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Continuous Casting of Cu-Mg Alloy Rod

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ABSTRACT **Nowadays, different processes are used to make copper rod. Among these methods, there is a direct casting method which is also divided into upward vertical casting and horizontal casting. Cu-Mg alloy is one of the copper alloys produced by continuous casting which has not been widely studied and which has interesting properties such as high conductivity with good tensile strength, excellent weldability and excellent plateability. In this study, the effect of horizontal continuous casting parameters on the microstructures, mechanical properties and electrical conductivity on the Cu-Mg alloy rod was investigated. Pulling distance and pause time were gradually changed during the manufacturing of the Cu-Mg alloy rod. The evolution of the cast rod microstructure was studied by optical microscopy and scanning electron microscopy. The texture in cast copper alloy was analyzed by electron backscatter diffraction technique. The chemical composition was measured by energy dispersive spectroscopy. The mechanical properties of the cast rod were determined by hardness measurements. Electrical conductivity was measured with an eddy current conductivity meter. It has been found that the grain size and their distribution vary with the casting parameters. Columnar and fine grains were observed in the same cast metal which gave higher hardness in fine grain areas and low electrical conductivity.**

Keywords: Horizontal casting; Cu-Mg alloy; Microstructures; Mechanical Properties; Electrical Conductivity; Grains.

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1. INTRODUCTION

Continuous casting is a metal forming process in which the metal is cast continuously, rather than poured into conventional molds [1]. Continuous casting technology is widespread, surpassing the conventional ingot casting method in the mid-1980s. Today, the continuous casting rate has reached the level of 95 % [2]. . This technology is used in the manufacturing industry to cast a continuous length of metal such as steel, aluminum, copper and other alloys to produce a wide range of different profiles such as such as wire rod, cylindrical bars, square bars and tubes, hexagonal profiles, tube shells, billets and strips, slabs of different thicknesses and widths [3,4].

From an economic point of view, continuous casting is better than mold casting, because it consumes less energy and produces less scrap. In addition, product properties can be easily changed by modifying casting parameters [3, 5]. The main casting parameters are melt temperature, withdrawal system, continuous casting direction, cooling water flow rate, casting speed, pull distance, and casting die material [3]. According to the direction of drawing, continuous casting technologies are divided into horizontal, vertical or inclined casting machines. Vertical continuous casting is characterized by a parallel orientation of the drawing direction and the gravitational field. For horizontal continuous casting machines the product is stretched in a direction perpendicular to the gravity field [6]. It has been proven that the horizontal continuous casting method is more economical compared to vertical continuous casting, because it requires less investment, its installation is easier and technically more convenient for the operator [3].

During the horizontal continuous casting process, the metal flows out the front of the crucible and enters a water-cooled die where solidification occurs. The drive rollers pull the bar along the roller tables. With the precise control of the parameters of metal casting, the size and distribution of its grains can be controlled, which makes it possible to obtain the desired metallurgical properties [7]. In this context, some research works have been carried out to better understand and also to control the horizontal continuous casting of copper and its alloys. Sha et al. [8], studied the effect of rotary electromagnetic stirring on the solidification process by horizontal continuous casting of round copper billets. They determined the optimal current intensity and frequency for a better product. Franczak et al. [9] studied the process of horizontal continuous casting of Cu-Cr-Zr cast rods by the incorporation of Sc with different weights, and which are intended for the manufacture of welding electrodes. They found that the mechanical properties were improved by the addition of Sc. Strzępek et al [10] studied the influence of horizontal continuous casting conditions on the properties of high-strength two-phase CuMg alloys (Cu- 4.5% and Cu-5 wt% Mg). Microscopic observations revealed the presence of α phase (Cu) and β phase (Cu_2Mg) and which were confirmed by X-ray diffraction. They also found that increasing the casting feed resulted in a change significant in the density and size of the CuMg alloy. These two phases aggregate, forming more grain boundaries as casting feed increases, influencing the hardness of the material.

The objective of this study is to understand the microstructural, mechanical, and electrical evolution of the Cu-Mg alloy rod, manufactured by horizontal continuous casting, after varying the casting conditions.

2. EXPERIMENTAL PROCEDURE

2.1. Horizontal continuous casting process

Cu-Mg alloy rods were produced on a continuous horizontal casting laboratory machine manufactured by Termetal (Fig.1) from the pure metals Cu (purity 99.99 %) and Mg (purity 99.9 %) which were supplied by Stanchem. This machine consists of an adjustable induction furnace, with a nominal power of 20 kW containing a cylindrical graphite crucible in which a graphite crystallizer is screwed onto the thread located near the bottom. The solidification of the molten metal is ensured by a primary cooling system mounted on the crystallizer. At the outlet of the crystallizer, the casting rod is subjected to secondary cooling by direct spraying. The rod extraction control is regulated by an extraction system made up of two cylinders driven by a direct current motor. Withdrawn cycles were adopted (Fig.2). These withdrawn cycles consisted of intermittent extraction with a pause technique, meaning the rod is withdrawn a certain distance (called pull distance), then the withdrawn stops for a given amount of time (called pause time) and then the cycle repeats.

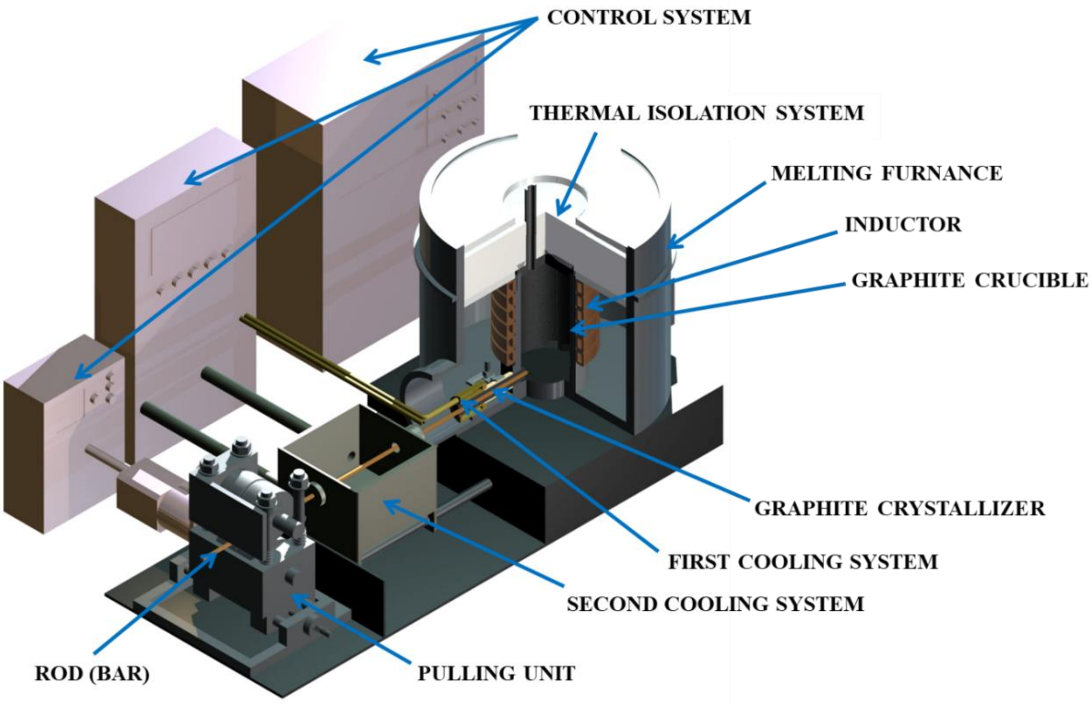


Fig. 1. Laboratory line for continuous horizontal casting non-ferrous metals and alloys

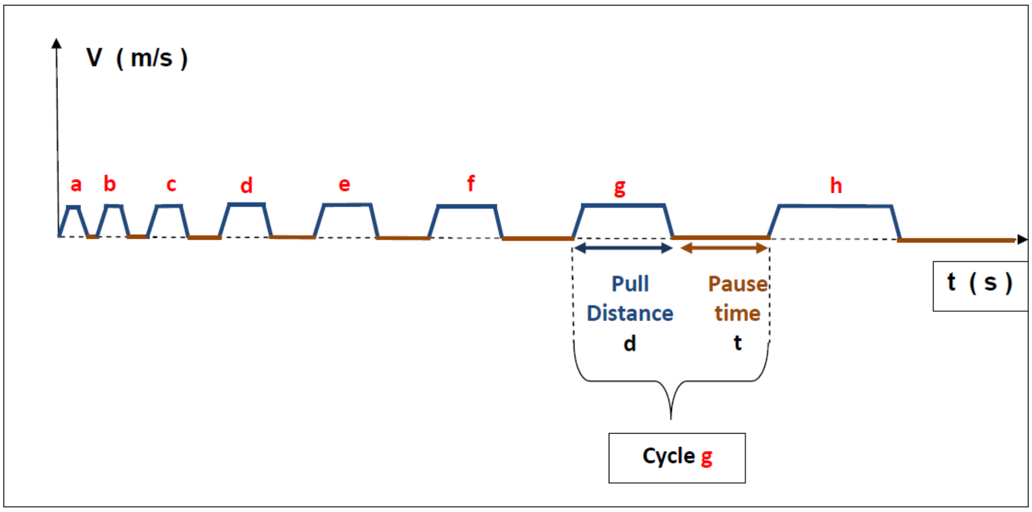


Fig.2.Withrawn cycles(Casting speed V vs time t) during the continuous horizontal casting process of Cu-Mg alloy : (a) : d= 4mm t = 2s, (b) : d= 6 mm t = 3 s, (c) : d= 12 mm t = 6 s, (d) : d= 18 mm t = 9 s, (e) : d= 24 mm t = 12 s, (f) : d= 30 mm t = 15 s, (g) : d= 36 mm t = 18 s, and (h) : d= 42 mm t = 21 s.

The main continuous casting process parameters are presented in Table 1.

Table. 1. Continuous casting parameters.

Parameter	Value
Temperature of liquid metal	1250°C
Primary cooling medium outlet temperature	35 - 45°C
Cast rod surface temperature after secondary cooling	35 - 40°C
Continuous casting speed	120 mm/min

Chemical composition of cast material is given in table 2.

Table 2. Chemical composition of Cu-Mg cast material (Wt. %).

Cu	Mg	Si	Sn	P	Mn	Fe	Ni	Pb	Cr	Te	As
97.4	2.51	0.01	>0.01	>0.01	>0.01	>0.01	>0.01	>0.01	>0.01	>0.01	>0.01
Sb	**Cd**	**Bi**	**Zn**	**Co**	**Al**	**S**	**Zr**	**Sc**	**Be**		
>0.01	>0.01	>0.01	>0.01	>0.01	>0.01	>0.01	>0.01	>0.001	>0.001		

2.2. Technical characterization

Vickers hardness tests were performed on a Tukon 2500 Knoop/Vickers automated with a motorized table hardness tester manufactured by Wolpert-Wilson.The test load was 5 kg (accuracy: +/-1% of the load measurement value). For microscopic observation, the transverse and longitudinal sections were polished using a Labopol type polisher (Strues).To reveal the microstructure, the polished samples were chemically attacked with a solution containing FeCl3-HCL (5g iron(III) chloride, 10cm^3 hydrochloric acid, 100cm^3 ethanol).Microstructure observations were carried out using Olympus GX51 inverted metallurgical microscopy and Hitachi SU-70 type scanning electron microscopy equipped with Energy Dispersive Spectroscopy (EDS). Electric resistivity measurements of the tested samples were performed by eddy current conductivity meter Sigmatest 2.069 made by Foerster. For the electron backscatter diffraction (EBSD) analyses, a Zeiss Supra 50 FEG-SEM operating at 20 kV coupled with the OIMTM (Orientation Imaging Microscopy) software from the company TSL-EDAX was used.

3. RESULTS AND DISCUSSIONS

3.1. Optical Observations

Microscopic observations were carried out along the longitudinal and transverse direction. For the longitudinal direction (Fig.3), very elongated columnar grains are observed for short pulling distances and pause times and with the increase in the pulling distance and pause time, fine grains are formed. Typically, the columnar structure is observed in ingots, strands or rods produced by continuous casting [11]. It has been reported that the formation of a columnar structure is controlled by the thermal gradient and diffusion phenomena existing at the solid/liquid interface [12]. However, latent heat is transported through the solid and the heat flow is directed towards the surface of the crystallizer while the solute is rejected at the solid/liquid interface [13]. This is why the columnar grains are oriented towards the surface of the rod.

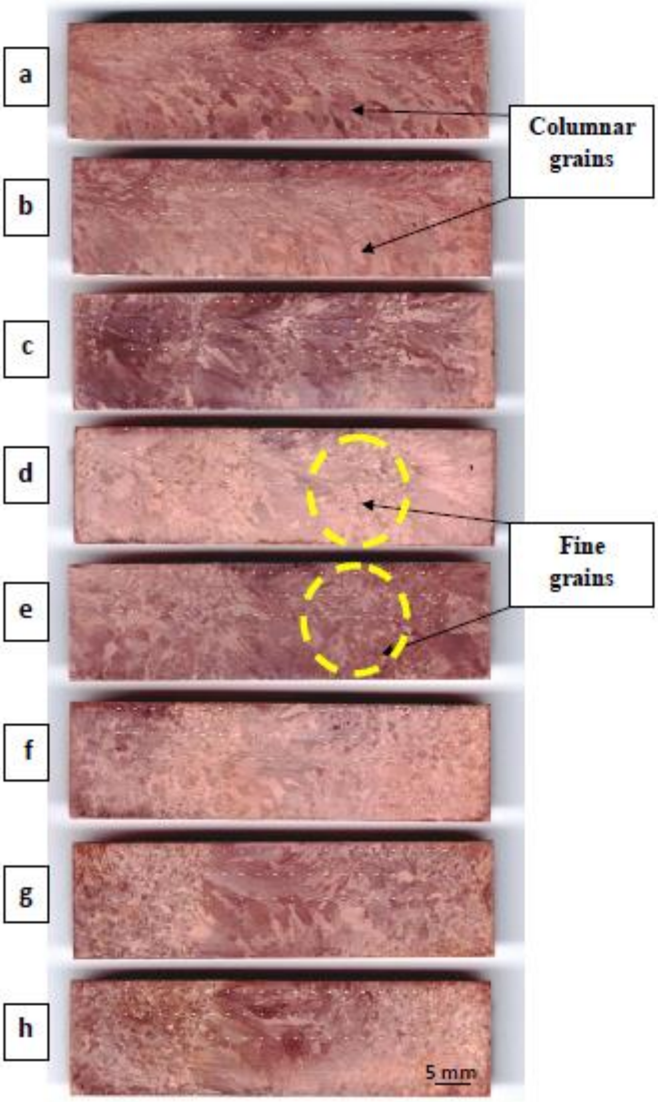


Fig. 3. Microstructures evolution along the longitudinal direction of the casr rod Cu-Mg alloys during the increasing the pull distance d and the pause time t. (a) : d= 4mm t = 2s, (b) : d= 6 mm t = 3 s, (c) : d= 12 mm t = 6 s, (d) : d= 18 mm t = 9 s, (e) : d= 24 mm t = 12 s, (f) : d= 30 mm t = 15 s, (g) : d= 36 mm t = 18 s, and (h) : d= 42 mm t = 21 s.

Figure 4 presents the microstructural evolution the transversal view of the Cu-Mg alloy wire after increasing the pull distance and the pause time during the horizontal casting process. For the pull distance and the pause time from **(**d= 4 mm t = 2 s **)** to **(** d= 18 mm t = 9 s **),** two different grain sizes are formed, large grains are located on the upper half-section of the wire section and small grains in the lower half-section of the copper wire. This grain distribution can be attributed to the effect of gravity. This phenomenon was mentioned by Vijayaram [3] and explained by the fact that the bottom in horizontal casting is generally better cooled and has a finer grain. Liu et al. [14] observed also this phenomenon in the horizontal continuous casting of billet. However, for the increasing of pull distance and the pause time (d= 24 mm t = 12 s) to (d= 42 mm t = 21 s)**,**a new grain distribution has formed, i.e., the small grains are located on the periphery of the wire section and the large grains are at the core of the rod. As it has been reported, control of solidification and cooling is essential for the continuous casting process [3].

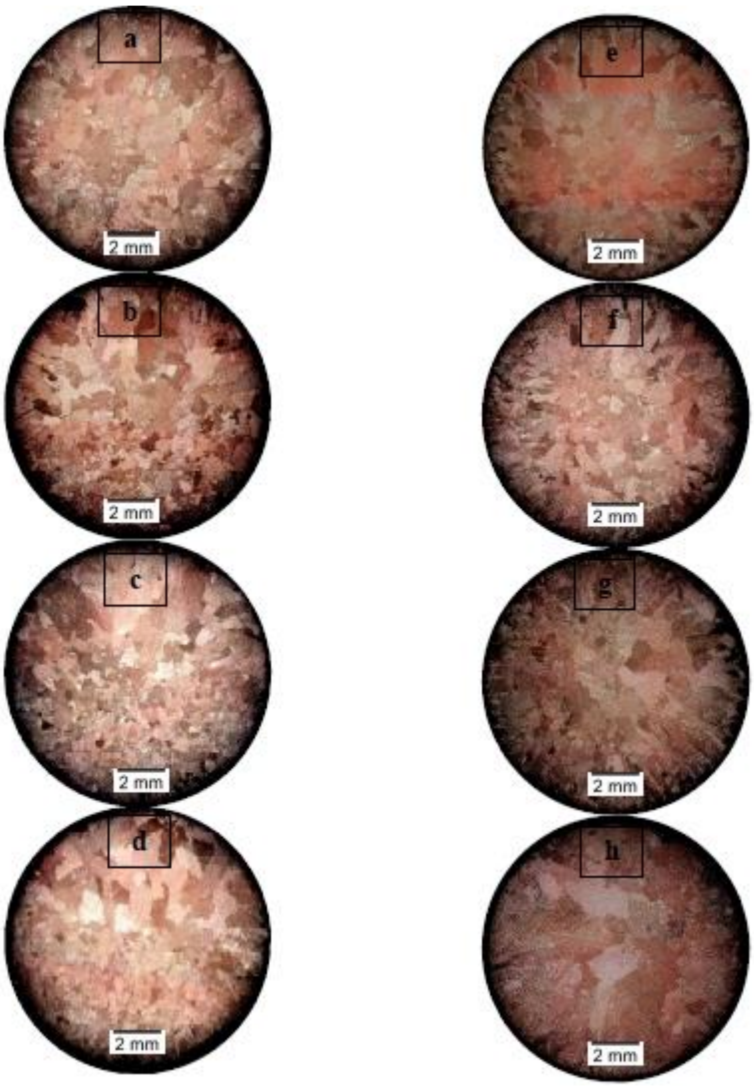


Fig.4. Microstructures evolution on the cross section of the cast rod Cu-Mg alloy after the increasing the pull distance d and the pause time t. (a) : d= 4mm t = 2s, (b) : d= 6 mm t = 3 s, (c) : d= 12 mm t = 6 s, (d) : d= 18 mm t = 9 s, (e) : d= 24 mm t = 12 s,(f) : d= 30 mm t = 15 s, (g) : d= 36 mm t =18 s, and (h): d= 42 mm t = 21 s

Based on the microstructural observation after the short pull distance and short pause time, a schematic representation of the grain distribution in the Cu-Mg alloy rod was established (Fig.5). The core of the rod is formed of columnar grains while the periphery is formed of small grains. This distribution of grains is the effect of the solidification mechanism. This representation changes by changing the withdrawn cycle during the horizontal continuous casting process. This configuration changes if the pulling distance and the dwell time increase, that is to say, there will be formation of fine grains even in the heart of the rod.

Fig. 5. Schematic representation of the grains distribution in the Cu-Mg alloy rod.

The EBSD maps are measured in the plane (A1, A2), along the longitudinal section of the Cu-Mg alloy rod, where A2 is the casting direction and A3 is the direction normal to the observed surface. Figure 6 shows the EBSD A3-IPF map of the Cu-Mg alloy rod after the horizontal continuous casting process for the pulling distance d (d = 36 mm) and dwell time t (t = 18 s) (A2 represents the direction of continuous casting). This map shows the fine grains connected to the long columnar grains which confirms the microstructural observations. From the color code, the fine grains do not have a preferred crystallographic orient.

Fig.6. A3-IPF EBSD maps of the Cu-Mg alloy rod for the pull distance d and the d= 36 mm t = 18 s (A2 represents the continuous casting direction).

3.2. Hardness Measurements Variation

Figure 7 presents the Vickers hardness variation in periheric and central zone of the Cu-Mg alloy wire during the increasing of the pull distance and the pause time**.** Overall, the hardness in the peripheral zone (near the surface) of the Cu-Mg alloy rod is higher compared to the central zone for the entire pulling distance and the intermittent pulling time, because the peripheral zone is composed of fine grains unlike the central zone.

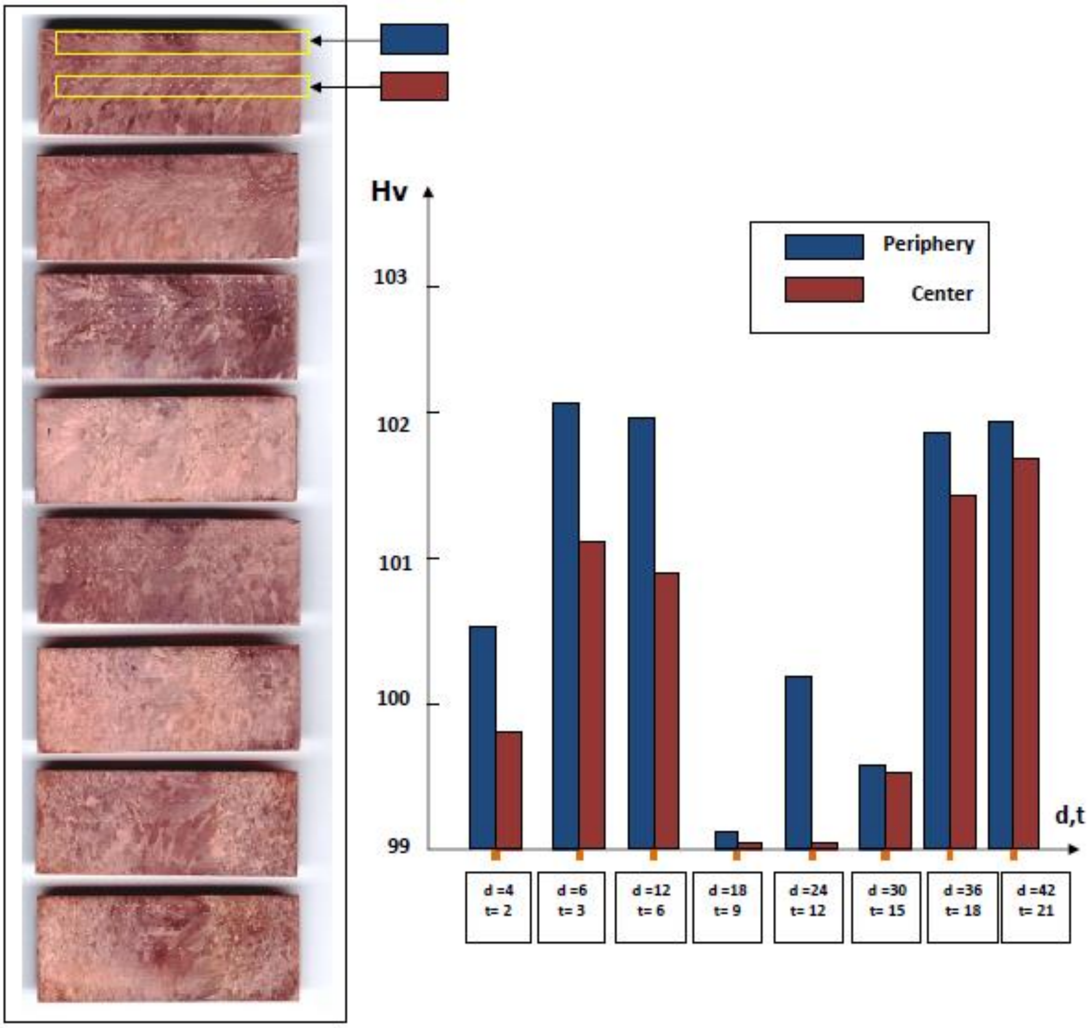


Fig. 7. Vickers hardness variation in peripheral and central zone of the Cu-Mg alloy rod during the increasing the pull distance and the pause time**.**

3.3. Electrical Conductivity Variation

The electrical conductivity results showed the effect of grain size on the electrical conductivity value of Cu-Mg alloy rods. The electrical conductivity in the coarse-grained zone reached an average value of 26.77 MS/m, unlike the fine-grained zone where an average value of (23.33 MS/m) was recorded. It can be concluded that the conductivity electric is not homogeneous in the Cu-Mg alloy rod.

3.4. SEM Observations

The objective of this part of study is to give more microstructural details on the Cu-Mg alloy after casting. For this reason, high magnification observations and chemical analyzes were carried out by SEM. Since the same phenomenon was observed on all samples, the choice fell on two samples, a sample with a short pull distance and a short pause time (d =4 mm, t = 2 s)and a second of long distance and long stopping time (d = 42 mm, t = 21 s) (Fig.8).These SEM images were obtained using backscattered electrons, where the lighter area is the one that is rich in elements with a higher atomic number. These microstructures revealed a dendritic microstructure formed by two distinct phases, a dark zone formed by long branches inside a light zone. The light zone is attributed to the matrix which is a copper-based phase and the dark zone is the magnesium-rich compound. This compound can only be the phase with the chemical formula Cu_2Mg as mentioned in previous investigations [10, 15, 16]. To confirm what was observed, spot chemical analyzes were carried out on each area (Fig. 9). The chemical composition in the light zones (1, and 2) are copper-rich zones containing approximately (99.39 to 99.46 %) copper and the remainder a very small quantity of Mg (0.6) which correspond to the matrix. On the other hand, the dark zones (3, 4 and 5) contain approximately (6.99 % Mg and 93.01% Cu) and which belong to the phase rich in Mg. It is important to note that this dendritic structure was observed in columnar grains and fine grains. This microstructure is a solidification macrostructure generally observed in a cast metal.

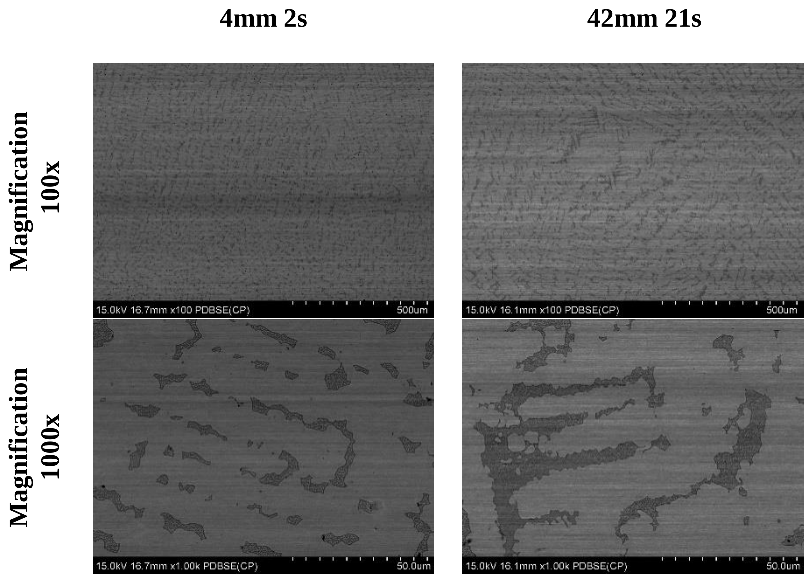
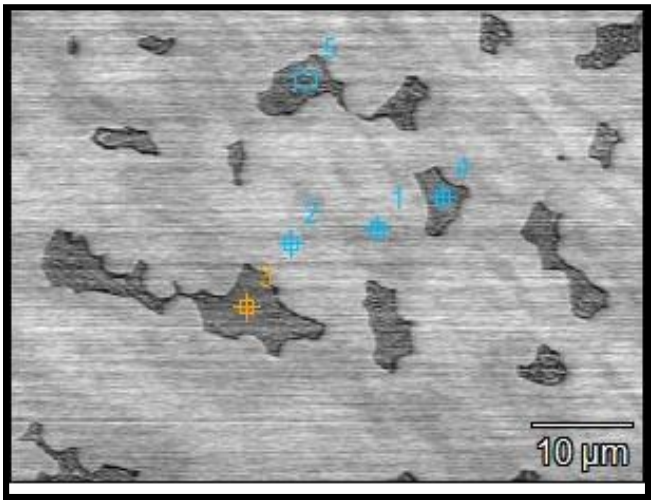


Fig. 8. SEM observation ure of the selected cast samples:
(d= 4mm t = 2s), and (d= 42 mm t = 21 s).



Zone	Mg (wt. %)	Cu (wt. %)
1	0.61	99.39
2	0.54	99.46
3	6.99	93.01
4	6.95	93.05
5	6.99	93.01

Fig. 9. Energy Dispersive Spectroscopy (EDS) of the selected cast sample:
(d = 4 mm , and t = 2s).

4. CONCLUSION

Based on the obtained results, the following conclusion can be deduced:

- Observations by optical microscopy showed very elongated columnar grains for short drawing distances and dwell times but with the increase in the drawing distance and the dwell time, fine grains are formed.
- The EBSD analysis confirmed the formation of fine grains connected to the elongated columnar grains.
- It was found that the hardness in the peripheral zone (near the surface) of the Cu-Mg alloy wire is higher compared to the central zone.
- The electrical conductivity is not uniform in the Cu-Mg alloy rod.
- The electrical conductivity is higher in the coarse-grained zone compared to the fine-grained zones.
- SEM observations revealed a dendritic microstructure formed of two distinct phases.

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