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NUMERICAL SIMULATION OF ELECTROMEGNETIC CASTING OF ALUMINUM ALLOYS

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Abstract:

This work deals with the improvement of surface quality, microstructure of the aluminum alloy ingot by electromagnetic casting using finite element method with the help of Ansys program. Magnetic flux density and magnetic flux density gradient are used as indicators for uniform temperatures distribution and new liquid metal flow. Two models are simulated in this study; the first one represents a solid cylinder with a single coil where the effects of current intensity and frequency on the melt metal are studied. The second model is a hollow cylindrical with outer/inner coils. The effects of current intensity, due to the interaction between the outer and inner coil are studied. The results of the first model simulation indicate three stages with the current increasing. The first one near the center of the ingot enhanced approximately homogeneous behavior, while the increasing occurs gradually in the second and third stages. Also with decreasing of frequency the magnetic flux density at the center of ingot increasing. The second model results of hollow ingot show that the magnetic flux density increases linearly with outer coil current increasing from (85 – 380) A at the same inner coil current value, and the homogeneous behavior enhanced in 0.55 outer/inner coil current ratio also illustrates homogeneous behavior at different current values but with the same ratio.

الخلاصة:

هدا العمل يتعلق بتحسين سطح وتركيب مسبوكة الالمنيوم بواسطة السباكة الكهرومغناطيسية باستخدام طريقة العناصر المحددة بمساعدة برنامج Ansys 5.4. كثافة الفيض المغناطيسي وانحدار كثافة الفيض المغناطيسي استخدمت كمؤشرات لانتظام توزيع درجات الحرارة ونظام جريان جديد للمعدن السائل. نموذجين تمت محاكاتهما في هذه الدراسة الاول يمثل اسطوانة صلدة مع ملف حيث ان تاثيرات شدة التيار والتردد على المعدن المنصهر تمت دراستها.النموذج الثاني يمثل اسطوانة مجوفة مع ملفين خارجي وداخلي حيث ان تاثيرات شدة التيار نتيجة للتفاعل بين الملفين تمت دراستها. نتائج محاكاة الجزء الاول اظهرت ثلاث مراحل مع زيادة التيار. الاولى قرب مركز المسبوكة اظهرت تصرف متجانس تقريبا بينما الزيادة حدثت تدريجيا في المرحلة الثانية والثالثة. ايضا مع نقصان الترددمن (١٠٠ - ١٠) هرتز تزداد كثافة الفيض المغناطيسي في مركز المسبوكة. نتائج النموذج الثاني للمسبوكة المجوفة اظهرت ان كثافة الفيض المغناطيسي تزداد خطيا مع زيادة تيار الملف الخارجي من (٨٥ – ٣٨٠) أمبيرعند نفس قيمة تيار الملف الداخلي، واظهرت تصرف متجانس عند نسبة 0.55 مابين قيمة تيار الملف الخارجي الى قيمته في الملف الداخلي ايضا اظهرت تصرف متجانس عند قيم تيار مختلفة ولكن بنفس النسبة.

KEYWORDS: Electromagnetic Casting, Controlling Heat and Flow, Surface and Structure Improvement, and Ansys program.

INTRODUCTION:

The solidification process is complex in nature and the simulation of such process is required in industry before it actually undertaken. Finite element is used to simulate the heat transfer process accompanying the solidification process. The metal and the mould along with the air gap formation are accounted in the heat transfer simulation. Distortion of casting is caused due to non-uniform shrinkage associated with the process. Residual stresses are induced in the final casting [*Seetharamu*,2001]. Composite casting were manufactured in stir casting process and poured in the sand moulds under external electromagnetic field. Improvement of reinforcing particles distribution can be observed. Electromagnetic field processing positive influence on reinforcing phase distribution and matrix crystallization process was proved. [*Duleba*,2007]. Horizontal direct chill (HDC) casting is an advanced method of producing an aluminum alloy ingot for subsequent thermo mechanical processing into final products, ranging from extrusion to rolling.. The application of the electromagnetic field on the direct chill casting process has been come anew research direction in recent years, and considerable progress has been achieved. Among these application, electromagnetic casting (EMC) [*Zhu*,2008].

The microstructure characterization shows that under the influence of low frequency (30-50Hz) electromagnetic field it is possible to obtain finer and more homogeneous microstructure with reduced porosity. Electromagnetic casting (EMC) is the technology developed as by combining the magnetic hydrodynamic and casting technique. Electromagnetic forces, arising from the interaction of eddy currents induced in the metal by inductor magnetic field, caused an increased flow of the fluid, forced convection, more uniform temperature field and weak gravitation influence thus changing the conditions of solidification. The advantages of EMC reflect in obtaining a better quality of ingots compared to conventional continuous casting process. The structure obtained is finer and more uniform through the cross section, with reduced segregation of alloy element and porosity [*Pataric*,2002]. The multi-physical model taken into account of electromagnetic field, fluid dynamic, heat transfer, solidification, steel quality and process control expresses the real process phenomena qualitatively and/or quantitatively [*Fujisaki*,2004]. The influence of inhomogeneous static magnetic field on a liquid metal flow in insolating planer channel shows an extensive of three regions of flow formation: before, inside and behind magnetic field. In the first region, flow fluctuation are damped; in the second region, new flow with velocity M-shape profile is formed; in the third region, two shear layers near side walls are developed. In an industrial practice in a majority of MHD situations a flow of an electrically conducting fluid is situated in a sufficiently inhomogeneous magnetic field. Owing to the certain technological or design requirements the poles of a magnet system are performed either with a breach of discontinuity or with dimensions that are smaller than a size of a flow. The problem of molten metal control by spatially in homogeneous magnetic fields is getting more important for industrial applications in metallurgy and crystal growth. This method is called also electromagnetic brake, for example, in the process of continuous casting [*Andreev*,1998].

Recently, the electromagnetic casting technique of aluminum alloys attracts attention of researches because it can improve surface quality and as cast structure of ingots.1) A metal melt forms a meniscus under the action of Lorentz force, which reduce the contact between the metal melt and crystallizer and weakens primary cooling intensity, thus improving the quality of ingot surface $[Vives, 1989]$. 2) The forced convection driven by Lorentz force can promote heterogeneous nucleation, and reduce the solute concentration gradient and temperature gradient in melt, simultaneously; it can make the molten pool shallower and the mushy zone wider, leading to improve microstructure of ingot $[Zhang, 2002]$. Electromagnetic field acts on the metal melt, which can strengthen the diffusion of solute element, can increase solute element content in crystalline grain and make them homogeneous $[Dong, 2004]$.

In this work, two models for electromagnetic casting process of 2024 aluminum alloy with the chemical composition (wt pct) Cu 4.5, Mg 1.6, Mn 0.6, and Al balanced are studied by finite element method with the help of Ansys program 5.4. The first one is two dimensional axis-symmetric model of solid cylinder of $\phi 200 \times 30mm$ with a single coil, and the second one is two-dimensional axis-symmetric model of hollow cylinder of $\phi 300 \times 30mm$ with outer and inner coil see **Fig. (1)**.The effects of alternating current of different intensity, and frequency on the electromagnetic field of the first model are analyzed, while the effects of alternating current of different intensity, on the electromagnetic field of the second model are analyzed due to the interaction between the outer and inner coils. Magnetic flux density distribution and magnetic flux density gradient are essential parameters in this study.

1- PROBLEM DESCRIPTION AND THEORETICAL ANALYSIS:

Magnetic flux density distribution and magnetic flux density gradient indicators are used to

(1) electromagnetic force behavior which produce from interaction between the eddy current and magnetic inductive intensity from one side, and to the melt metal properties from the other side.

(2) Lorents force (braking force) which consists of forced convection (rotation component) and potential force or static pressure of the melt, which is responsible of any surface and microstructure improvement in the ingot as shown in **Figs (2 and 3)**.

The problem consists of two regions; the first one contains the metal melt, ingot, inner coil and outer coil, which called the eddy current region. Induced current J_e can be generated by induced electromagnetic force in this region. Where the second region surrounding the first one , free of eddy current, and contains source current, air dielectric, inner and outer induction coil. Electromagnetic field is described by the magnetic vector potential A and electric scalar potential V , the fields vectors are obtain from the potentials $[Biro, 1988]$:

$$B = \nabla \times A \tag{1}$$

$$E = -\frac{\partial A}{\partial t} - \nabla V \tag{2}$$

In first region:

$$\nabla \times v \nabla \times A - \nabla v \nabla . A + \sigma \frac{\partial A}{\partial t} + \sigma \nabla V = 0 \tag{3}$$

$$\nabla.\left(-\sigma\frac{\partial A}{\partial t}-\sigma\nabla V\right)=0 \tag{4}$$

In second region:

$$\nabla\times v\nabla\times A-\nabla v\nabla.A=J_e \tag{5}$$

$\Gamma_{B,}$ the normal component of flux density and $\Gamma_{H,}$ the tangential component of magnetic field density On boundary $\Gamma_{B,}$ $[Biro,1988]$

$$n\times A=0 \tag{6}$$

$$v\nabla.A=0 \tag{7}$$

On boundary $\Gamma_{H,}$:

$$v\nabla\times A\times n=0 \tag{8}$$

$$n..A=0 \tag{9}$$

The boundary conditions on Γ_{12} between the first and second region are as follows:

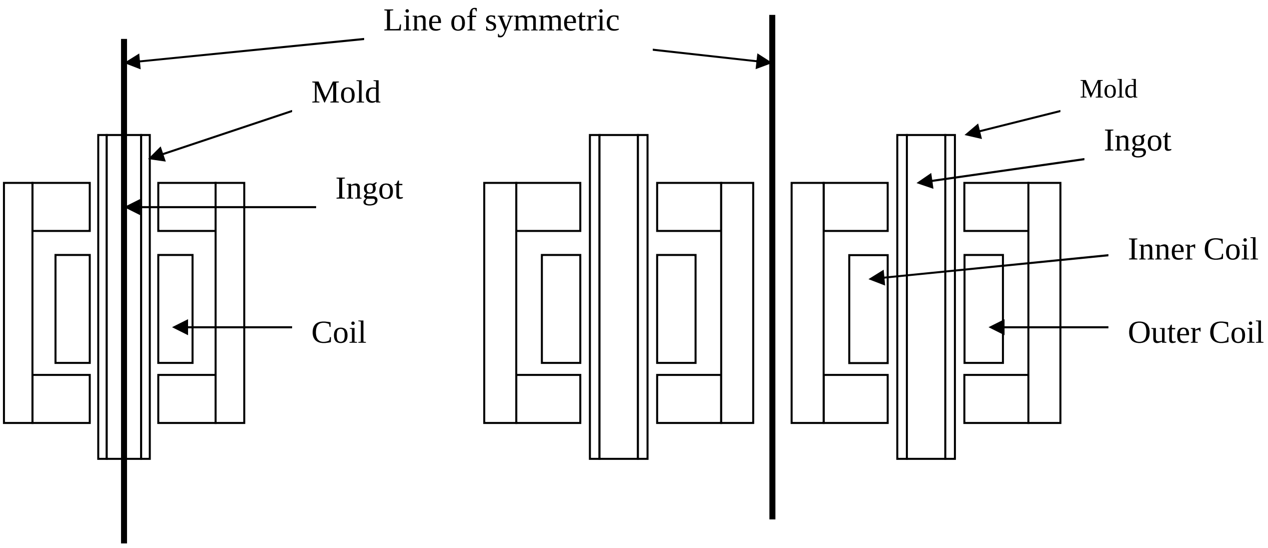
$$A_1=A_2 \tag{10}$$

$$v_1\nabla\times A_1\times n_1+v_2\nabla\times A_2\times n_2=0 \tag{11}$$

$$v_1\nabla.A_1-v_2\nabla.A_2=0 \tag{12}$$

$$n.\left(-\sigma\frac{\partial A}{\partial t}-\sigma\nabla V=0\right) \tag{13}$$

Where the **n** is outer normal on the corresponding surface**,** and the subscripts **1** and **2** refer to quantities in the first and second regions. v_1, v_2 is magnetic reluctivity of first and second region respectively. In numerical calculation, electrical conductivity of metal melt, ingots, and crystallizer are $3.9\times10^{6}1/\Omega m, 3.1\times10^{7}1/\Omega m, and, 1.01\times10^{7}1/\Omega m$ respectively, relative permeability of aluminum alloy, crystallizer and atmosphere are



-a- **-b-**

Fig. (1): a- 2D Axis-Symmetric Finite Element Model of Aluminum Alloy Solid Cylinder (First Model), b- 2d Axis-Symmetric Finite Element Model of Aluminum Alloy Hollow Cylinder (Second Model).

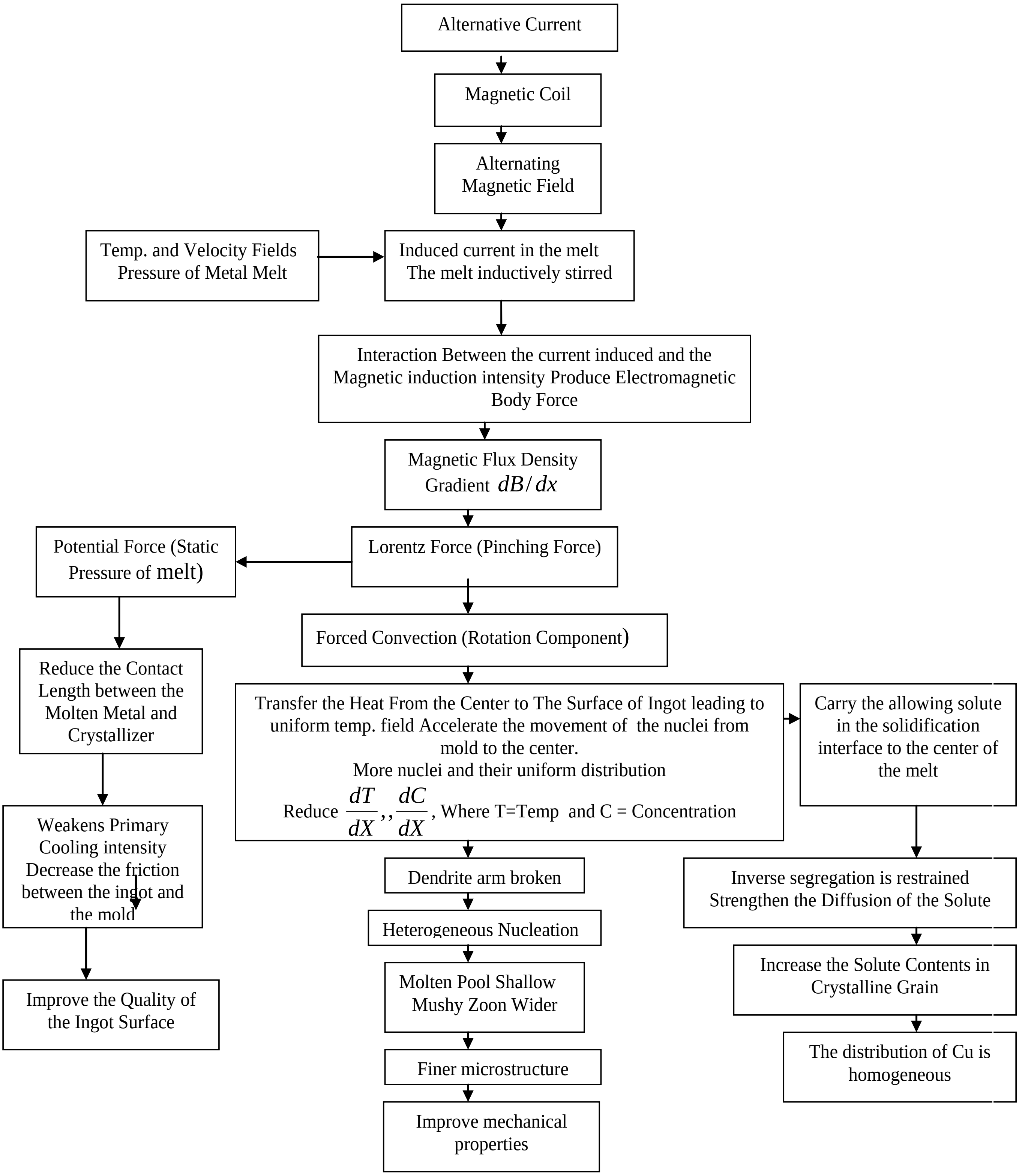


Fig. (2): Flow chart of Electromagnetic Casting Process of Aluminum Alloy.

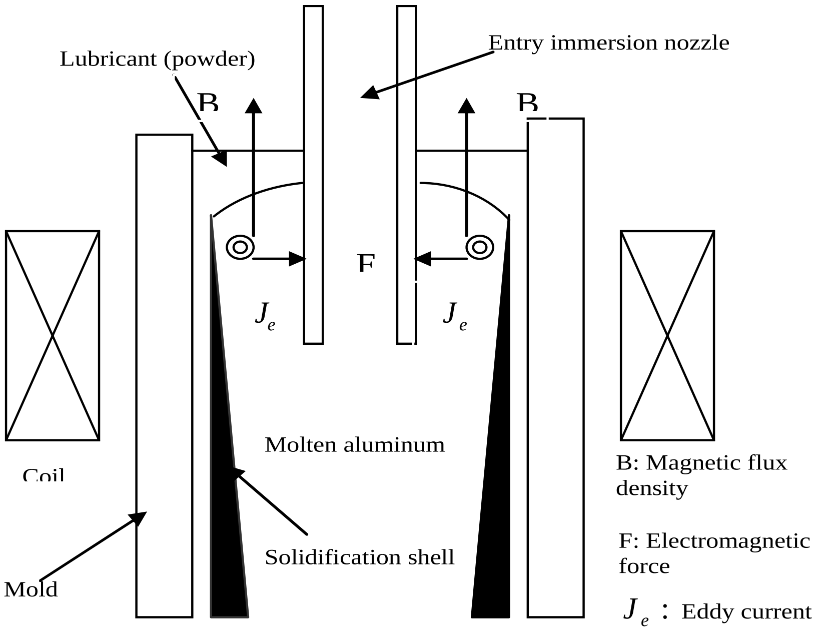


Fig. (3): Schematic of Electromagnetic Casting (EMC) Process. [Zhang,B., Cui,J. and et al., 2002]

2- RESULTS AND DISCUSSIONS:

2-1-Results of The First Simulation:

Qualitative Results: Fig. (4), illustrates the axis-symmetric finite element representation for the first model, **Fig. (5)**, shows the nodal display of electromagnetic field, which clear the magnetic flux density distribution in the model. **Fig. (6):** indicates the 2D magnetic lines of electromagnetic field which mostly concentrated in the center of ingot due to the high current induced in the center of the ingot between two poles of magnet. The high the concentration of these lines the high the magnetic flux density and then high magnetic flux density. **Fig. (7),** shows the vectors loop of electromagnetic field with clockwise direction from top to bottom of ingot. The magnetic induced intensity with eddy current in the melt produce magnetic flux density gradient, which affects on the Lorentz force (Brake force).

Quantitative Results: **Fig. (8)**, shows the magnetic flux density distribution along the vertical line Y draw in **Fig. (6),** which indicates the maximum value at the half distance due to the high current value induced at mid position between two poles of magnet. Two positions where chosen for that testing the first one at the center of the ingot and the second one at the outer surface of ingot. The maximum value of magnetic flux density of the second position is more than that of first one, which means the increasing of this property directed from center of ingot to the outer surface. Therefore measures of magnetic flux density must be taken at position of maximum value along X line draw in **Fig. (6)**. **Fig. (9)** indicates the magnetic flux density distribution along line X with the current value 380 A**. Fig. (10)** shows the magnetic flux density distribution along line X with the current value increases from 85 to 380 Amp. The behavior of each current curve is approximately the same and

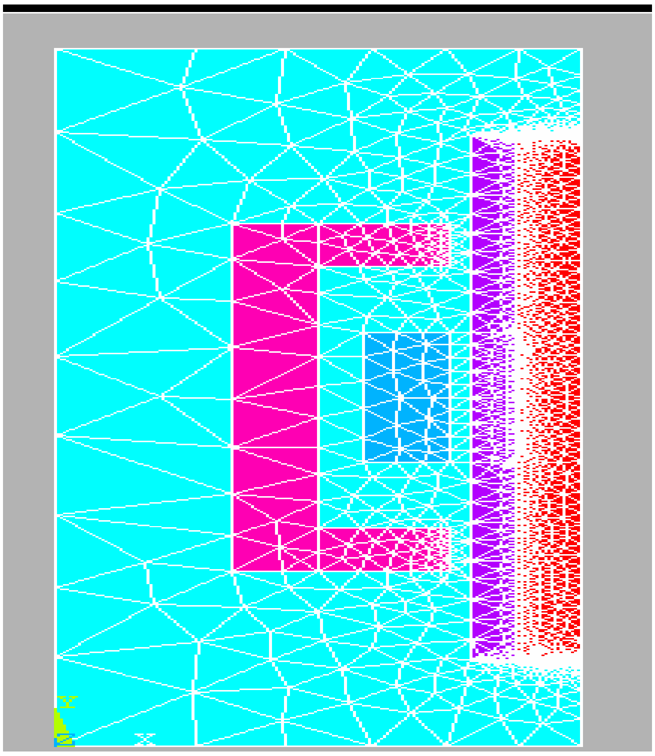


Fig (4): Finite Element Representation for The First Model.

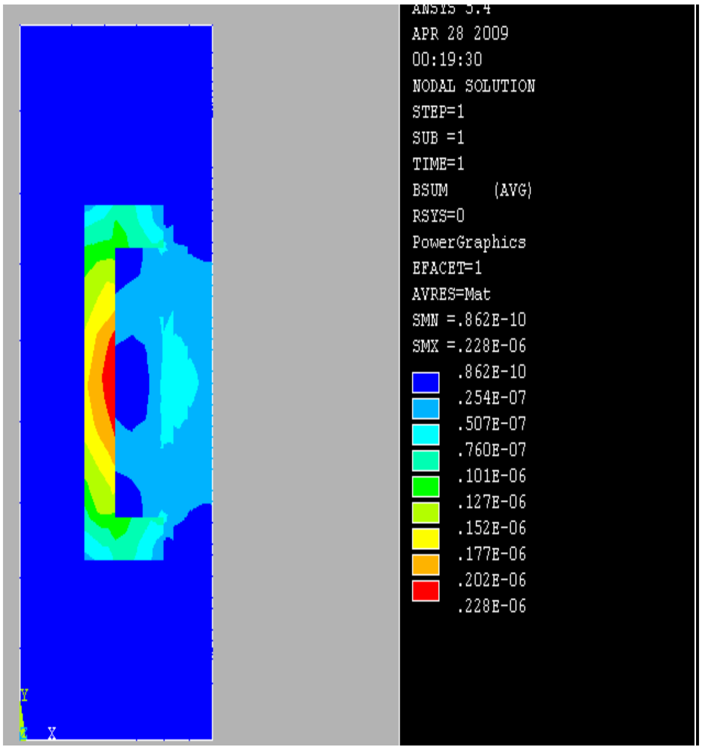


Fig. (5); Nodal Display of Electromagnetic Field of the First Model.

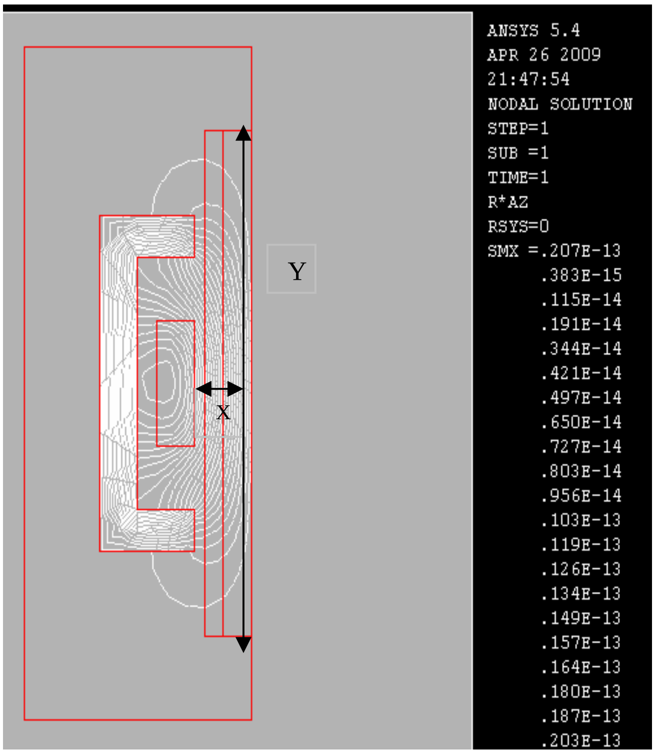


Fig. (6): 2D Magnetic Lines of Electromagnetic Field of the First Model.

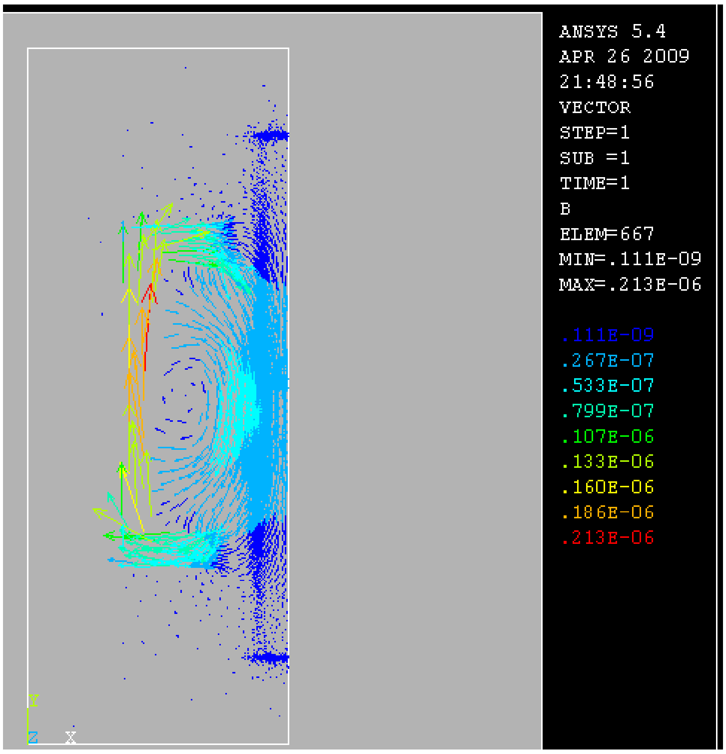
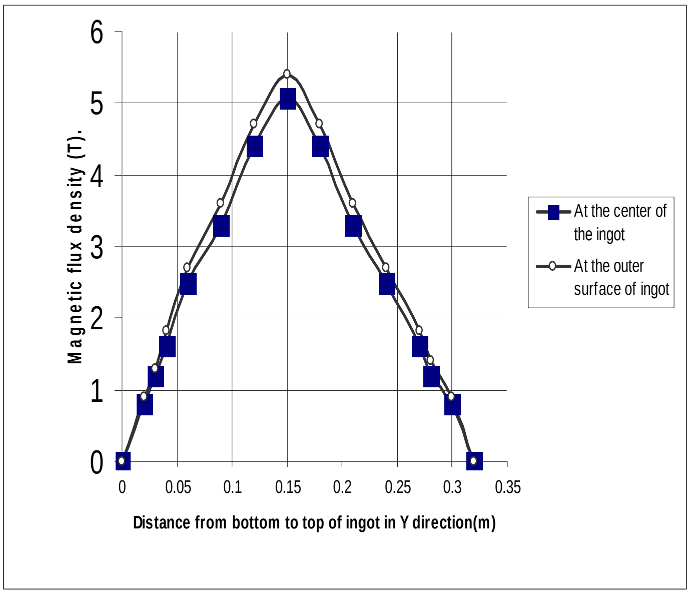


Fig. (7): Vector Display of Electromagnetic Field of the First Model



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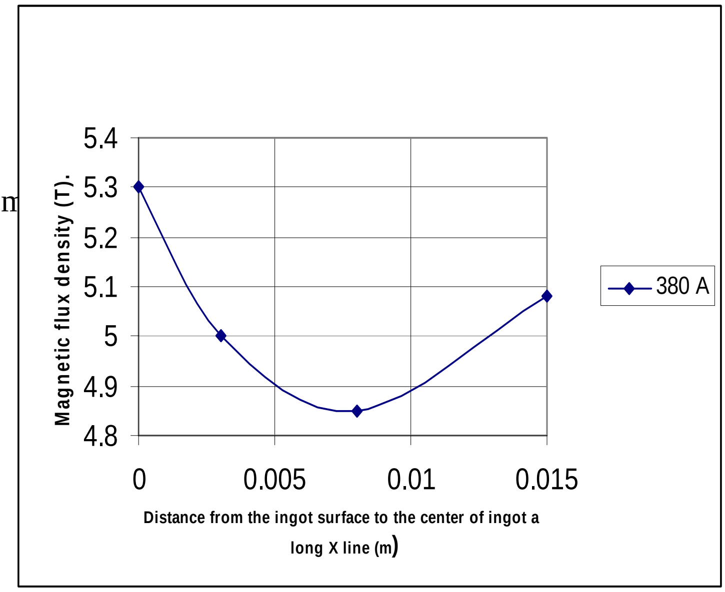
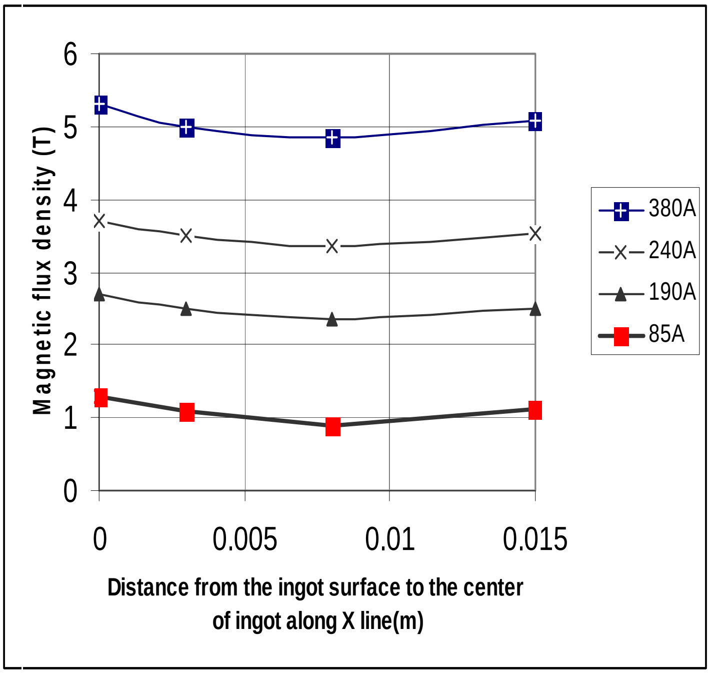


Fig. (8): The Magnetic Flux Density along the Line Y in Fig.(6), at Center and outer surface of ingot.

Fig. (9): The Magnetic Flux Density Versus Current Intensity at 380 A.



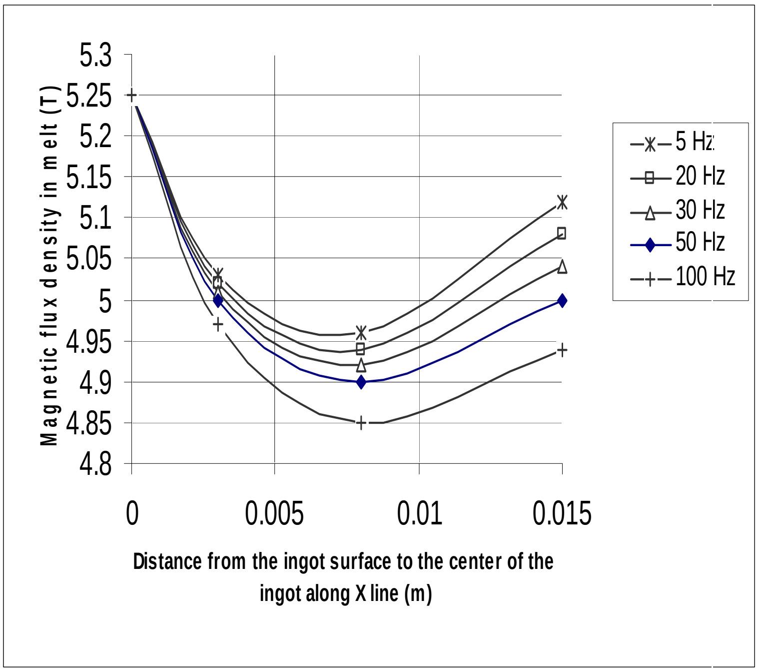


Fig. (10): The Magnetic Flux Density Versus Current

Fig. (11): The Magnetic Flux Density Versus Frequency

current value increases from 85 to 380 Amp. The behavior of each current curve is approximately the same and it consists of three stages. Starting from the center of the ingot the magnetic flux density distribution enhanced uniform behavior at the first stage, slight increasing in the second stage and more increasing in the third stage. Therefore, prospect of the ingot properties improvement may be starting from the second stage towards the ingot surface. The penetrating of magnetic field in the ingot depends on the electrical conductivity and frequency. In general the increasing in the magnetic flux density values is small which produce small magnetic flux density gradient. **Fig. (11),** illustrates small change in the magnetic flux density distribution along X line at 240 A with the frequency decreasing from 100 to 5 Hz. The magnetic flux density and then the magnetic flux density gradient may be increase with the frequency decreasing at the center of the ingot , therefore temperatures and concentration gradient may be occurs and improve the mechanical properties of the ingots. The results have a good agreement with the previous results of Zhang,B.

2-2: Results of the Second Simulation:

Qualitative Results: Fig. (12) shows the finite element representation of second model by Ansys program, the mesh of inner and outer coil, mold, and back iron is free, while the mesh of ingot is mapping to simplify the quantitative results. **Fig. (13)** Illustrates the 2D electromagnetic field distribution with current 380 / 190 Amp., frequency of 50 Hz, and phase difference of 0. **Fig. (14)** shows the vectors display of electromagnetic field which consists of two loops together directed up-down the ingot, by applying inversely current value on the coils. **Fig. (15)** Illustrates the nodal display of electromagnetic field.

Quantitative Results: The distribution of magnetic flux density must be accurately expressed in order to study the solidifying mechanism in electromagnetic fields. The magnetic flux density gradient produces from interaction of induced current and magnetic inductive intensity. The Lorentz force, which depends directly on magnetic flux density gradient, is controlling on the heat transfer via homogeneous temperatures distribution and reduces the fluctuations of liquid metal and then surface quality, and microstructure ingots, see Fig **(2). Fig. (16),** indicates the relation between the magnetic flux density along the distance D draw in **Fig.(13)** with the inner coil current value of 380 A and the outer current range from 85 to 380 A. The phase difference and frequency value are 0, and 50 Hz respectively. It illustrates that the magnetic flux density is increased with the increasing of current value in the outer coil from 85 to 380 A, and became more homogeneous at current value of 190 A, which means when the current value of outer coil is about half of inner coil current.. The magnetic flux density increases along with the current value while the increasing is very small at the center of the pipe wall.

Fig. (17), shows the behavior of magnetic flux density at outer / inner coil current value 190/380 A. By controlling on this ratio may be reach high homogeneous level. The value of magnetic flux density approximately the same at corresponding positions from center to the right and from center left of ingot. The homogeneous and high magnetic flux density value produce homogeneous and high magnetic flux density gradient, which produce less temperature gradient and less concentration gradient and may be enhanced homogeneous structure. Also the increasing in the magnetic flux density gradient in the direction to outer surface of ingot may be reducing the oscillation between the ingot and the mold, which improved the ingot surface quality. The liquid metal velocity may be increased near the surface of ingot and reduce in the center of ingot due to the magnetic flux density increasing towards the ingot surface, which produce the M velocity profile. The explanation and analyze of results may have a good agreement with the figures (2and 3).

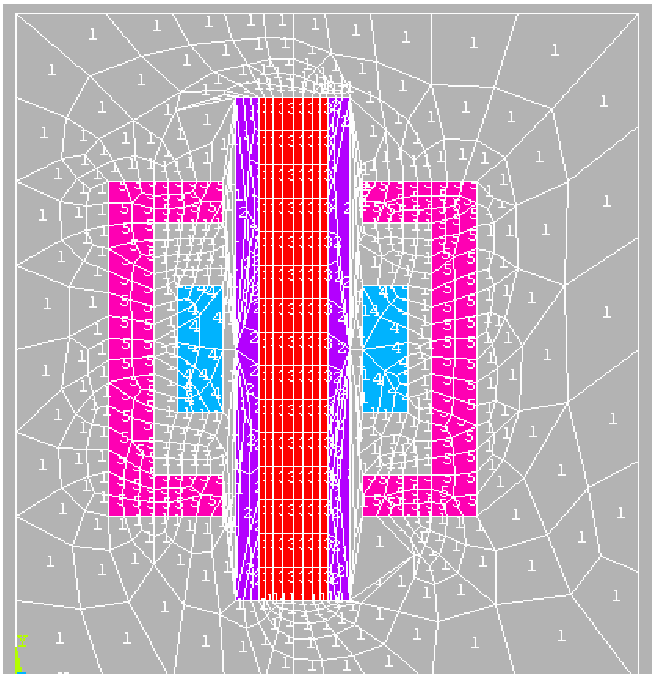


Fig. (12): Finite Element Representation of Axisymmetric First Model and Second Model

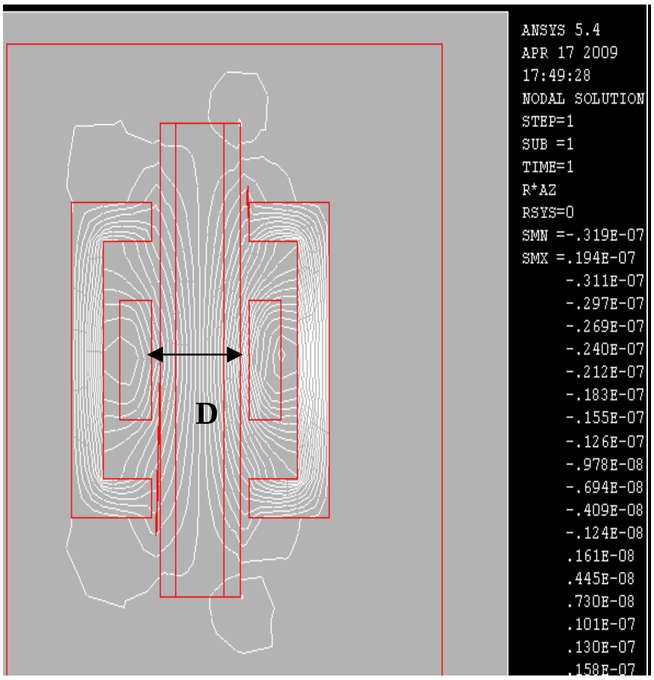


Fig. (13): Distribution of Magnetic Flux Density in Electromagnetic Casting Process (380/190 A, 50 Hz

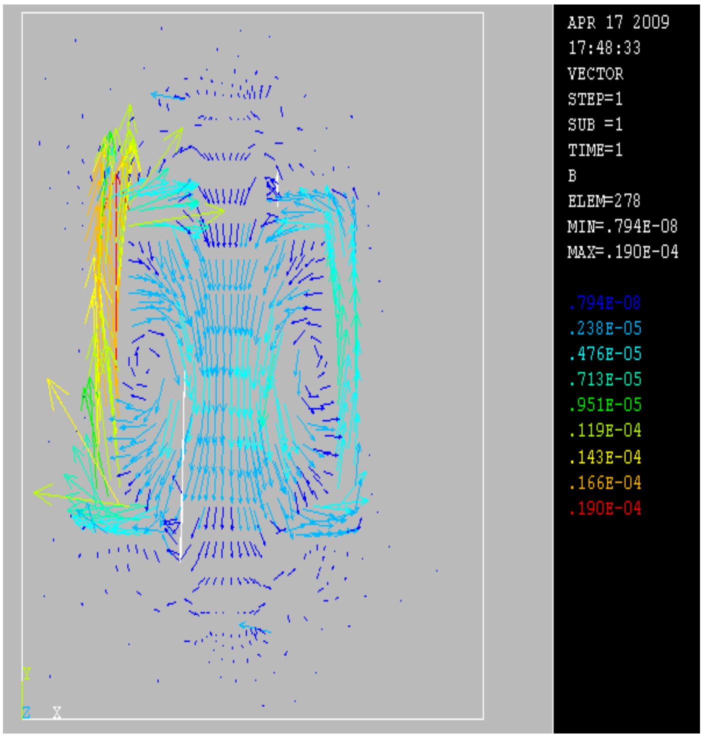


Fig. (14): Vectors Display of Magnetic Flux Density in Electromagnetic Casting Process (380/190 A,

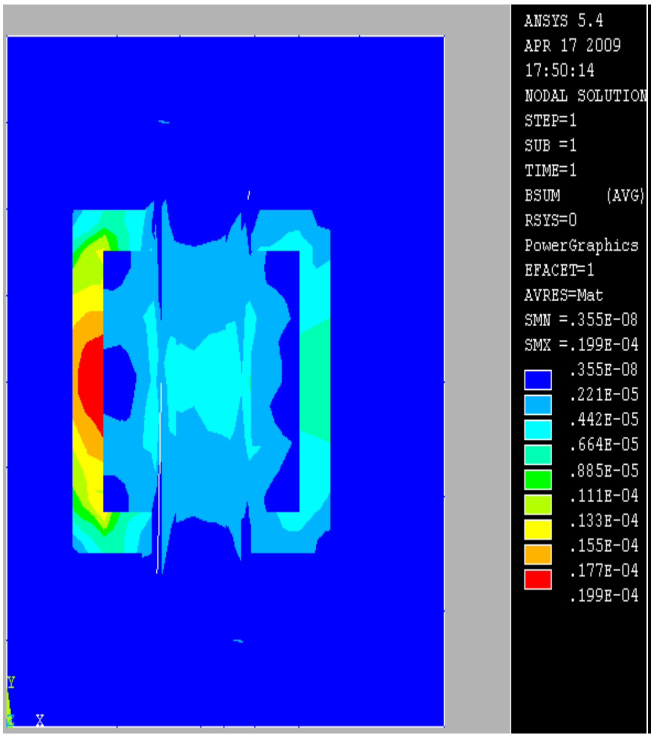


Fig. (15): Nodal Display of Magnetic Flux Density Electromagnetic Casting Process (380/190 A, 50 Hz)

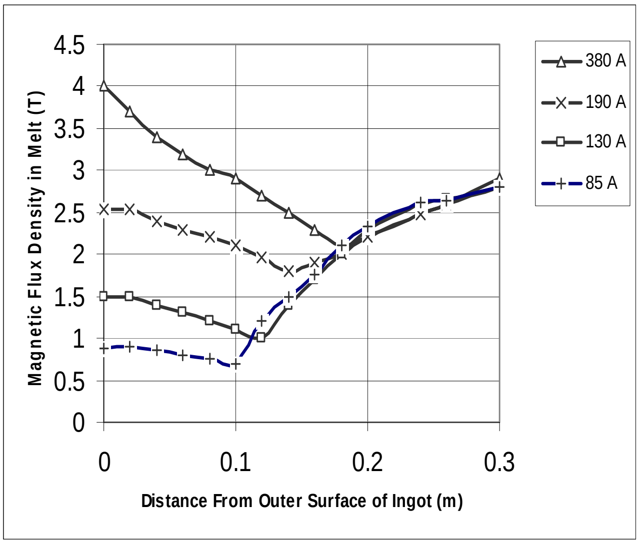


Fig. (16): Magnetic Flux Density Versus Different Outer / inner Coil Current with the Same Inner Coil Current.

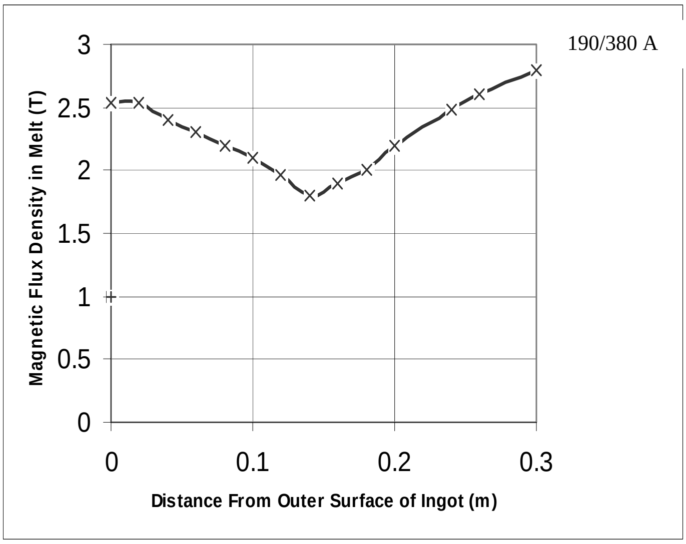


Fig. (17): Magnetic Flux Density Versus Outer / inner Coil Current Ratio 190/380 A.

3-CONCLUSIONS

1- Homogeneous temperatures distribution and fluctuations reduction of liquid metal due to the ……….magnetic flux density in electromagnetic casting is an efficient advanced process

2- Alternative current with different intensity, and frequency applied at the solid ingot, and with different intensity, applied at the hollow ingot. The improvement of the surface quality, microstructure, and of aluminum ingot in electromagnetic casting, is performed by controlling on the magnetic flux density distribution and magnetic flux density gradient, which produce from interaction between the current induced in magnetic field and the melt metal condition such as temperatures field, velocity field, and static pressure of melt.

3- The magnetic flux density distribution in solid ingot (first model) increases linearly with current intensity increasing while in hollow ingot it increases homogenously with increasing of a certain ratio (1/2) between out/inner coils current. At the same inner current value the magnetic flux density increases at the outer surface of pipe wall with the outer coil current increasing.

4- The magnetic flux density increases at the center of solid ingot with the frequency decreasing,

5- The magnetic flux density and magnetic flux density gradient values in hollow ingot are greater than that for solid ingot. The surface quality, microstructure of solid ingot may be improved in about 2/3 depth, while the improvement may starts from the center of the wall to the surface of each wall of hollow ingot.

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NOMENCLATURE:

Symbol	Definition	Units
A	**Magnetic vector potential**	
B	**Magnetic flux density**	$T, Tesla$
C	**Concentration**	
E	**Electrical field intensity**	V/m
EMC	**Electromagnetic casting**	
H	**Magnetic field intensity**	A/m
HDC	**Horizontal direct chill**	
J_s	**Source current in induction coil**	A/m^2
J_e	**Induced current**	A/m^2
MHD	**Magneto hydrodynamic**	
n	**Unit normal vector**	
T	**Temperatur**	$^\circ C$
t	**Time**	s
V	**Electrical scalar potential**	
ν	**Magnetic reluctivity**	A^2/M
σ	**Electrical conductivity**	$1/\Omega m$
μ	**Magnetic permeability**	N/A^2