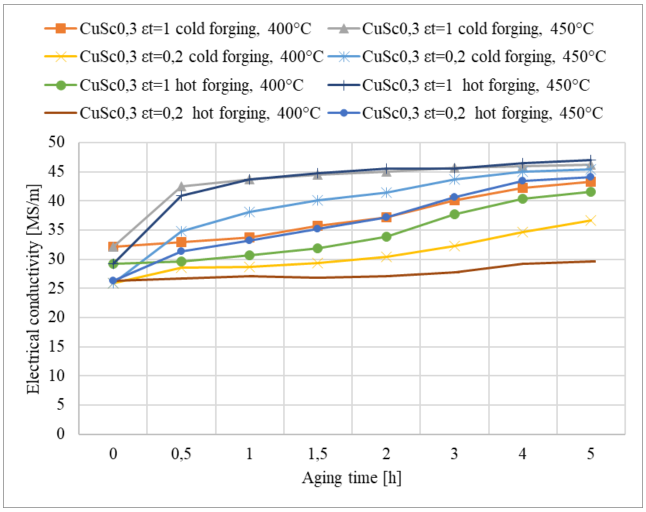

Fig. 19. Characteristics of electrical conductivity for the CuSc0,3 alloys during artificial aging – strain hardened samples after cold and hot forging processes

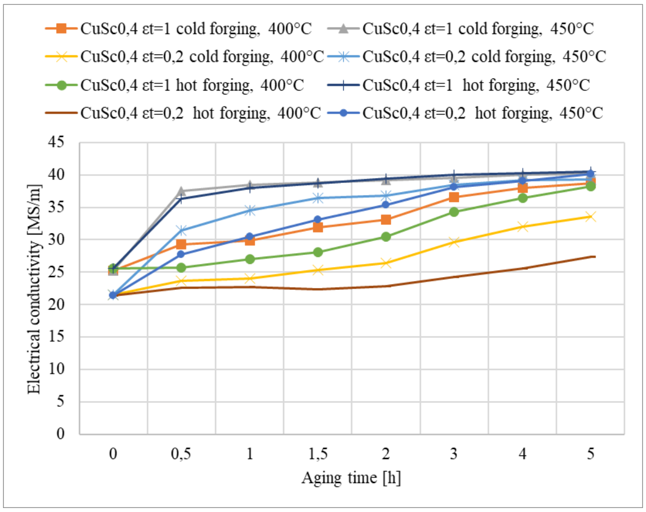

Fig. 20. Characteristics of electrical conductivity for the CuSc0,4 alloys during artificial aging – strain hardened samples after cold and hot forging processes

Analysis of obtained test results, shows that selected materials exhibit different mechanical and electrical properties depending on the applied variant of thermo-plastic treatment. The tests done for the CuSc0.1 alloy show (fig. 13, fig. 17) that this material is characterized by the highest hardness after cold working and aging with deformation of εt=1. The hardness at the level of 157 HV10 is obtained as a result of aging at a temperature of 400°C for 4h and at a temperature of 450°C and time of 3h. Referring to the obtained results of electrical conductivity, it can be stated that the divergence of results for individual heat treatment and forging variants ranges from 38.15 MS/m for the material hot forged with a deformation of εt=0.2 and aged at a temperature of 400°C for 5 h to a value of 50.18 MS/m for the material hot forged with a deformation of εt=1 and aged at a temperature of 450°C for 5 h (a comparable value of electrical conductivity is shown by the cold forged variant with εt=1 and aged at a temperature of 450°C, for which the conductivity is 49.44 MS/m). Research results for CuSc0.2 alloy (fig. 14, fig. 18) subjected to the cold and hot forging process with different deformations shows that the highest hardness of the material is achieved in the case of ageing temperature of 400°C for 5h, for cold deformation sample and εt=1, which is 176 HV10. Obtained results of the electrical conductivity for CuSc0.2 alloy showed that the maximum conductivity values for different thermo-plastic conditions range from 30.52 MS/m to 44.26 MS/m. Considering the results of the hardness tests for CuSc0.3 alloy (fig. 15, fig. 19) the highest hardness of this material is observed after cold deformation with εt=1 and ageing temperature of 400°C (5h), which is 179 HV10. The analysis of the electrical conductivity of the CuSc0.3 alloy shows that it ranges from 29.67 MS/m to 46.96 MS/m, depending on the heat treatment and forging path. Analyzing the hardness research results of the CuSc0.4 alloy (fig. 16, fig. 20), it can be concluded that the highest hardness is achieved by cold deformation processing with εt=1 and the ageing process at a temperature of 400°C for 3 hours, which is 216 HV10. The conducted electrical conductivity measurements for CuSc0.4 alloy showed that, depending on the heat treatment and forging path, the alloy exhibits electrical conductivity in the range from 27.30 MS/m up to 40.10 MS/m.

To sum up, the conducted tests indicate that the optimum heat treatment conditions for the indicated deformation levels (taking into account the highest achieved hardness for the material and the resulting specific electrical conductivity for this ageing time) for the copper alloys tested are shown in Tables 4 – 7.

Table. 4.
Comprehensive hardness and electrical conductivity data in the best artificial aging time (400°C) after cold forging of Cu-Sc alloys with various strain deformation level

	ε_t=1				
Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
		x	s	x	s
CuSc0,1	4	156	3,06	44,68	0,03
CuSc0,2	5	176	6,51	41,31	0,04
CuSc0,3	5	179	5,20	43,29	0,03
CuSc0,4	3	216	3,51	36,53	0,16
	ε_t=0,2				
Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
		x	s	x	s
CuSc0,1	4	127	0,58	40,80	0,06
CuSc0,2	5	132	6,35	36,36	0,21
CuSc0,3	1,5	140	2,00	29,36	0,20
CuSc0,4	4	162	2,3	32,08	0,09

Table. 5.
Comprehensive hardness and electrical conductivity data in the best artificial aging time (450°C) after cold forging of Cu-Sc alloys with various strain deformation level

	ε_t=1				
Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
		x	s	x	s
CuSc0,1	3	157	5,86	48,48	0,11
CuSc0,2	2	163	2,89	42,68	0,10
CuSc0,3	2	166	2,08	45,07	0,09
CuSc0,4	1,5	193	5,77	38,86	0,04
	ε_t=0,2				
Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
		x	s	x	s
CuSc0,1	3	121	1,53	44,95	0,14
CuSc0,2	5	133	8,50	42,74	0,19
CuSc0,3	4	138	8,14	45,06	0,24
CuSc0,4	4	164	3,00	39,17	0,25

Table. 6.
Comprehensive hardness and electrical conductivity data in the best artificial aging time (400°C) after hot forging of Cu-Sc alloys with various strain deformation level

	ε_t=1				
Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
		x	s	x	s
CuSc0,1	4	129	2,08	43,47	0,27
CuSc0,2	5	146	5,29	39,34	0,21
CuSc0,3	5	159	8,39	41,54	0,22
CuSc0,4	3	180	5,13	34,30	0,28
	ε_t=0,2				
Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
		x	s	x	s
CuSc0,1	4	82	5,55	38,08	0,24
CuSc0,2	3	87	6,68	29,30	0,19
CuSc0,3	5	91	6,66	29,67	0,08
CuSc0,4	5	113	6,0	27,30	0,30

Table. 7.
Comprehensive hardness and electrical conductivity data in the best artificial aging time (450°C) after hot forging of Cu-Sc alloys with various strain deformation level

	ε_t=1				
Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
		x	s	x	s
CuSc0,1	5	135	7,23	50,18	0,09
CuSc0,2	3	142	6,03	43,36	0,17
CuSc0,3	4	157	3,79	46,45	0,13
CuSc0,4	3	169	7,23	40,06	0,09
	ε_t=0,2				
Material	Aging time [h]	Hardness HV10		Electrical conductivity [MS/m]	
		x	s	x	s
CuSc0,1	4	90	9,48	41,50	0,30
CuSc0,2	5	103	4,37	40,57	0,27
CuSc0,3	4	111	5,69	43,41	0,30
CuSc0,4	5	135	5,51	40,10	0,05

To summarize, the obtained results of hardness and specific electrical conductivity measurements for materials subjected to heat treatment after cold or hot forging correlate with findings reported in previous publications [8-9]. Observed increase in hardness properties can be attributed to the precipitation of the Cu4Sc phase, which has been identified and described in the literature [10, 12].

In this article, in addition to studies on materials in their as-cast state, where the strengthening mechanism is solely linked to the precipitation of the Cu4Sc phase, research were conducted to assess the impact of cold and hot deformation. These investigations complement the results previously published in other articles. The studies revealed that the degree of mechanical property enhancement is correlated with the magnitude of material deformation and its temperature during plastic processing. The greatest increase in hardness was observed for Cu-Sc alloys subjected to cold forging with a deformation of εt = 1. It can be concluded that in highly deformed materials, the precipitation of the Cu4Sc phase occurs, which, along with structural defects (primarily dislocations) amplifies the hardness increase.

In contrast, materials processed with hot forging exhibit lower hardness compared to those after cold forging, due to structural changes associated with recrystallization processes, as confirmed by the authors in publication [9].

Analysing the changes in the electrical properties of Cu-Sc alloys, it can be observed that, in all cases of heat and plastic processing, electrical conductivity increases with aging time. The research also demonstrated that forging with a deformation of εt = 1 enables higher electrical conductivity under the same heat treatment parameters and Sc content compared to a deformation of εt = 0.2.

The results of mechanical and electrical properties presented in this article expand the current knowledge on Cu-Sc alloys, which have become a subject of research around the world in recent years, especially due to their potential to tailor properties for given applications through heat treatment and plastic deformation.

4. Conclusions

The conducted experimental studies on the production and shaping of functional properties of Cu-Sc alloys allowed for the formulation of the following conclusions:

1. The addition of scandium to copper in an amount of up to 0.4 wt. % does not reduce the technological properties of Cu-Sc alloys in the area of metallurgical synthesis and horizontal continuous casting system.
2. The research demonstrated that Cu-Sc alloys produced by the continuous casting method achieve the most favorable hardness properties when subjected to heat treatment at a temperature of 450°C.It has been shown that Cu-Sc alloys have high susceptibility to cold and hot metal forming i.e open die forging in the range strain deformation up to εt=1.
3. Cu-Sc alloys in the range of Sc alloy addition from 0.1 up to 0.4 wt. % are subject to heat treatment, thanks to which it is possible to shape their mechanical and electrical properties in precipitation strengthening processes, with the most advantageous configuration (in terms of highest possible final properties): homogenization and supersaturation of the material combined with cold plastic processing and artificial ageing.
4. The highest hardness is achieved by the CuSc0.4 alloy in the cold forging variant with a deformation of εt = 1, combined with heat treatment at 400°C for 3 hours, reaching a level of 216 HV10 with a specific electrical conductivity of 36.5 MS/m.

It is worth to continue research on the addition of Sc to copper, as these alloys achieve excellent technological properties, allowing for better selection of materials to specific industrial applications, especially where a combination of high hardness and good electrical conductivity is required.

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