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INFLUENCE OF THE SPEED OF DOWNWARD SEMI-CONTINUOUS CASTING ON THE CRYSTAL SIZE AND MECHANICAL PROPERTIES OF RECYCLED COPPER

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In this study, the influence of the speed of downward semi-continuous casting on the crystal size and mechanical properties of recycled copper after casting and cold deformation was investigated. It was shown that the increase in the casting speed from 0,09 m / min to 0,22 m / min resulted in refinement of the macrostructure and reduction of the crystal cross-sectional area from 3,221 mm^2 to 1,2 mm^2, which resulted in an increase in microhardness after casting by 8 %, while in the state after cold working, an increase in microhardness by 3 % and ultimate tensile strength by 2,5 %.

Keywords: copper, semi-continuous casting, macrostructure, crystal size, mechanical properties

INTRODUCTION

Copper and its alloys, due to their properties, are used in many branches of the industry, such as construction, energy, electronics, maritime and automotive industry. High mechanical properties of copper and its alloys can be achieved through the use of many strengthening mechanisms of metallic materials, such as solution hardening, precipitation hardening, strain hardening, grain and subgrain boundary strengthening. One of the most effective mechanisms of material strengthening without loss of ductility is the refinement of the microstructure. In addition to increasing the strength properties of the material, homogeneity of properties in the entire volume, better susceptibility to cold working and increased fatigue resistance and cracking resistance are obtained [1-4]. In the case of cast materials, there are many possibilities of grain refinement. One of the way of refining the microstructure of castings is the introduction of alloying elements to the chemical composition, which form oxides or intermetallic phases and constitute nuclei of crystallization during solidification. Effective grain refinement by alloy additions is difficult because, apart from ensuring a sufficient amount and size of highly dispersed particles, special melting and casting conditions must be met, including an appropriate casting temperature and a high degree of undercooling [5-7]. Refinement of the microstructure in the continuous casting process is possible primarily by controlling the casting parameters such as feed, stops and the flow of the cooling medium in the primary and secondary cooling system. In addition to the parameters mentioned above, the crystallization conditions are greatly influenced by the roughness and quality of the outer surface of the crystallizers in contact with the surface of the cooler. Higher roughness of the crystallizer results in poorer heat transfer. Ensuring an appropriate heat balance, both by accelerating the casting process and by fast heat dissipation, contributes to microstructure refinement [8-9]. In the case of continuous casting processes, good results in terms of microstructure refinement are obtained by using a mixing electromagnetic field in the crystallization system. This interaction causes homogenization of the temperature at the front of the solid-liquid interface, disturbing the direction of heat flow, which affects the remelting of dendrites and the formation of equiaxed crystals [10-11].

This paper presents the results of the study of the influence of variable speed of downward semi-continuous casting of recycled copper on the macrostructure and mechanical properties. The research focused on verifying the possibility of obtaining pure copper rods with higher mechanical properties after casting and plastic working by refinement the casting macrostructure crystals using a higher casting speed.

EXPERIMENTAL PROCEDURE

Material

The test material consisted of rods with a diameter of 25 mm cast in a downward semi-continuous manner from copper. Pieces of pure Cu-ETP copper and recycled copper from power cables (51 % of the charge weight) were used to produce the copper rods. A small

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amount of magnesium addition was used to deoxidize the liquid copper. The average chemical composition of tested material measured on the spark emission spectrometer is presented in Table 1. Three measurements of the chemical composition were made for each sample.

Table 1 **Average chemical composition of samples / ppm**

Zn	Pb	Sn	P	Fe	Ni	Si*	Mg	Cr	Te
<15	<3	4,2	<2	10	<2	78	138	<2	3,9
As	Sb	Cd	Bi	Ag	Co	Al	S	Be	Zr
<2	<10	<1	<5	16	<4	<3	9	<1	4,4
Au	B	Ti	Se	Pt	Cu				
<5	<2	<2	<3	45	rest				
* increased Si content caused by grinding the sample before testing on SiC sandpaper									

An INDUTHERM VCC3000 installation was used for melting and downward semi-continuous casting. Melting in a graphite crucible in an induction furnace at a temperature of 1250 °C was carried out. The liquid copper was protected by an argon blast. Rods with a diameter of 25 mm and a length of 1,5 m were cast. Casting parameters of the tested samples are presented in Table 2.

Table 2 **Downward semi-continuous casting parameters**

Sample	Casting temp. / °C	Crystalizer temp. / °C	Feed / mm	Stop / s	Casting velocity / m / min
1	1200	1130	2	0,7	0,09
2	1198	1138	2,5	0,6	0,13
3	1193	1146	4	0,5	0,22

Method of macrostructure analysis

The samples for macrostructure analysis were ground on sandpaper with a gradation of 500# to 4000#. A water solution of HNO3 was used for etching. Observations of the macrostructure were performed using a Keyence-VHX 7100 digital microscope. The crystal size was analysed using the ImageJ analysis software (developed in the public domain at the National Institutes of Health). In the binary image of the macrostructure, the number of crystals in the cross-section and their area were counted. The mean crystal size, standard deviation, minimum and maximum values were calculated. The view of the transformed image of the macrostructure into a binary image using the ImageJ software is shown in Figure 1.

Tensile test

The static tensile test was carried out on the Instron 100 kN universal testing machine. Three samples of each material at a speed of 2 mm / min were tested after cold deformation. The ultimate tensile strength Rm and the yield strength $Rp_{0,2}$ were determined. The A50 elongation was calculated on the basis of the dimensional changes of the applied datum on the samples.

Microhardness test

Microhardness measurements were made for samples as cast and for samples after cold working. Microhardness was measured by the Vickers method with the universal Future-Tech FM-700 hardness tester. A load of 1 kg of the indenter was applied for 15 seconds. After casting, 25 measurements were made on the samples, and 20 measurements after cold working. The mean value was calculated based on the measured values.

Cold working

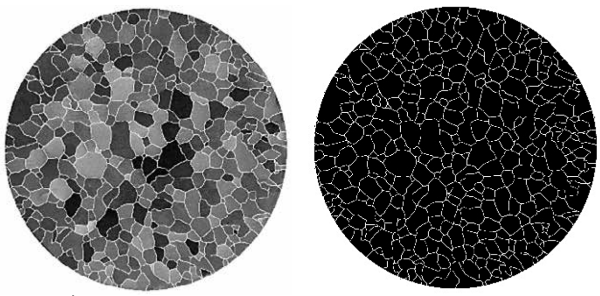
After casting, samples with a diameter of 25 mm were subjected to groove rolling (square cross-section) to the size of 7 x 7 mm. The samples were rolled with a unit reduction of 20 %. After the rolling process, the rods were subjected to a drawing process with a unit reduction of 20 % to a diameter of 4,5 mm. Drawing was carried out on a bench drawing machine. The total relative cold deformation level was 97 %.

RESULTS AND DISCUSSION

Macrostructure analysis

The macrostructure of tested alloy as cast is shown in Figures 2 - 4. The results of the crystal size measurements are shown in Table 3 and Figure 5.

The highest degree of macrostructure refinement in the cross-section and longitudinal section was found for sample no. 3 cast at the highest speed of 0,22 m / min.



8-bit macrostructure image — Binary macrostructure image

Figure 1 Converting an 8-bit image macrostructure to binary in ImageJ software

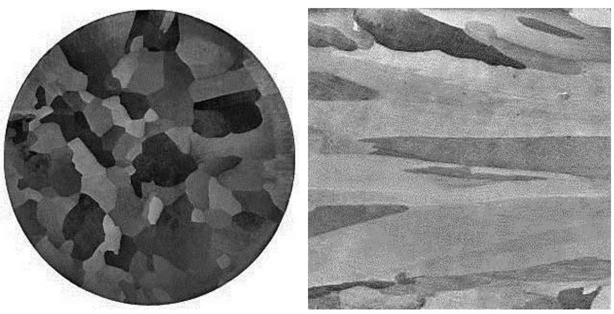


Figure 2 Macrostructure of sample 1 – casting speed 0,09 m / min

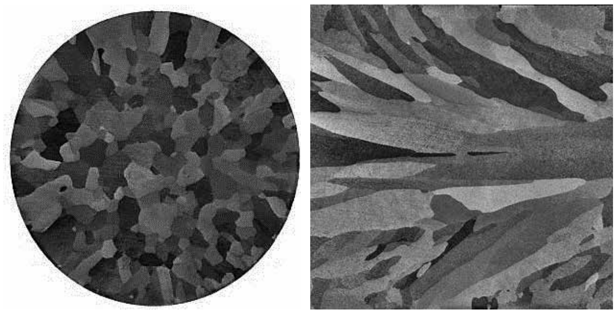


Figure 3 Macrostructure of sample 2 – casting speed 0,13 m / min

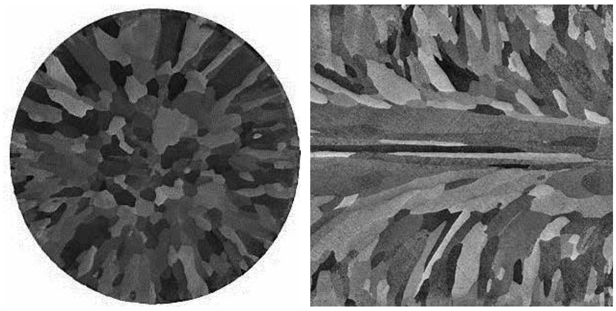


Figure 4 Macrostructure of sample 3 – casting speed 0,22 m / min

Table 3 **Measurement results of the mean size of crystals in the cross-section**

	Crystal Surface area / mm^2		
	Sample 1	Sample 2	Sample 3
Mean	3,221	1,585	1,200
Min	0,011	0,022	0,006
Max	26,933	10,134	10,161
SD	4,238	1,667	1,460

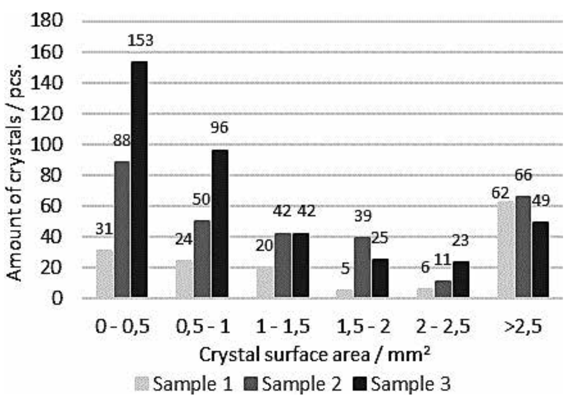


Figure 5 Measurement results of the mean size of crystals in the cross-section

The measurements carried out in the cross-section showed 388 crystals with an average surface area of 1,2 mm^2. In this sample, most crystals were in the range under 0,5 mm^2 (153 pcs.) and from 0,5 to 1 mm^2 (96 pcs.). For sample no. 1 cast at the lowest speed, the measurements showed 148 crystals with an average surface area of 3,221 mm^2 (almost 2,5 times larger than sample no. 3). The largest number of crystals in this sample (62 pieces) was in the area above 2,5 mm^2. For sample no. 2 cast at a speed of 0,13 m / min, 296 crystals with an average surface area of 1,585 mm^2 were counted. The largest number of crystals was in the range under 0,5 mm^2 (88 pcs.) and in the range above 2,5 mm^2 (66 pcs.).

Microhardness and tensile test

The results of the Vickers microhardness measurements in the cross-section of the tested samples in the as-cast condition and after cold working are shown in Figure 6, while the results of the static tensile test after cold working are shown in Figure 7 and Table 4.

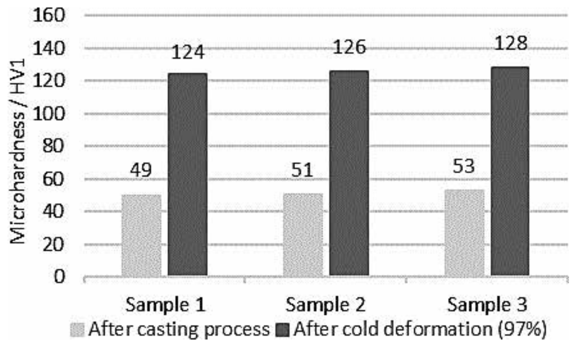


Figure 6 Measurement results of Vickers microhardness in the cross-section of samples after casting process and cold working

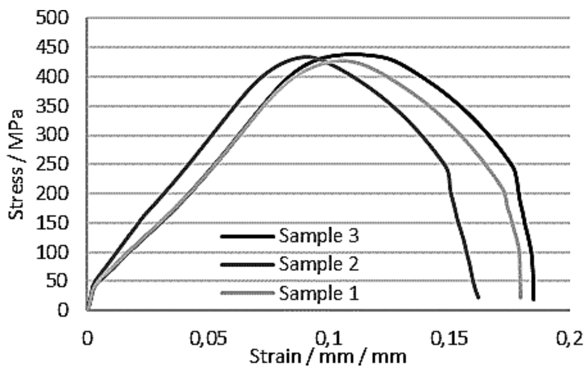


Figure 7 Stress-strain curve for selected samples after cold working

Table 4 **Results of tensile test after cold working (ε=97%)**

Sample	Rm / MPa	$Rp_{0,2}$ / MPa	A 50 / %
1	428	410	7,2
2	433	413	6,8
3	439	413	7,2

The increase in the casting speed, in addition to the refinement of the macrostructure, increased the mechanical properties of the copper rods in the as-cast state and after cold working. Obtained results correlate with the research in work [14], which also showed an increase in hardness after increasing the casting feed of CuMg alloys. For sample no. 2, increasing the casting speed from 0,09 m / min to 0,13 m / min resulted in an increase in microhardness from 49 HV1 to 51 HV1 (increase by about 4 %) in the as-cast state and from 124

HV1 to 126 HV1 (increase by about 2 %) in the cold-deformed state. A greater increase in mechanical properties was observed for the sample cast at twice the casting speed. Increasing the casting speed from 0,09 m / min to 0,22 m / min for sample 3 resulted in an increase in microhardness from 49 HV1 to 53 HV1 (an increase of about 8 %) in the as-cast condition and from 124 HV1 to 128 HV1 in the as-cold worked state (increase by about 3 %). The results of the static tensile test correlate to the microhardness results. The increase in the casting speed increased the tensile strength while maintaining a similar level of yield stress and elongation. Compared to sample no. 1, the increase in the casting speed for sample no. 2 increased the tensile strength by 5 MPa (about 1,5 %), and for sample no. 3 by 11 MPa (about 3 %).

CONCLUSIONS

After testing the macrostructure and mechanical properties in the as-cast state and after cold working of the copper rods, the following conclusions and observations were made:

Increasing the casting speed contributed to the refinement of the macrostructure of copper rod. The best effect was observed when increasing the casting speed from 0,09 m / min to 0,22 m / min. The number of crystals in the cross-section increased more than twofold, which resulted in a decrease in their size from 3,221 mm^2 to 1,2 mm^2.

The refinement of the macrostructure increased the level of microhardness and tensile strength of the tested samples. For extreme casting speeds, the microhardness increased 8 % in the as-cast state and 3 % after cold working. The tensile strength increased about 2,5 % while maintaining a similar level of yield strength and elongation.

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Note: The translator responsible for English language: Małgorzata Krystowska, Gliwice, Poland