

IMPROVING THE QUALITY OF COPPER SHEET PRODUCED BY SEMI-CONTINUOUS CASTING AND ROLLING

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Abstract

The paper is concerned with the technological peculiarities of the production of copper sheet from CuNiSi alloy by the method of semi-continuous casting and subsequent stages of hot and cold rolling. Pouring defects which have an impact on the copper sheet quality are presented. There was shown that gas pores in a cast billet are among the main causes for appearance of defects in the copper sheets after rolling.

The emphasis is placed on the influence of the secondary cooling rate of the melt in the crystallizer on the change in the size of the liquid phase. It has been established that increasing the cooling water flow rate leads to accelerated formation of a hard crust and a shift of the crystallization front up the casting axis. The established decrease in the depth of the liquid phase favors heat removal in the crystallizer and leads to the production of a casting with reduced porosity.

In the work, a chemical analysis of the cast alloy was performed, the stages of subsequent thermo-mechanical treatment until obtaining a copper strip with a thickness of 0.8 mm were traced, a visual analysis of the defects observed after rolling was carried out. The quality of the copper strips obtained by rolling slabs cast at different flow rates of secondary cooling water was established through physical and mechanical tests. A technological regime of semi-continuous casting and rolling is proposed, in which a sustainable improved quality of the copper strip is achieved.

Keywords: CuNiSi alloy, semi-continuous casting, secondary cooling, quality of rolled sheet, properties

1. INTRODUCTION

The development of modern metallurgy is characterized by the optimization of technological processes in order to reduce production costs while maintaining high quality of the resulting metal products. The increased requirements for the quality of metals are a prerequisite for increasing their service life and the reliability.

Alloys of the Cu-Ni-Si system are widely used in the electrical engineering and automotive industries due to the combination of high electrical conductivity, excellent elasticity and good mechanical strength [1,2]. Many studies have been conducted to clarify the influence of combining various deformation processes with aging on the evolution of the microstructure and properties of these alloys [3-9].

Controlling the changes occurring in the metal at all stages from its processing to the final product is very important for achieving high quality. Quality control of rolled strip is related to determining the structure and properties of the metal and identifying various possible manufacturing defects in the metal.

The quality of the metal forming product is largely determined at the metal casting stage [10]. At this stage, strict control is required, since the casting defects are transferred to the final product, manifesting themselves during plastic deformation. In casting of Cu-alloys, the stability of the technological process is a critical factor for achieving a homogeneous structure and a minimum of defects in the castings [10]. Deviations in casting parameters (temperature of the cast metal, casting speed, intensity and uniformity of cooling) affect the quality of billets and can appear gas pores, surface cracks, internal stresses and structural inhomogeneities [11,12].

The present work examines a combined method for semi-continuous casting in a vertical crystallizer and rolling of CuNi1.5SiP alloy to obtain copper strip in 1/4 hard temper. The main task of the study was to prevent or significantly reduce defects in the rolled strip while maintaining mechanical properties and electrical conductivity. For this purpose, the relationship between the casting-crystallization processes and the quality of the strip was analyzed. The influence of the intensity of secondary cooling on the structure, defects, mechanical properties and electrical conductivity of a strip obtained by hot and cold rolling was studied.

2. EXPERIMENTAL WORK

The technologies for casting and rolling for the production of CuNi1.5SiP strips and their quality are under investigation. The research was conducted in an industrial environment. The low-alloyed CuNi1.5SiP alloy (C19010) contains Ni (0.8 - 1.8 %), Si (0.15 - 0.35 %) and P (0.01 - 0.05 %). The experimental material was melted in an induction furnace with intermittent operation. Semi-continuous casting was carried out, in which the liquid metal was cast directly into a vertical crystallizer with dimensions of 710 cm x 75 cm x 24 cm. During casting in crystallizer, a constant metal level and a constant casting speed (70 mm/min) were maintained. The cooling of the metal in the crystallizer was carried out by the movement of water in the crystallizer walls (primary cooling) and by direct injection of water onto the metal in the form of a spray (secondary cooling). In order to analyse the influence of the intensity of secondary cooling on the crystallization process, three slabs were cast at different flow rates of secondary cooling water injection onto the metal, Q_{sec} [l/min]: regime 1 - 260 l/min, regime 2 - 310 l/min and regime 3 - 370 l/min. All other parameters of the casting-crystallization process were the same. For each of the regimes, the depth of the liquid phase, h [mm], was measured. The first measurement was made after filling the first meter of the casting height in the vertical crystallizer. The measurement was made by immersing a copper rod until reaching a solid phase and subsequently measuring the length of the trace of liquid metal left on the rod. Analogous measurements, for each of the three regimes, were carried out three times during the casting. The results are presented in **Table 1**, where the liquid phase depth is calculated as the average value of the measurements taken.

To determine the exact chemical composition of the cast copper alloy, a chemical analysis of the slabs was performed using an optical emission spectrometer. The results are presented in **Table 2**.

The strips were produced through successive stages of hot and cold rolling of the cast slabs in regimes 1, 2 and 3 to the final product. Depending on the temper of the final strip - soft, halfhard and hard - after hot rolling, different thermomechanical treatment of the metal was performed, consisting of cold rolling and annealing [13]. For the purpose of the study, CuNi1.5SiP slabs were rolled to the final product - strips with a thickness of 0.8 mm and a 1/4 hard temper, suitable for the production of various electrical components. The standard requirements for this temper, according to ASTM B601, are shown in **Table 3**.

Table 1 Depth of the liquid phase obtained in semi-continuous casting under three different regimes

Parameter	Casting in regime 1	Casting in regime 2	Casting in regime 3
Casting speed (mm/min)	70	70	70
Secondary cooling flow rate, Q_{sec} (l/min)	260	310	370
Depth of the liquid phase, h (mm)	850	670	550

Table 2 Chemical composition of the obtained CuNi1.5SiP alloy slabs under three casting regimes (wt%)

Casting regime	Ni	Si	Zn	Sn	Pb	Fe	P	S
Regime 1	1.4000	0.2650	0.1130	0.0162	0.0029	0.0500	0.0166	0.0038
Regime 2	1.3900	0.2600	0.1211	0.0141	0.0022	0.0325	0.0166	0.0034
Regime 3	1.3800	0.2600	0.1163	0.0106	0.0020	0.0334	0.0197	0.0034

Table 3 Physical and mechanical characteristics of CuNi1.5SiP alloy strips

Casting regime	Thickness of strips (mm)	Tensile strength, R_m (MPa)	0.2% yield strength, (MPa)	Elongation, $A_{L50\%}$ (%)	Vickers hardness, HV	Electrical conductivity (MS/m)
Regime 1	0.8 mm (after annealing)	460	389	15	138	36.8
Regime 2		463	407	15	138	35.6
Regime 3		441	380	16	135	36.6
	Requirements for ¼ hard temper	420 - 480	360	> 10	125 - 150	34.8 (60% IACS)

The cast CuNi1.5SiP slabs were preheated in a three-zone heating furnace at a temperature of 870 °C for 6 hours and were hot rolled on a duo reversible rolling mill. Hot rolling was carried out in 12 passes, from an initial slab thickness of 240 mm to a final thickness of the hot-rolled sheet of 21 mm (91 % reduction). After hot rolling, the coils were placed in a bell annealing furnace at 600 °C for 6 hours, during which a degassing process takes place, in which the gases closed in the metal during crystallization can diffuse and leave it. The technological process continues with milling, during which the surface is cleaned of oxides and surface defects.

To obtain a strip in ¼ hard temper, a three-stage cold rolling process was applied. In the first stage, cold rolling was carried out on a quarto reversible rolling mill in 10 passes, in which the thickness was reduced from 18 mm to 1.8 mm (reduction 90 %). The second stage of cold rolling was carried out in 3 passes - the thickness was reduced to 0.98 mm (45 % reduction). After that, the strip was subjected to annealing at 470 °C for 1 h, in order to remove internal stresses caused by cold working and to achieve complete recrystallization and homogenization of the structure. After annealing, the strip was finally cold rolled (third stage) with 18% reduction, to an exact final size - 0.8 mm. In order to achieve mechanical properties corresponding to ¼ hard temper, the cold rolled strip was subjected to annealing, which was carried out in a horizontal line for annealing of strips. In the line, the heating temperature is 450 °C, and the metal moves at a constant speed of 42 m/min.

To determine the properties of strips, standard mechanical tests (EN ISO 6892-1) were carried out in uniaxial tension using a Zwick/Roell testing machine. To determine the hardness of the strips, Vickers hardness tests (EN ISO 6507-1) were carried out using an Instron hardness tester. Tests were carried out to determine the electrical conductivity using a Sigma electrical conductivity tester. The test results are presented in **Table 3**.

3. RESULTS AND DISCUSSION

3.1 Effect of secondary cooling on the crystallization process

The process of semi-continuous casting in a vertical crystallizer is one of the main and highly efficient methods for producing billets from copper and copper alloys. The crystallizer is a short, intensively water-cooled mold, into which the metal is poured, the block is pulled down. A deep V or U-shaped liquid zone is formed in its core [14]. The length of the billet, respectively the depth of the well, directly depends on the casting speed and the thickness of the billet; a deeper well increases the risk of defects and breakthrough of liquid metal, it is necessary to find an optimal balance between casting-crystallization parameters and billet geometry [14].

The density, homogeneity and quality of the casting depend on the formation of the solid phase and the development of the metallosstatic liquid zone. In order to successfully manage the size of the liquid zone it is necessary to apply strictly controlled two-stage cooling. Since copper has high thermal conductivity, intensive secondary cooling rapidly shrinks the liquid zone in depth and accelerates crystallization of the billet. To determine the influence of the secondary cooling, three slabs were cast at a constant casting speed and three secondary cooling regimes, characterized by different flow rates of cooling water injection onto the metal, Q_{sec} [l/min]. The depth of the liquid phase was measured during the semi-continuous casting; the results are

averaged and presented in **Table 1**. The experimental data, together with their mathematical description (in graphical and analytical form), are presented in **Figure 1**. With increasing cooling water flow rate (casting speed is constant), the depth of the liquid phase decreases and the crystallization front shifts upward along the casting axis, as a result of the accelerated heat removal in the crystallizer.

3.2 Casting defects control

Casting defects are often transferred to the final product, which requires strict control at this stage. The slabs produced under the regimes 1, 2 and 3 were subjected to non-destructive control in order to identify possible defects in the slabs (**Figure 2**). Based on visual inspection, it was found that the surface of the plates was of good quality and no casting defects were observed. This is evidence that during casting in the experimental regimes 1, 2 and 3, crystallization along the axis of the billet proceeded stably.

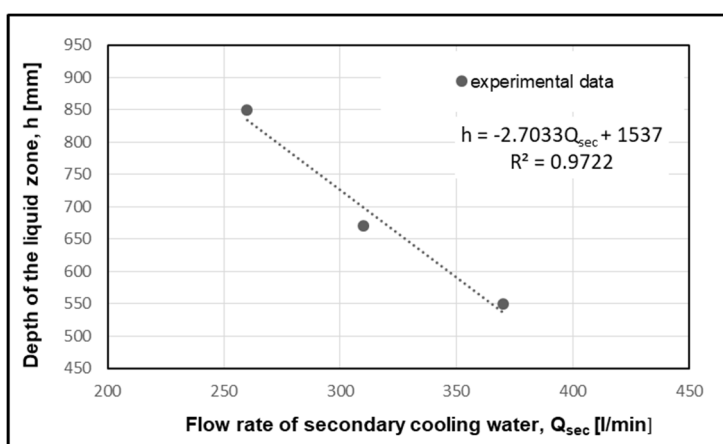


Figure 1 Dependence of the depth of the liquid zone on the flow rate of secondary cooling water; constant casting speed

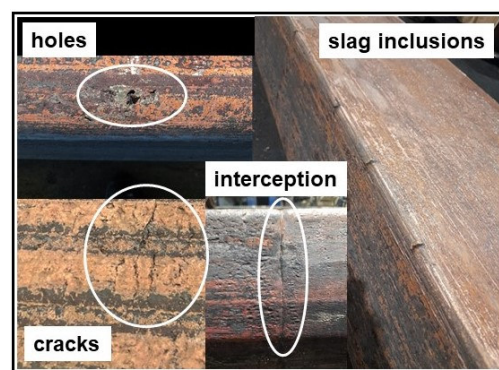


Figure 2 Typical casting defects in semi-continuous casting in a vertical crystallizer

The three cast slabs in modes 1, 2 and 3 were subjected to a penetration test to detect possible internal casting defects. For this purpose, the front and rear ends of the slabs, corresponding to the beginning and end of the casting process, were cut off at a distance of 20 mm from the edge. The cross-sections of both ends of the slabs were treated using a standard method with colored penetrants to reveal internal defects. The test is based on the good permeability and capillary action of the penetrants, and the type, location and size of the internal defects that appeared were assessed visually, **Figure 3**.

The comparative analysis of the results shows that when casting in regime 1, at the front end of the slab (beginning of casting) very small holes are observed in the central zone, indicated by a square in **Figure 3a**, in contrast to the rear end of the slab (end of casting), where larger holes are found that extend across the width of the slab, indicated by an oval in **Figure 3b**. This proves that the observed defects appeared as a result of metal shrinkage during crystallization. This conclusion is supported by the fact that similar defects were not observed in the plates cast in regimes 2 and 3 (**Figure 3**), where the secondary cooling water flow rate was increased and a decrease in the metallostatic liquid phase was found (**Figure 1**). It was concluded that sufficient secondary cooling is essential for reducing casting defects and achieving high productivity in semi-continuous casting. On the one hand, increasing Q_{sec} limits the conditions for the development of internal porosity and improves the density of the material. On the other hand, for subsequent plastic deformation processes, a softer material (obtained at a low crystallization rate) is sought to reduce energy loss during deformation. This requires in-depth cooling studies to optimize the microstructure [14]. The present study found that with insufficient secondary cooling, an extended liquid zone is present in the slab, creating conditions for

gas retention, the formation of micropores and shrinkage cavities. These defects are undesirable, since during plastic deformation they manifest themselves as surface imperfections and lead to an increase in scrap.

3.3 Rolling processes and final testing of the produced strips

For quality control, the rolled strips were subjected to visual inspection of the surface to detect possible surface defects resulting from the deformation processes and/or from casting defects that appeared after rolling. It was found that in the strip obtained by rolling the slab cast in regime 1, surface elongated bubbles were found that appeared after cold rolling, **Figure 4**. The observed defects are the result of internal casting defects. The presence of the described defects is evidence of the direct relationship between the parameters of secondary cooling and the quality of the final strip. This is evidence of the direct relationship between the parameters of secondary cooling and the quality of the final strip. It was confirmed that at a lower intensity of secondary cooling (in l/min) conditions are created for an extended liquid zone and difficult evacuation of dissolved gases, as well as for the formation of micropores and cavities as a result of metal shrinkage. Strips produced from slabs cast in regimes 2 and 3 have improved structure and homogeneity compared to the strip produced from the slab cast in regime 1. The formation of the above-described defects was significantly reduced. This confirms the positive influence of the increased intensity of secondary cooling on limiting porosity in the metal billet and defect formation in the rolled products.

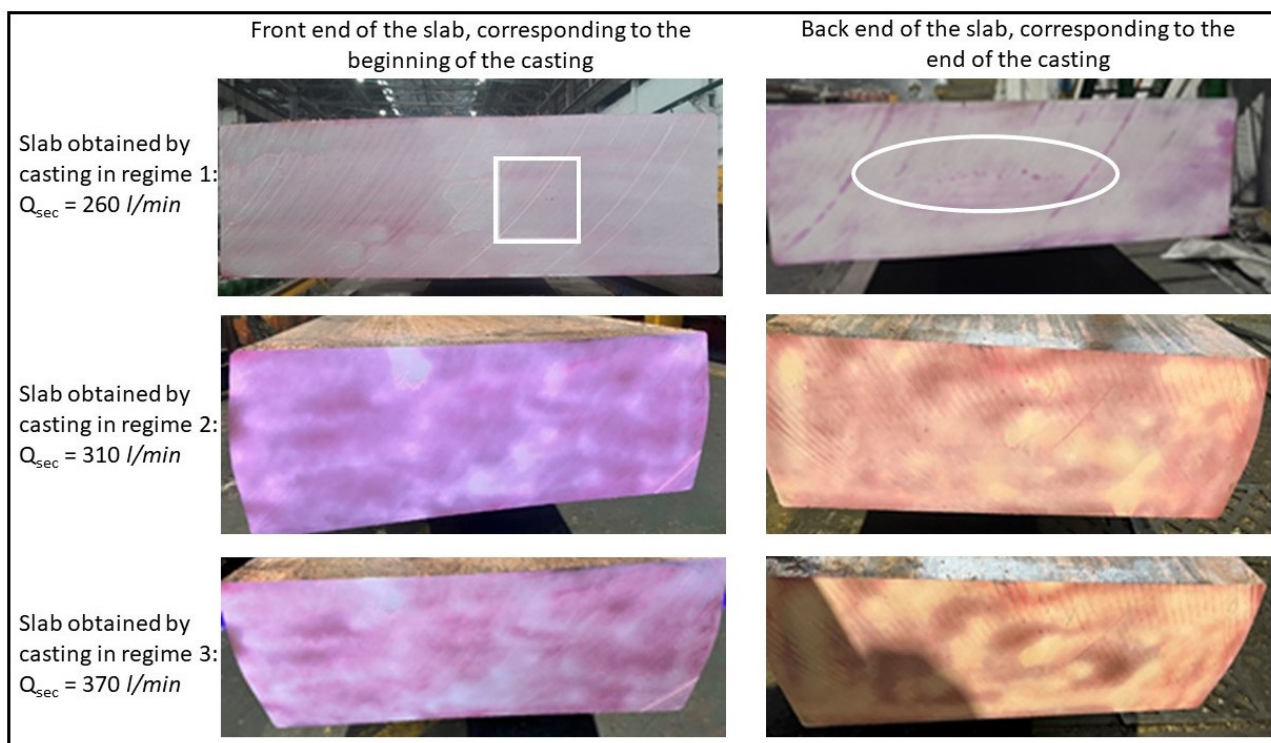


Figure 3 Results of penetrant testing to detect internal defects in slabs produced under the three regimes - cross-section of the slab, corresponding to the beginning and the end of the casting

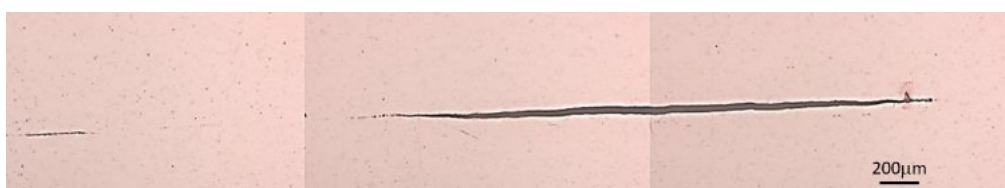


Figure 4 Microphotographs of defects on the surface of rolled strip

In order to establish the final physical and mechanical properties of the produced strips, tests were carried out and the results are presented in **Table 3**. Analysis shows that all produced strips have the desired physical and mechanical properties. However, in the slab cast under regime 1, primary casting defects were found, which appeared on the surface of the strip after rolling in the form of elongated bubbles, **Figure 4**. These defects were cut out, which led to an increase in technological scrap, respectively, metal consumption.

The final physical and mechanical properties of the produced strips were determined, **Table 3**. The analysis shows that all rolled strips were produced in 1/4 hard temper, i.e. they meet the quality requirements. However, in the slab cast in regime 1, casting defects were found, which appeared on the surface of the strip after rolling in the form of elongated bubbles, **Figure 4**. To obtain a quality strip, these defects were cut out, which led to an increase in metal scrap.

4. CONCLUSION

In this study, three semi-continuous casting processes of a Cu alloy were examined, carried out in an industrial environment. At a constant casting speed, the influence of different secondary cooling regimes on the depth of the liquid phase and its subsequent influence on the formation of defects in rolled strips was analysed. The quality of the copper strips, obtained from the slabs cast under different regimes, was established by: (a) visual inspection - casting defects in the slabs and surface defects in the strips after rolling were established; (b) physical and mechanical tests - electrical conductivity, hardness and mechanical properties were determined. It was established that quality strips in a 1/4 solid state were obtained from the three slabs.

The quality control of the produced slabs and rolled strips from them showed that there is a direct relationship between the depth of the liquid phase during casting and the quality of the final product: (a) at the lowest cooling flow rate an increased tendency to the formation of internal gas porosity is observed, which subsequently manifests itself as surface bubbles after rolling; (b) at higher secondary cooling rates a significant reduction in the liquid zone depth was found, resulting in better surface characteristics after plastic deformation treatment. By increasing the secondary cooling flow rate (in the studied ranges), increased productivity and quality during casting is achieved, with a subsequent reduction in defect formation in the strips. The produced strips have high surface quality and suitable physical and mechanical properties for the production of reliable electrotechnical components with a long service life.

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