International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 19 (2017) pp. 8492-8501

The Effect of Electromagnetic Stirring on the Homogenization of the Temperature and Composition of a Copper Alloy

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Abstract

One of the most important advances made in the field of solidification in recent years is the use of electromagnetic forces, these forces being created by a sliding and / or rotating electromagnetic field. Among the beneficial effects of electromagnetic stirring, mention may be made of: reducing the defects caused during casting; Homogenization of temperature and chemical composition; Reduction of overheating; And reducing the crystal size favoring an equiaxed structure. This electromagnetic stirring is currently in frequent use in continuous casting.

We conducted this research, to show the effect of electromagnetic stirring on the homogenization of composition and temperature. The work consisted of an experimentally study of the solidification of copper and then the copper tin alloy. For the temperature we proceeded by measuring the temperature inside the liquid metal (pure copper). For the homogenization of the composition, X-ray fluorescence analysis (copper-tin alloy) was used. All these experiments were carried out initially without stirring and in a second step with electromagnetic stirring.

For the copper alloy used which is 2% tin, its composition has been determined (% Sn and% Cu) using X-ray fluorescence analysis at different points of each ingot. The beneficial effect of electromagnetic stirring was thus demonstrated on the homogenization of the composition.

The theoretical study of the electromagnetic stirrer was based on the mathematical model of Y. SUNDBERG for the calculation of the average agitation force and speed. This model considers a laminar flow, it uses the fundamental wave of the magnetic field while making other simplifying assumptions.

Keywords: Electromagnetic stirring, Copper structure, equiaxed structure.

INTRODUCTION

In the solidification processes among the problems encountered is that of the structure obtained. In fact, the columnar crystals dominate instead of those which are desirable, that is to say the equiaxed crystals. And this takes place in the important case of copper and its alloys. To remedy this problem, electromagnetic stirring has shown its effectiveness. As shown in the continuous casting processes, this agitation makes it possible to homogenize the temperature of the metal and its chemical composition and to reduce the superheat. In this framework, the main objective of our study is to demonstrate the effect of stirring on the structure of copper and one of its alloys. Thus experiments were carried out to solidify the copper and a copper-tin alloy with stirring and without electromagnetic stirring.

Since the development of the electromagnetic stirrer was essential for our experiments, current measurements were made in the stirrer coils as well as measurements of the electromagnetic induction.

The means of measurement are essential for proving the effects of stirring during solidification and on the products obtained. Thus, for the temperature, suitable thermocouples were used for the measurements in the liquid metal, and in order to characterize the homogeneity, X-ray fluorescence analysis was used

The design of our stirrer was based on a mathematical model inspired by Y. Sandberg. Using this model, the average stirring force and the velocity of the liquid metal were calculated...

PRESENTATION OF EXPERIMENTAL WORK.[3]

Our system is based on experimental model of H.LOWRY and A.KLEIN [3]. Simpler design, it uses electromagnetic stirring that is a new promising method using the linear motor principle. In this method the sliding field promotes separation of the grains on the walls and gives a greater extension in the equiaxed zone in the center of the ingot. An essential feature of the equiaxed zone is the size of grains contained therein. In our research subject we shall therefore validate the theory of A. Ohno. In this purpose we shall use an electromagnetic stirrer to move the liquid metal during solidification; this will allow to extract the nuclei formed on the wall of the crucible prior to growth and to promote solidification of equiaxial grains.

THE LEVITATION CASTING PROCESS

Before presenting our experimental dispositive, we present now a different system that is the levitation casting process [3] which has the same objectives, after this description we shall present the principles of our model.

Solidification tests make trolleys are using this experimental model, for simulating the continuous casting process with 25kg mass of molten metal. In figure 1 we can see the experimental model

Based on the interaction between the hydrostatic pressure in the liquid metal column and the gravitational force that suppresses the adhesion and friction at the interface between the cooled mold and the solidified product, the pressure is writing using a block which moves in the middle of a melting furnace to push the liquid metal, which supplies permanent the solidification zone. The solidification zone is equipped with a sliding field stirrer vertical mold and which one does not specify the nature of the material. The solidified ingot, 12mm in diameter, is pulled up at a speed of 60 to 70 mm / min. once the metal enters the mold under the conjugated effect of pressure and electromagnetic, forces are exerted produce a pinching of the liquid metal column, a space of 25 microns (0.001 inches), is created to the interface between the mold and the solidified product, and its minimizes friction with the wall of the product and ensures better surface quality.

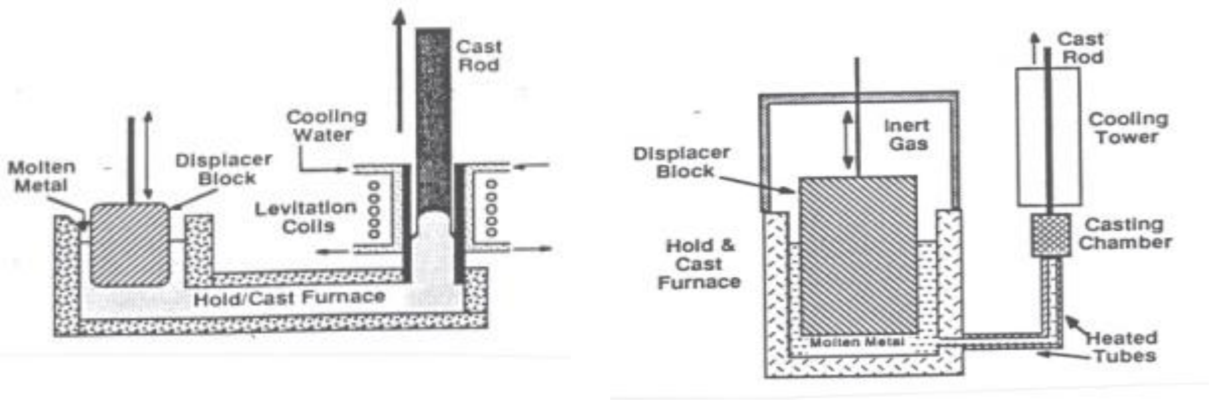

Figure 1: component of the levitation casting process

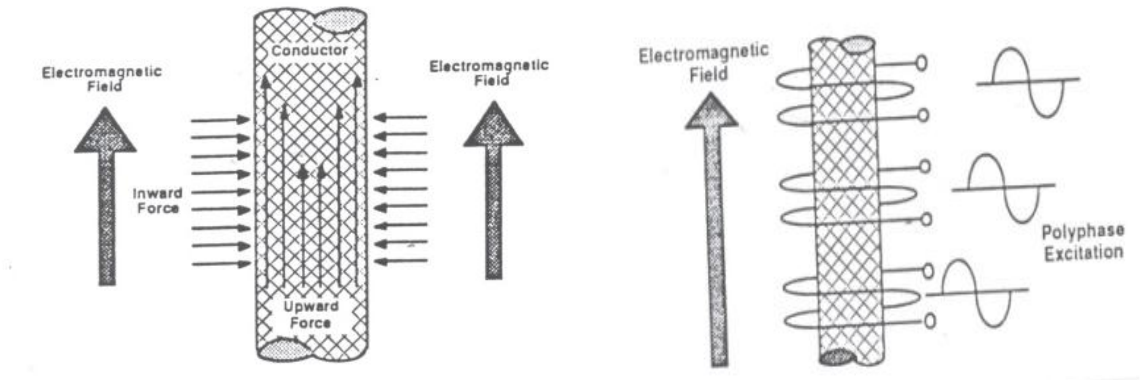

Figure 2: Component of the levitation casting process model. Hugh R;Lowry [3]

DESCRIPTION OF OUR EXPERIMENTAL

Experimental device used in the solidification test is composed of [1]:

- ✓ An induction furnace which is an enclosure for melting metal in a graphite crucible.
- ✓ A second enclosure which is an electromagnetic sliding field stirrer.
- ✓ A gas ring for cooling the crucible.
- ✓ A gas nozzle for cooling the crucible by the bottom.
- ✓ A mechanism for moving the crucible with its contents of liquid metal between the furnace and the solidification area. The descending speed of the crucible in the solidification zone is variable.

In figure 3 we can see the experimental model of solidification tests.

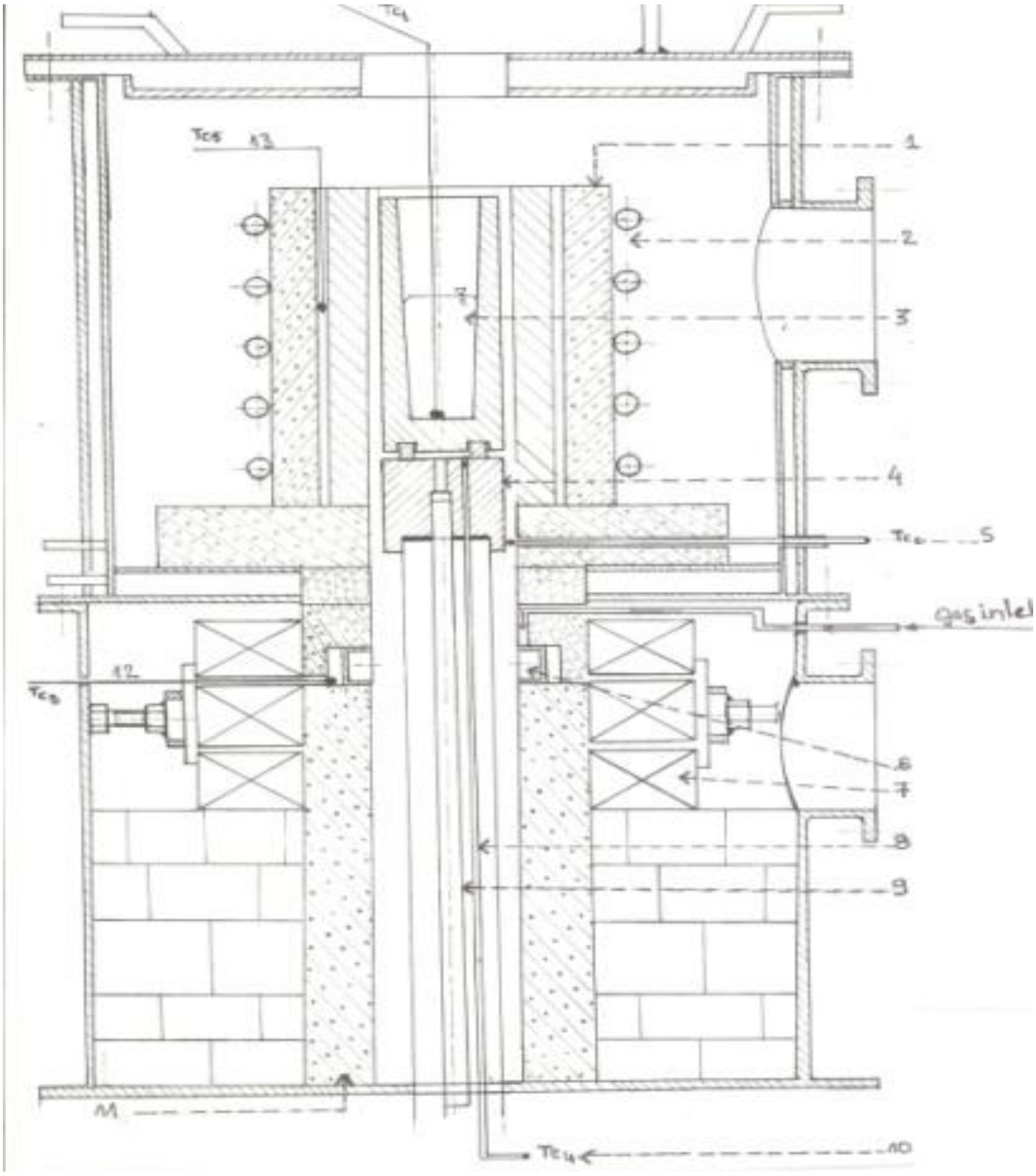

Figure 3: Experimental model of solidification tests [1]

1: refractory cylinder, 2: furnace coil, 3: molten copper in graphite crucible, 4: graphite holder of crucible, 5: thermocouple, 6: gas cooling crown, 7: stirrer coils, 8: a piston for the displacement of the crucible, 9: a pipe for the passage of cooling gas, 10: thermocouple, 11: refractory cylinder, 12: thermocouple, 13: thermocouple Pt-Rh18, Tc1: thermocouple in the metal bath

THE ELECTROMAGNETIC STIRRER

Our stirrer is of cylindrical type; in Figure3 we can see the details of this stirrer.

The stirrer consists of three cylindrical coils aligned vertically on the same axis and supplied by a three-phase alternating voltage system. See figure 5 and 6

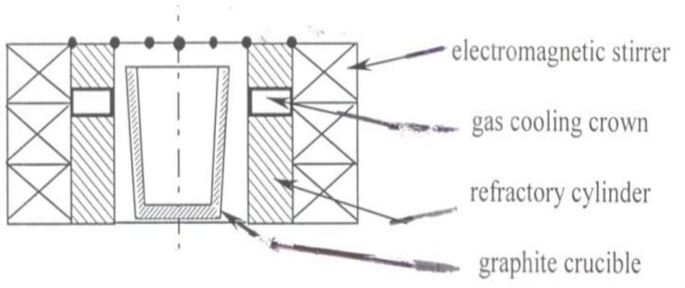

Figure 5: Area of solidification

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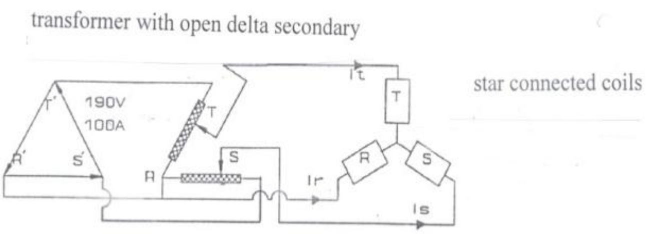


Figure 6: Supply circuit of the stirrer coils R- S- T

The measurements of the currents and voltages in the three coils of the stirrer made it possible to trace the curves in fig7. It is noted that the current in the coil R is greater because it has a mutual with the other two coils. It can also be seen that the electrical characteristics become quasi-linear as soon as the supply voltage exceeds 10 V.

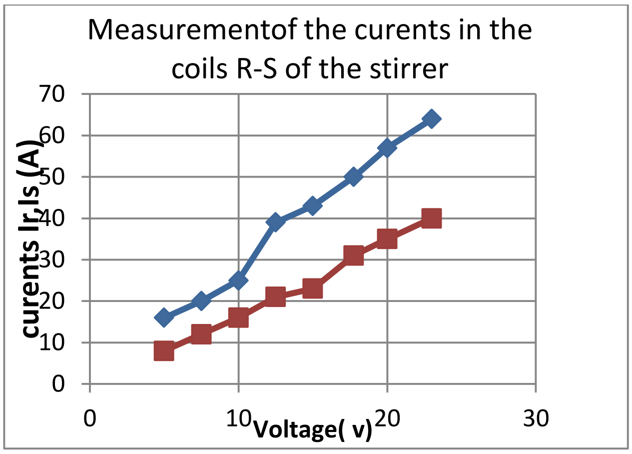


Figure 7: Measurement of the Ir and Is currents in the R-S coil of the stirrer as a function of the voltage.

In inoperative state of our system, we measured the magnetic induction of our stirrer at different distances from the stirrer axe. This measurement was conducted in two orthogonal directions. The points of measurements are indicated in Figure8. The first series of measurements was performed in the presence of the empty crucible and the cooling ring in stainless steel, the second series without the cooling ring. The results are indicated in Figure 9

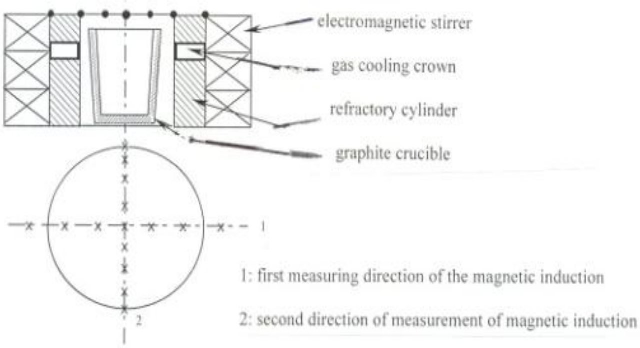


Figure 8: Measuring the magnetic induction in two directions.

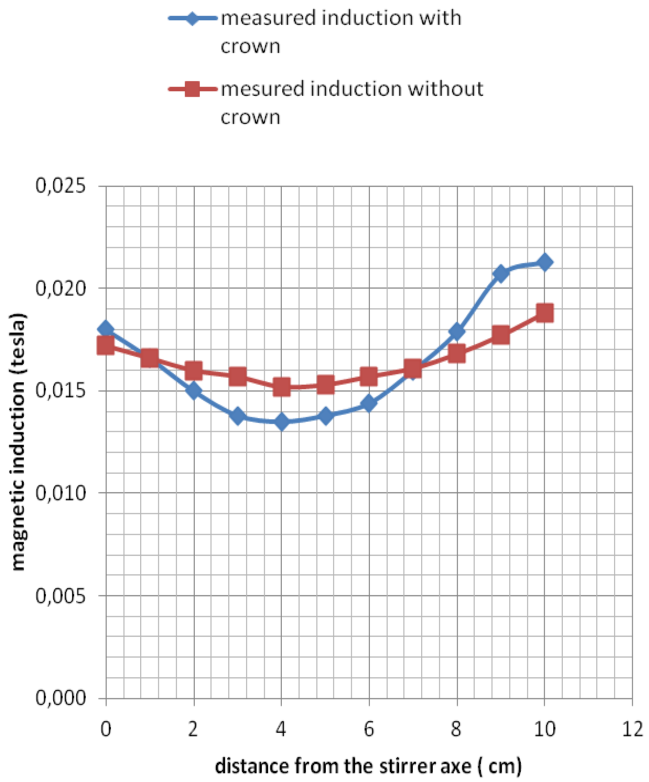


Figure 9: Variation of the magnetic induction (B) as function of the diameter of the stirrer

It can be seen that the presence of the ring of stainless steel and its feeding tube causes a slight attenuation of the magnetic field.

We also measured the magnetic induction with respect to the height of the stirrer at the 0 - 5 - 10 - 15 cm levels from the bottom of the crucible. This measurement was carried out at three points on the walls and in the center of the crucible. The measurement points are marked in figure 10.

The results are indicated in figure 11.

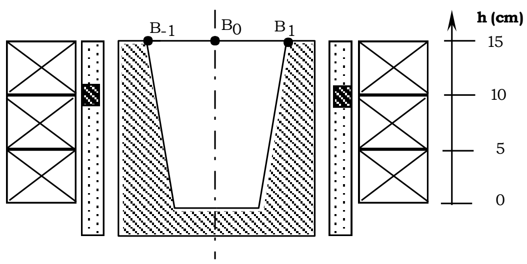
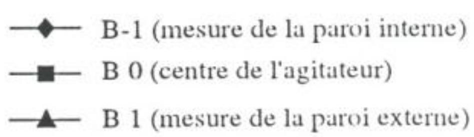


Figure 10: Marking the measuring points of the stirrer induction



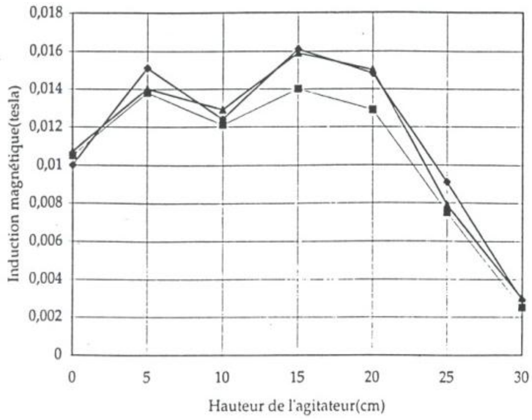


Figure 11 : Variation of the magnétique induction (B) par rapport à la hauteur de l'agitateur

It can be seen from Figure 11 that the effect of the steel crown results in a slight attenuation of the magnetic field in front of this crown (at a height of 10 cm from the bottom of the agitator).

PRINCIPLE OF OPERATION AND MATHEMATICAL MODEL OF THE ELECTROMAGNETIC STIRRER

The three coils of the stirrer supplied by three-phase currents give rise to a field which slides longitudinally in its own direction. This sliding field induces currents in the liquid metal. The interaction between this field and the induced currents gives rise to a non-zero resultant force in the direction of its displacement, ie upwards (according to the LENZ law). The charge moves less rapidly than the field, and therefore the speed of drive of the liquid metal is a small proportion of the synchronous speed.

Inspired by the study of Y S, the equation of the cylindrical electromagnetic stirrer with sliding fields is now presented. This equation will result in formulas giving stirring forces on the liquid metal. [4]

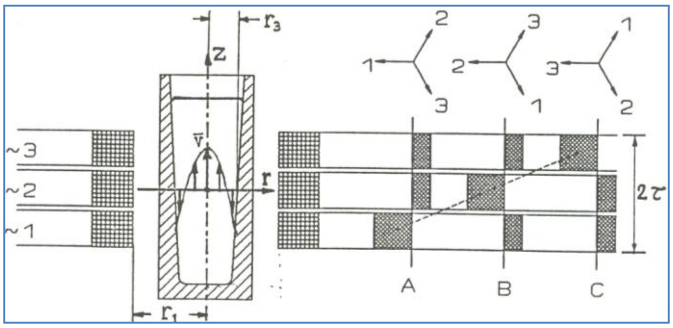


Figure 12: Three-phase winding of a cylindrical stirrer

If ν1 is the frequency of the supply voltage and τ is the polar pitch, the field slips at the speed V1 such that:

$$V_1 = 2\,\nu_1\,\tau \qquad (1)$$

The amplitude of the fundamental sinusoidal wave at the inner cylindrical surface of the stirrer:

$$\hat{H}_{ZO} = As.\ \sqrt{2}.\ f1 \qquad (2)$$

f1 : Winding factor for the fundamental wave

As= Number of ampere turns per meter in rms

The equation of the fundamental wave at the cylindrical surface of the stirrer is

$$H_{Z0} = \hat{H}_{Z0} \cos\left(\frac{\pi Z}{\tau} - \omega_1 t\right) \qquad (3)$$

With $\omega_1 = 2\,\pi\,f_1$ (4)

The axial component of the field in the *stirrer is:*

$$H_Z = \hat{H}_{Z0} \frac{I_0\left(\frac{\pi\ r}{\tau}\right)}{I_0\left(\frac{\pi\ r_1}{\tau}\right)} \cos\left(\frac{\pi Z}{\tau} - \omega_1 t\right) \qquad (5)$$

And the radial component is:

$$H_r = \hat{H}_{Z0} \frac{I_1\left(\frac{\pi\ r}{\tau}\right)}{I_0\left(\frac{\pi\ r_1}{\tau}\right)} \sin\left(\frac{\pi Z}{\tau} - \omega_1 t\right) \qquad (6)$$

r1 The inner radius of the coil

I0, I1: the modified Bessel function of first species

The active height of the stirrer is two pole pitches, i.e. 2.τ

The magnetic field induces currents in the liquid metal. The current density J is calculated by Maxwell's second law

$$\rho \operatorname{rot}\bar{J} = \mu_r\ \mu_0\ \dot{Z}H/\dot{Z}T \qquad (7)$$

$$\rho\left(-\frac{\partial\bar{J}}{\partial Z}\ \bar{J}_r + \frac{\partial\bar{J}}{\partial r}\ \bar{J}_Z\right) = -\mu_0\,\mu_r\left(\frac{\partial\bar{H}_r}{\partial t}\ \bar{i}_r + \frac{\partial\bar{H}_Z}{\partial t}\ \bar{i}_Z\right) \qquad (8)$$

ρ: liquid metal resistivity

The frequency of the induced current □3 is lower than the frequency of the current in the agitator

$$\nu_1\nu_3 = \nu_1 - V_3 / 2\,\tau \qquad (9)$$

Where V3 : is the speed of the melt

If the translational field is cylindrically symmetrical, the current flows in the liquid metal in circular paths in planes perpendicular to the axis of the stirrer.

The force of Lorentz is calculated as follows:

$$\bar{F} = \bar{J} \times \bar{B}; \qquad \bar{B} = \mu_r \mu_0 \bar{H}$$

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 19 (2017) pp. 8492-8501
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$$\bar{F} = \mu_r \mu_0 \bar{J} \left(\bar{H}_r \bar{i}_r + \bar{H}_Z \bar{i}_Z \right) = \mu_r \mu_0 \bar{J} \left(\bar{H}_Z \bar{i}_r - \bar{H}_r \bar{i}_Z \right) \quad (10)$$

$$\frac{\partial \bar{J}}{\partial Z} = \frac{\mu_r \mu_0}{\rho} \frac{\partial H_r}{\partial t} \quad \rightarrow \quad \bar{F}_r = \mu_r \mu_0 \, J H_Z$$

$$\frac{\partial \bar{J}}{\partial r} = \mu_r \mu_0 \frac{\partial H_Z}{\partial t} \quad \rightarrow \quad \bar{F}_Z = - \mu_r \mu_0 \, J H_\rho$$

$$\bar{F}_Z = \mu_r \mu_0 2 \alpha_3^2 \frac{\tau}{\pi} \hat{H}_{Z_0}^2 \left[\frac{I_1\left(\frac{\pi r}{\tau}\right)}{I_0\left(\frac{\pi r_1}{\tau}\right)} \right]^2 \sin^2\left(\frac{\pi Z}{\tau} - \omega_1 t\right) \quad (11)$$

Axial mean force per square meter along Z axis is :

$$\bar{F}_Z = \mu_r \mu_0 2 \alpha_3^2 \frac{\tau}{\pi} \hat{H}_{Z_0}^2 \frac{r_3}{2} \left[\frac{H_{Z_3}}{H_{Z_0}} \right]^2 \phi\left(\frac{\pi r_3}{\tau}\right) \sin^2\left(\frac{\pi Z}{\tau} - \omega_1 t\right) \quad (12)$$

Where: J0, J1, J2 are Bessel functions

r3 : liquid radius

$$\bar{H}_Z = \mu_0 \mu_r \alpha_3^2 \frac{r_3 \tau}{\pi} \hat{H}_{Z_0}^2 \left[\frac{H_{Z_3}}{H_{Z_0}} \right]^2 \phi\left(\frac{\pi r_3}{\tau}\right) \sin^2\left(\frac{\pi Z}{\tau} - \omega_1 t\right)$$

This mean force is a sinusoidal function of time t

Taking the average and replacing. $\sin^2 (\pi Z/\tau - \omega_1 t)$ by 1/2

$$\bar{F}_Z = \mu_r \mu_0 \alpha_3^2 \frac{r_3 \tau}{2\pi} \hat{H}_{Z_0}^2 \left[\frac{H_{Z_3}}{H_{Z_0}} \right]^2 \phi\left(\frac{\pi r_3}{\tau}\right) \quad (13)$$

Where $\alpha_3^2 = \dfrac{\mu_r \mu_0 \omega_1}{2\rho} = \dfrac{\mu_r \mu_0 \pi \nu_1}{\rho}$

And $\hat{H}_{Z_0} = A_s \sqrt{2} = n I f_1 \sqrt{2}$

The stirring mean force is [4]:

$$\bar{f}_Z = \frac{\mu_r^2 \mu_0^2}{g} \nu_1 r_3 \tau n^2 I^2 f_1^2 \frac{\left[I_1\left(\frac{\pi r_3}{\tau}\right) \right]^2 - I_0\left(\frac{\pi r_3}{\tau}\right) I_2\left(\frac{\pi r_3}{\tau}\right)}{I_0\left(\frac{\pi r_1}{\tau}\right)^2} \quad (14)$$

In the following we give the calculation of the mean stirring force, and the average speed of liquid metal, the Bessel function is developed to the 10th term, the following terms are negligible. The result of this calculation is given in Figure 13, and 14

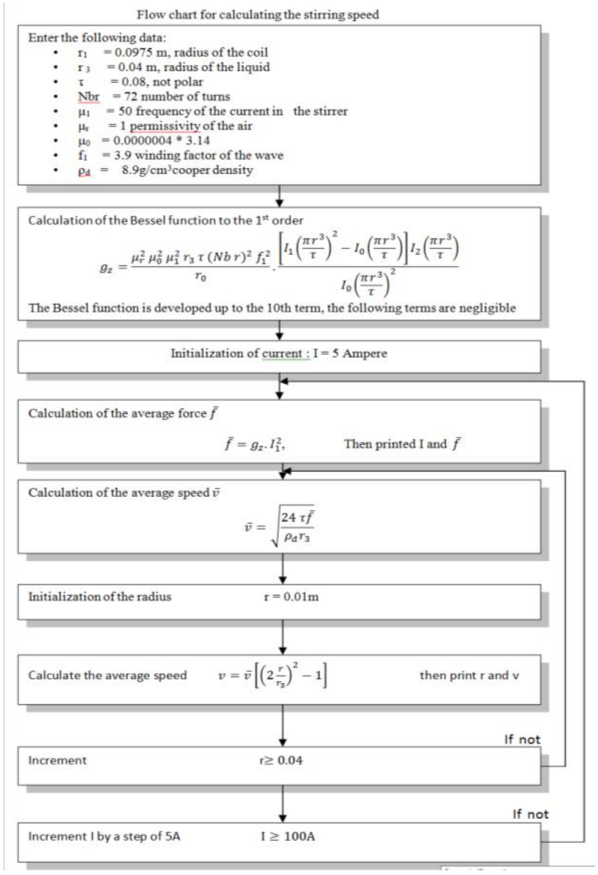

Figure 13: Chart for calculating of stirring speed

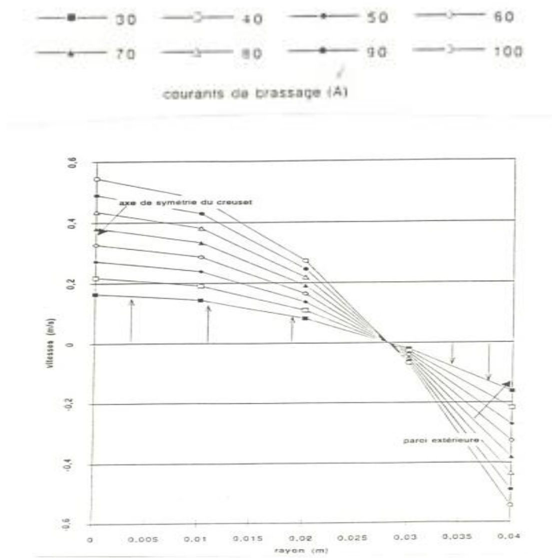

Figure 14: Variation of the velocity of liquid metal as a function of the radius of the crucible calculated at different intensities of the current

The controlling parameters of the crystal size are:

Overheating: it is defined as a temperature difference between the casting temperature and the liquidus. With low overheating, the number of equiaxed crystals increases and, consequently, their size decrease. When overheating increases, the number of nuclei formed is limited, and most are remelted, therefore, few equiaxed crystals grow, their size is larger and the length of columnar crystals (columnar) is greater. And also the tensile strength decrease

Presence of a solute in the metal: this parameter increases the solidification range (temperature difference between solidus and liquidus). [9,10]

Nature of the mold: its cooling capacity promotes germination, and its surface roughness facilitates separation.

Composite mold: promotes germ formation by the presences of a wetting matrix in the mold, these germs are hindered in their growth by the presence of the non wetting material in the mold and therefore are easily torn from the wall of the mold.

Metal stirring: it sets in motion the molten metal by the action of an electromagnetic field and controls the solidification, eliminating overheating by standardizing the grain structure and the composition of the product. Stirring also greatly accelerate the elimination of overheating trough the mass of liquid to the mold wall .The stirring effect removes the preferential orientation of solidified product which then consists of isotropic equiaxed crystals, and this is an advantage for forming operations.

The crystal grain refiners: are germinant agents added in the liquid metal as a solid particle, they can serve as a site for nucleation and they strangle the basis of crystals which germinate on the mold walls. This phenomenon promotes the separation of the seeds from the mold wall. For a columnar structure, it is necessary, unlike the case of equiaxed crystals, to form first a stable solid skin on the wall of the mold and then prevents separation of crystals from this wall.

HOMOGENIZATION OF TEMPERATURE IN THE CASE OF PURE METAL

The used experimental device in the solidification test (figure 2)

In the case of copper, we measured the temperature inside the liquid bath. For this purpose, 3 thermocouples were placed in the crucible along the vertical axis. The first at the bottom of the crucible; the second at 5 cm from the bottom and the third at 10 cm. To show the effect of the agitation on the homogenization of the temperature, these measurements were carried out without stirring and then with stirring.[6,7]

In figures 15 and 16, it is possible to follow the variation of the temperatures in the case with stirring and without stirring

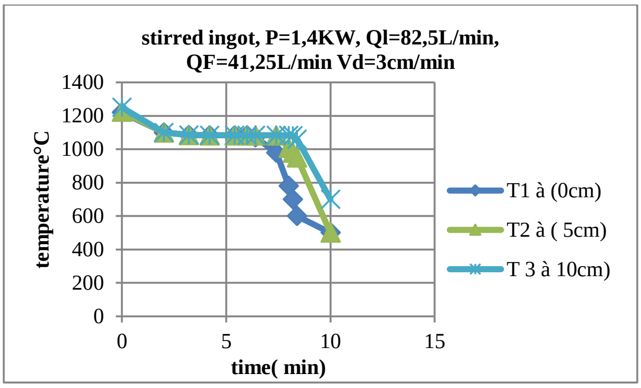

Figure 15: Temperature variation in the case with stirring.

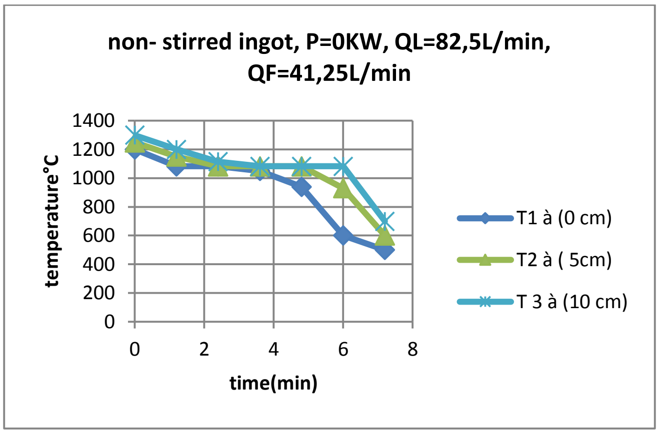

Figure 16: Temperature variation in the case without stirring.

HOMOGENIZATION OF THE COMPOSITION THE COPPER ALLOY [8,9]

The solidification of the alloys is often accompanied by a rejection of the solute towards the liquid phase, which causes a difference in composition in the solidified products, hence the inhomogeneity of the product obtained. The purpose of the studies carried out is to show the effect of agitation on the chemical composition of a 2% Sn copper alloy. To determine the chemical composition, a few samples of the ingot were cut out and analyzed by the X-ray fluorescence method. The results of these analyzes are shown in figure. 17 and 18

Figure17. Concerning an ingot made without agitation, there is seen a fluctuation of the percentage of tin according to the position in the ingot, a fluctuation which is very marked in the upper part of the ingot. The statistical study of this percentage gives a standard deviation of 1,06

Figure18 shows an ingot made with agitation, showing a small variation in the percentage of the tin according to the position in the ingot. The statistical study of the percentage of tin gives in this case a standard deviation of 0,18

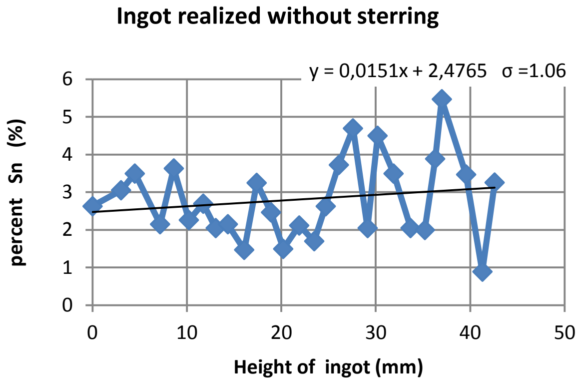

Figure 17: Variation of tin proportion following the height of the ingot

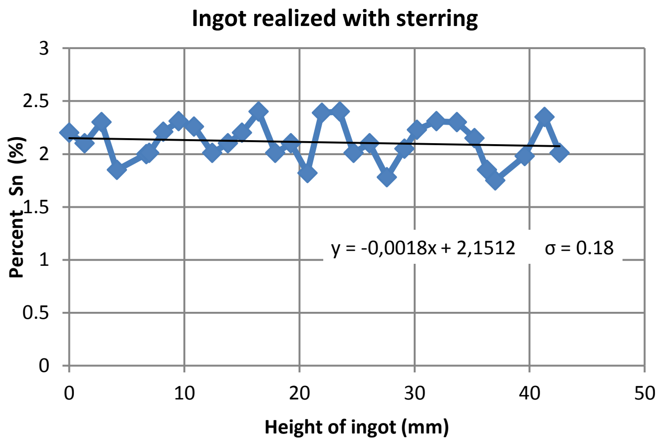

Figure 18: Variation of tin proportion following the height of the ingot

Temperature measurement in liquid copper relative to the diameter of the ingot:

Remember that the measurements were performed in the following developing conditions:

- Power of the stirrer: P = 0 - 1.4 kW
- Cooling lateral side: QL = 82, 5 l/min, cooling by the bottom QF = 41, 25 l/min.
- descending speed of crucible: Vd = 3 cm/min.

The objective of this experiment is how to vary the temperature in the direction of diameter at a given height, which will allow us to estimate the shape of the solidification front. To do this, we have made a montage that allows one hand to keep the canes upright in the liquid metal and also their attachment to a given height.fig .19 shows schematically the setup used for this measurement.

Three thermocouples in series according to the diameter of the crucible, are protected each one by an alumina rod. The canes are set at a height of 7 cm from the bottom of crucible. The graphite part is placed on the crucible cover, these two parts bearing a 8.5 mm diameter through-holes allow to fix the distance between the alumina rods.

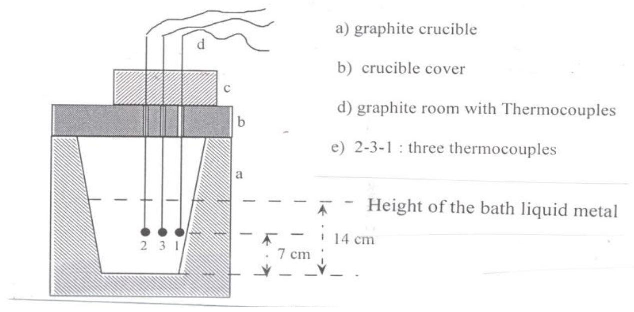

Figure 19: device used to measure the temperature along the diameter

Three thermocouples are placed in the diameter direction in the following order:

Thermocouple 1: in contact with the inner side wall of the crucible

Thermocouple 2: in the center of the ingot

Thermocouple 3 intermediate between 1 and 2.

A: temperature measurement with stirring:

Conditions: h = 7 cm (height from the bottom)

Power of stirrer P= 1, 4 kW

Cooling lateral side QL = 82, 5 l/min, cooling by the bottom QF = 41, 25 l/min

Descending speed of crucible Vd = 3 cm/min

As shown in Figure20. the bath temperature is higher near the walls and decreases going towards the center, this temperature variation shows that the solidification front progresses concavely, see figure below

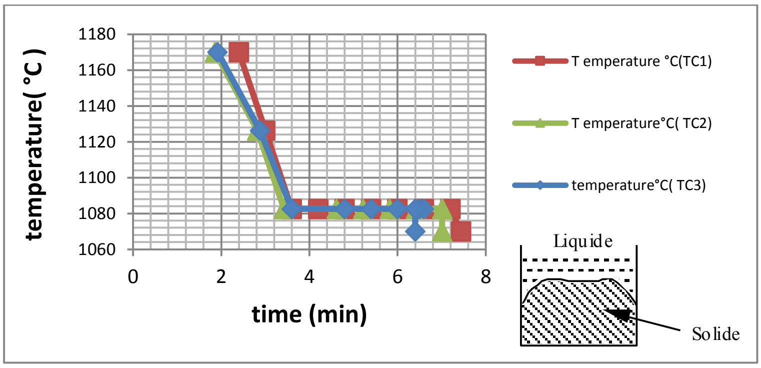

Figure 20: temperature measurement of the diameter of the ingot with stirring

B: Temperature measurement without stirring

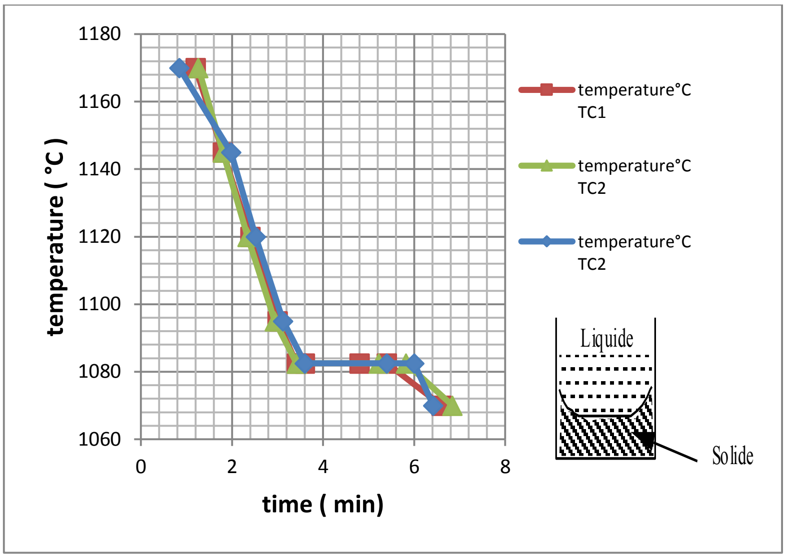

Figure 21: temperature measurement in relation to the diameter without stirring.

Conditions: h =7 cm, P = 0 kW, QL = 82,5 l/min, QF = 41,25 l /min, Vd =3 cm/min

As shown in Figure21. The temperature varied along the direction of diameter of the ingot; the side walls are cold relative to the center of the ingot thereby that the solidification front moves in a convex shape see figure 21.

CONCLUSION

The effect of stirring on the structure of the copper and copper alloy was carried out, we have shown through this study that the size of the copper and copper alloy crystals decreases when the stirring power increase. This was done in our previous work. In this part of the work, it has been shown that the effect or stirring makes it possible to homogenize the temperature of the liquid metal and also makes it possible to homogenize the chemical composition of the alloy. In order to show the effect of stirring on homogenization and on temperature, a temperature measurement technique was used inside the liquid metal, carried out with agitation and without stirring, when the metal is stirred and the heat exchanges are accelerated at the crucible wall. which makes it possible to promote a structure with uniform crystals.

By the X-ray fluorescence measurement method, we determined the proportion of Tin within a stirred and non-stirred ingot; we showed the effect of stirring on homogenization

Electromagnetic agitation has proved its importance with regard to the structure, homogenization and chemical composition, so it can be said that electromagnetic stirring will reach the stage of industrial development.

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