B. SMYRAK, M. ZASADZIŃSKA, T. KNYCH, A. MAMALA, A. KAWECKI, M. WALKOWICZ, P. STRZĘPEK

ISSN 0543-5846
METABK 61(3-4) 749-752 (2022)
UDC – UDK 546.56:539.417/621.778:620.17:621.317.3.002.61:621.785=111

SUSCEPTIBILITY TO DEEP PROCESSING IN THE WIRE DRAWING PROCESS OF ETP AND OF GRADE COPPER

Received – Primljeno: 2021-10-25
Accepted – Prihvaćeno: 2022-03-05
Original Scientific Paper – Izvorni znanstveni rad

The susceptibility to deep processing in the industrial wire drawing process has been investigated in the research paper regarding the copper grade influence on the process. The conducted research included the identification of the mechanical and electrical properties of wires manufactured from Electrolytic Tough Pitch Copper (Cu-ETP) wire rod and Oxygen-Free Copper (Cu-OF) cast rod in terms of the applied deformation. In particular, as main contribution of this research to the scientific and industrial community a mathematical model describing the wire strengthening and softening characteristics was determined.

Keywords: Cu-ETP and Cu-OF, copper wire drawing, mechanical properties, electrical properties, softening curves

INTRODUCTION

Copper is characterized with high electrical conductivity, excellent annealing susceptibility and formability. These features directly translate to the possibility of deep and advanced copper processing in the industrial wire drawing process of microwires for electrical purposes possible. However, the fact that there are many grades of copper differentiating from each other for instance in terms of chemical composition should be emphasized. The most important factor is the presence of oxygen in ETP grade copper and the lack of it in OF copper. The presence of oxygen and therefore Cu_2O oxide (non-deformable plastically ceramic inclusions) in the copper matrix influences a number of its properties [1 – 3]. Both abovementioned copper grades differ also in terms of the grain size which is related with the manufacturing process of the rods. ETP grade copper is characterised with a fine grained, homogeneous structure, typical for hot working process. On the other hand, OF copper shows typical foundry structure [4 – 7]. Such differences between these two copper grades affect as well their susceptibility to deep processing in the industrial wire drawing process, where parameters like recrystallization susceptibility determined based on the softening curves or the amount of deformation necessary for failure-free metal working process are important [8 – 10].

The knowledge on the properties differences between the copper grades and the factors influencing them makes it possible to define and design the entire technological process consisting of a series of operations affecting the final properties of the product.

B. Smyrak, M. Zasadzińska (e-mail: malgozas@agh.edu.pl), T. Knych, A. Mamala, A. Kawecki, M. Walkowicz, P. Strzępek
AGH University of Science and Technology, Faculty of Non-Ferrous Metals, Cracow, Poland

EXPERIMENTAL PROCEDURE

Two copper grades were used for the sake of this analysis, however, in the case of OF copper 3 various materials in terms of chemical composition were tested (various oxygen and other impurities content). It is generally accepted that OF copper cannot exceed 10 ppm. The chemical composition of the tested materials was presented at Table 1.

Microstructural analysis

Selected materials were subjected to microstructural observations using scanning electron microscopy (SEM) model Hitachi S-3500N.

Electrical properties

The electrical resistance of the tested copper materials was determined using a Thompson bridge (Resistomat type 2304) with the gauge length of 1 000 mm at the ambient temperature and the outcome was calculated into electrical resistivity.

Mechanical properties

The determination of the amount of deformation and mechanical properties of the tested copper materials was carried out using a Zwick/Roell Proline Z020 testing machine.

Wire drawing process

All of the tested materials were subjected to wire drawing process from the starting diameter of 8 mm to the final diameter of 1,65 mm with average unit coefficient of deformation λ_u = approximately 1,22. Table 2 presents the parameters of the wire drawing process.

Table 1 **Chemical composition of the copper materials / wt. ppm**

Material	Ag	Bi	Pb	Sb	As	Fe	Ni	Sn	Zn	S	**O_2**	**Sum**
Cu-OF 1	13	0,1	0,5	0,2	0,4	1,7	1,5	0,3	1,4	2,2	**1,5**	**22,8**
Cu-OF 2	8	0,1	0,6	0,8	0,4	2,2	1,2	0,3	1,4	2,0	**2,5**	**19,5**
Cu-OF 3	9	0,1	0,9	0,9	0,4	3,2	1,5	0,3	1,4	3,0	**9,5**	**30,2**
Cu-ETP	14	0,1	0,7	0,6	0,4	1,7	1,7	0,3	1,8	2,5	**168**	**191,8**

Table 2 **Parameters of the wire drawing process of copper rod ø 8 mm (n – no. of the draw, d – diameter, λ – total coefficient of deformation, ε - true strain)**

n	1	2	3	4	5	6	7	8
d / mm	7,3	6,7	6,0	5,4	4,9	4,5	4,0	3,66
λ	1,2	1,5	1,8	2,2	2,7	3,2	4,0	4,8
ε	0,18	0,37	0,56	0,78	0,98	1,17	1,36	1,56
n	9	10	11	12	13	14	15	16
d / mm	3,3	3,0	2,7	2,5	2,2	2,0	1,81	1,65
λ	5,8	7,11	8,8	10,7	13	16	19,5	24
ε	1,76	1,96	2,17	2,37	2,58	2,77	2,97	3,16

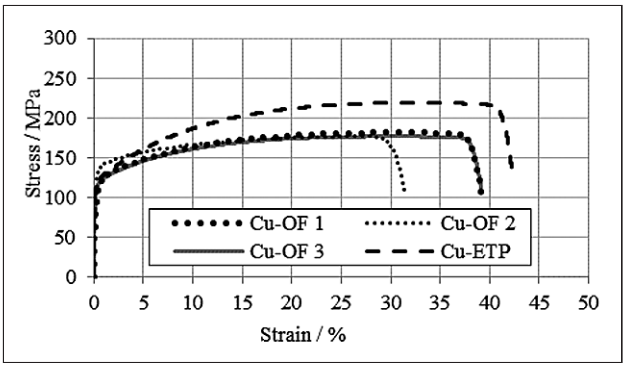

Figure 2 Stress-strain curves of batch materials

Softening curves

The obtained final wires with a diameter of 1,65 mm were exposed to an annealing process at the temperature range of 140 – 280 °C lasting one hour. Samples prepared this way were subjected to uniaxial tensile test and the obtained values were presented as a function of annealing time, thus creating the softening curves.

RESULTS AND DISCUSSION

Microstructural analysis

The structural analysis presented at Figure 1 clearly show the differences between Cu-OF and Cu-ETP as the grain size of oxygen-free copper is even a few mm whereas for ETP grade copper it is approx. 30 µm.

Electrical properties

Electrical properties study of the tested materials presented in Table 3 proved that Cu-OF material has higher electrical conductivity in comparison to ETP grade copper. The reason behind this is lower amount of grain boundaries and lack of Cu_2O oxide which directly translates into fewer obstacles for the free flow of electrons.

Table 3 **Properties of the batch material**

Material	Electrical Resistivity / nΩm	Electrical conductivity / MS/m	%IACS
Cu-OF 1	17,10	58,49	100,84
Cu-OF 2	17,15	58,33	100,56
Cu-OF 3	17,19	58,18	100,30
Cu-ETP	17,20	58,12	100,21

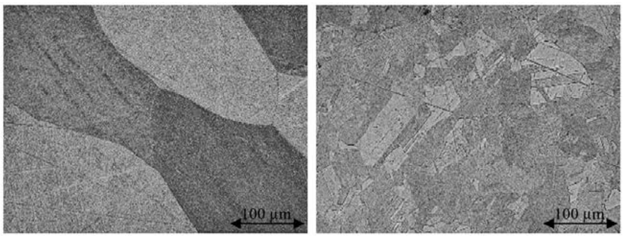

Figure 1 Structural analysis of CuOF cast rod (left) and Cu-ETP wire rod (right), magnification x 200

Mechanical properties

The stress-strain characteristics determine the hardening nature of tested materials in the uniaxial tensile test and are the macroscopic response of the materials structure. The obtained curves are presented at Figure 2.

ETP grade copper has higher ultimate tensile strength with simultaneously lower yield strength and higher total elongation than any of the Cu-OF materials. For a more detailed analysis of the strengthening of the tested materials known from literature sources Hollomon model being the power function of the deformation was used (Formula 1)

$$\sigma_p = Kln\lambda^n \tag{1}$$

where:

$ln\lambda$ – true strain,

K, n – experimentally determined material constants.

The equation parameters (K, n) were determined on the basis of the power approximation of the strain-stress curve part extracted between yield strength and ultimate tensile strength. The determination of K and n coefficients is possible transforming finding a logarithm of the Formula 1. The obtained function has the form of Formula 2.

$$\ln\sigma = \ln K + n\ln\lambda \tag{2}$$

In Table 4 the obtained values of K and n after power approximation for the batch materials were collectively presented.

The analysis of the presented in Table 4 values proves that ETP grade copper has the highest values of both linear K and power n coefficients, thus suggesting higher increase of the strength properties due to the applied deformation in comparison to oxygen-free copper. This may be explained by the fine-grained structure of Cu-ETP and typical foundry structure of Cu-OF characterised by large grains (even a few mm).

Table 4 **Hollomon equation parameters**

Material	Parameters determined through power approximation	
	K / MPa	n / -
Cu-OF 1	317	0,2310
Cu-OF 2	292	0,1898
Cu-OF 3	304	0,2187
Cu-ETP	375	0,2352

Wire drawing process

Susceptibility to deep processing in wire drawing process was tested as the next stage of the research. The applied deformation from diameter of 8 mm to 1,65 mm corresponds to true strain of approx. 3. Figures 3 and 4 show strengthening characteristics.

Strengthening of copper may be mathematically expressed with the following Formulae (3 and 4).

$$Rm = Jln\lambda^{n} \quad (3)$$

$$R_{0,2} = Jln\lambda^{n} \quad (4)$$

Based on the strengthening characteristics and the formulae 3 and 4 the strengthening parameters during the wire drawing process were determined and presented in Table 5.

Detailed analysis of the presented in Table 5 parameters distinguishes clearly between the two materials. ETP grade copper in the case of both yield strength and ultimate tensile strength has lower values of power coefficient n which suggests smaller increase of the mechanical properties as a function of the applied strain during the wire drawing process. However, coefficient K for both discussed values is the highest which may be explained by the higher set of mechanical properties of the batch material and its fine-grained structure. Oxygen-free copper regardless of the material due to its foundry structure has higher values of n coefficient and much lower values of K coefficient than ETP grade copper.

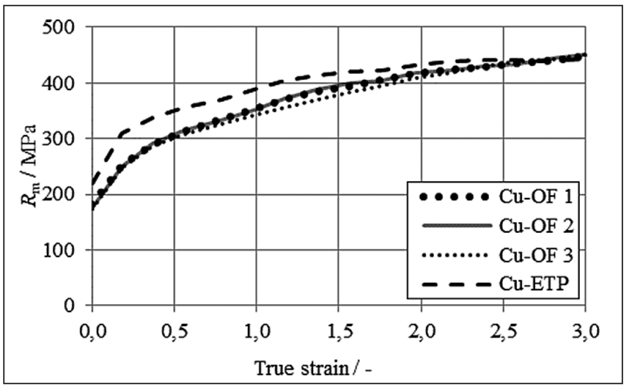

Figure 3 Ultimate tensile strength of Cu-ETP and CuOF as a function of true strain

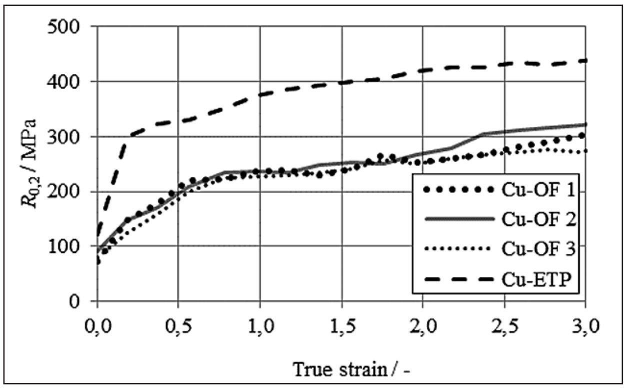

Figure 4 Yield strength of Cu-ETP and CuOF as a function of true strain

Table 5 **Wire drawing strengthening parameters of the tested materials**

Material	$R_{0,2}$		Rm	
	K/ MPa	n / -	K/ MPa	n / -
Cu-OF 1	232	0,1799	369	0,1205
Cu-OF 2	242	0,1645	370	0,1241
Cu-OF 3	223	0,1698	363	0,1256
Cu-ETP	373	0,1603	395	0,0941

Based on the obtained experimental results and calculated values it was proved that the strengthening parameters (power coefficient n) according to the Hollomon model are higher in comparison to the strengthening curves in the wire drawing process. The discussed differences between the values obtained in the uniaxial tensile test and the drawing process result from the presence of additional frictional forces throughout the wire drawing process as a portion of energy necessary for the plastic deformation of the wire must be used to surpass the frictional forces.

Softening curves

The susceptibility to deep processing of copper is determined by among others annealing process, however, in the discussed case it is "on-line" annealing throughout the industrial wire drawing process with drawing velocity of approx. 30 – 50 m/s. With such high drawing velocity the material has to soften in a fraction of a second. The abovementioned annealing conditions differentiate between the two discussed copper grades as their response vary. Static annealing tests of both OF and ETP grade copper were carried out for 1 hour at the temperature range from 140 to 280 °C – Figures 5, 6.

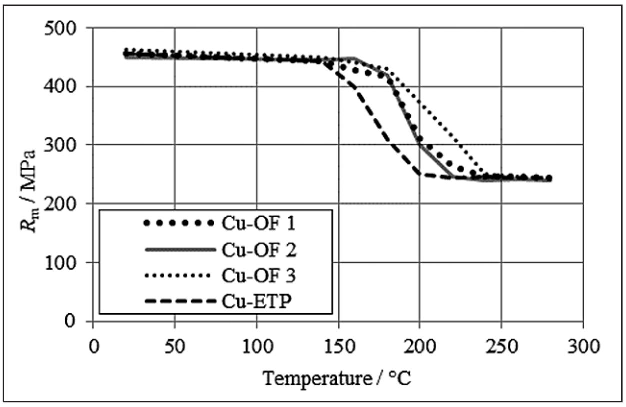

Figure 5 Temperature influence on the ultimate tensile strength of ETP and OF grade copper during 1 hour static annealing test

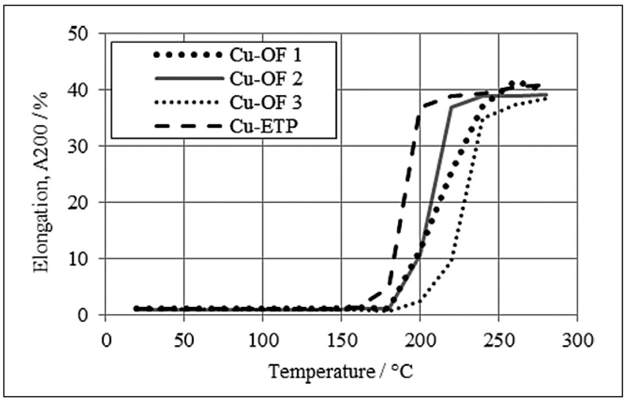

Figure 6 Temperature influence on the elongation of ETP and OF grade copper during 1 hour static annealing test

The obtained results unequivocally indicate the differences in the susceptibility to annealing of Cu-ETP and Cu-OF wires, especially the differentiation concerns the annealing kinetics. ETP grade copper exhibits faster reaction to temperature and transitions to the soft state at approx. 160 °C, whereas CuOF need temperature range of 220 – 250 °C to obtain a soft state.

CONCLUSIONS

Diversity of the strengthening characteristics were observed in the uniaxial tensile test and in the drawing test which is directly related to the differentiation of the structure, oxygen content and the presence of frictional forces during wire drawing copper.

Careful selection of the plastic deformation process and recrystallization parameters of copper with a specified oxygen content allows for the effective control of the course of the strengthening of copper and its ability to soften in the actual industrial process.

Acknowledgements

This research was funded by subsidy of the Faculty of Non-Ferrous Metals of AGH (contract No 16.16.180.006).

REFERENCES

[1] I. Goto, S. Aso, K. Ohguchi, et al., Deformation Behavior of Pure Copper Castings with As-Cast Surfaces for Electrical Parts, Journal of Materials Engineering and Performance 28 (2019) 3835–3843.

[2] M. Zasadzińska, T. Knych, The morphology of eutectic copper oxides Cu_2O in the processing of wire rod and wires made from ETP grade copper, Archives of Metallurgy and Materials 64 (2019) 4, 1611–1616.

[3] H. Pops, The metallurgy of copper wire, Essex Group Inc., The Copper Development Association, 1997.

[4] I Kinas, E. Tan, H. Can, The Effect of Oxygen Content on Mechanical and Conductivity Properties of Copper Rods Produced by Contirod and Up-Cast Continuous Casting Methods, International Journal of Scientific and Technological Research 4 (2018) 10, 384–391.

[5] D. Gusković, D. Marković, S. Nestorović, Effect of deformation and oxygen content on mechanical properties of different copper wires, Bulletin of Materials Science 20 (1997) 5, 693–697.

[6] C. Camurri, C. Carrasco, R. Leite, R. Mangalaraja, J. Dil, Influence of Impurities in Cathodic Copper on the Ductility of Copper Wires, Journal of Materials Engineering and Performance 21 (2017) 7, 1474–1478.

[7] C. Banganayi, K. Nyembwe, K. Mageza, Annealer curve characteristics of electrolytically refined tough pitch copper (Cu-ETP) and oxygen free up-cast copper (Cu-OF) for electrical cable wires, Results in Materials 8 (2020) 100146.

[8] E. H. Chia, G. R. Patel, Characterization of rod and wire defects produced during the manufacturing of copper, Wire Journal International 6 (1996) 50–59.

[9] H. Zhao, W. Chen, M. Wu, et al., Influence of Low Oxygen Content on the Recrystallization Behavior of Rolled Copper Foil, Oxid Met 90 (2018) 203–215.

[10] M. Zasadzińska, T. Knych, P. Strzępek, et al., Analysis of the strengthening and recrystallization of electrolytic copper (Cu-ETP) and oxygen free copper (Cu-OF), Archives of Civil and Mechanical Engineering 19 (2019) 1, 186–193.

Note: The translator responsible for English language: Grzegorz Kiesiewicz, AGH University of Science and Technology, Cracow, Poland