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A Dual EMS System for Stirring Liquid Metals at an Advanced Solidification Stage

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Abstract

A dual EMS system having the potential to cause effective stirring when applied at an advanced solidification stage during the continuously casting billets or blooms is described. The paper focuses on the application of simple models in order to explain key features of the system. Features predicted by the simple models are validated through the application of 3-D numerical modeling.

Introduction

Rotating magnetic field electromagnetic stirring systems (RMF-EMS) are widely used in the production of continuously cast billets and blooms. While the application of such systems in the mold region has been found to significantly improve the metallurgical quality of the cast product, results to date have been less impressive when conventional RMF-EMS has been applied near the final stages of solidification. For advanced solidification zone stirring (ASZ-EMS), two important problems need to be overcome: (1) diminished torque due to the small radius of the remaining molten metal column, and (2) the increasingly viscous nature of the metal itself.

Modelling plays an increasingly important role in the development and design of electromagnetic systems used for material processing. For the most part, present day modelling is based on relatively sophisticated numerical algorithms and software, most often involving a variation of the finite element method (FEM) to determine electromagnetic fields, heat transfer or mechanical deformation, or the control volume approach when formulating fluid flow problems. While advanced numerical software proves to be an extremely important tool when refining a design, simple "first principles" models often have greater utility at the conceptual development stage.

This paper describes a new stirring arrangement that offers potential advantages when applied at an advanced solidification stage during the casting billets and blooms. The purposes of the paper are threefold: (1) to provide a short description of the proposed stirring arrangement; (2) to illustrate key features of the method by using simple analytical models and first principle concepts; and (3) to use advanced electromagnetic models to illustrate that the proposed stirrer will develop the desired force distributions.

The Proposed Advanced Solidification Zone Stirring System

A key objective when stirring in the advanced solidification zone is to produce as much turbulence as possible throughout the increasingly viscous fluid in that zone. The electromagnetic stirring forces must not only be strong, but they must be of a nature that will promote the production of turbulence. A system that will produce electromagnetic forces that potentially have this desired characteristic is shown in Fig. 1. This system consists of two identical stirrers, displaced axially with respect to one another. Each individual stirrer is substantially identical to a conventional in-mold RMF-EMS unit. However, when used at the advanced solidification stage of the billet, the electromagnetic field produced by each stirrer is not shielded by a highly conductive copper mold. Thus, the operating frequency of each stirrer can be increased significantly, proportionally increasing the magnitude of the induced current and thus increasing the Lorentz force acting on the molten metal.

Important features of the arrangement shown in Fig. 1 include:

i. Independent control of the supply frequency to each stirring unit, thus allowing for the production of very low frequency modulated forces in the region between each of the individual stirring units.

ii. Selection of the spacing between the individual stirring units, leading to the development of strong secondary fluid flow regimes. Two important components are the counter-rotating double toroids on either side of the system mid-plane.

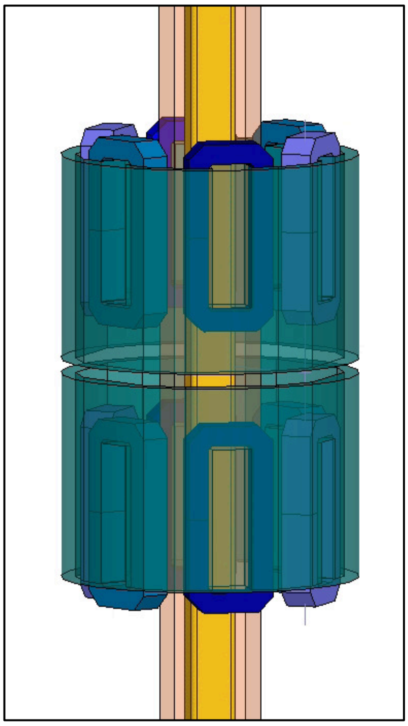

Fig. 1. Dual EMS system for advanced solidification zone stirring.

Simple Models Leading to Conceptual Design

Basic principles and a sequence of simple conceptual models will be used in this section to illustrate the fundamental ideas that have been incorporated in the proposed system for advanced solidification zone stirring.

1. Secondary Flow in Rotary EMS Systems

The proposed stirring system takes advantage of the secondary flow that is characteristic of conventional RMF-EMS. In such systems, the primary flow is in the azimuthal direction, as dictated by the rotating magnetic field. However, Davidson and Hunt showed that because of the finite axial distribution of magnetic force, there will also be a secondary, poloidal flow in the regions above and below the stirrer mid-plane [1]. This secondary flow is driven by centripetal forces caused by the rotary motion, together with unbalanced

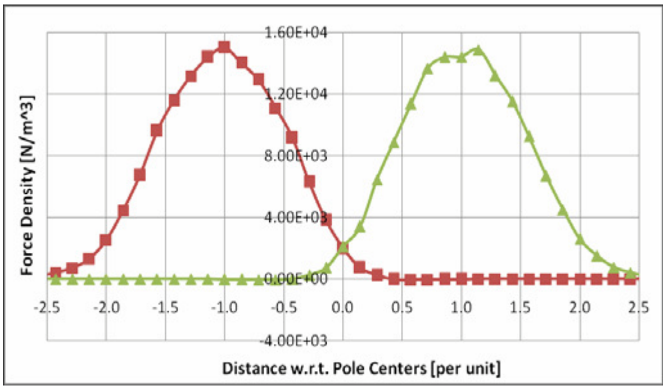

Fig. 2. Typical force distributions due to two axially displaced stirrers acting separately.

pressures that occur provided $\partial F_\theta/\partial z << F_\theta/R$. It is generally agreed that this secondary flow is weaker than the primary swirling flow.

Fig. 2 shows typical force distributions produced by two axially displaced stirrers and illustrates how the two stirrer geometry can generate a useful secondary flow in the solidification zone. Relative to the *system* mid-plane, $\partial F_\theta/\partial z$ is negative for one stirrer and positive for the other. The system will therefore cause counter-rotating secondary flows on either side of the system mid-plane. These two secondary flows collide at the mid-plane, thus enhancing the production of turbulence within the viscous, but still molten core.

2. *Low Pass Response to Time Varying Forces*

In a single stirrer RMF-EMS system operating at angular frequency ω, the Lorentz force acting on the molten metal has two components, one constant and the other double frequency. Symbolically, the force expression is of the form:

$$f(t) = F_0[1+\cos(2\omega t)] \tag{1}$$

Davidson has argued that within a liquid metal column being stirred by a rotating magnetic field, the central region of the molten core will essentially exhibit rigid body rotation since the flow is characterized by almost constant angular velocity [2]. Further, the angular velocity **Ω** in a conducting cylinder of radius R, acted upon by a rotating magnetic field of magnitude B_0, can be described by a first order nonlinear differential equation of the form [2,3]:

$$\frac{1}{2\omega}\frac{d}{dt}\left(\frac{\Omega}{\omega}\right)+\left(c_f+\frac{R}{20\ell_s}\right)\left(\frac{\Omega}{\omega}\right)^2=\lambda\left(1-\frac{\Omega}{\omega}\right)[1+\cos(2\omega t)] \tag{2}$$

where c_f is a dimensionless parameter, ℓ_S is the stirrer length and $\lambda = \sigma B_0^2/4\rho\omega$, with σ being the electrical conductivity and ρ the mass density, respectively. This system exhibits a low pass property; namely, it attenuates sinusoidal inputs at frequencies that are significantly greater than a critical (low) frequency. Consequently, for conventional stirring frequencies, although the input forcing function may vary with time, the output angular frequency will be relatively constant in the steady state due to inertial effects.

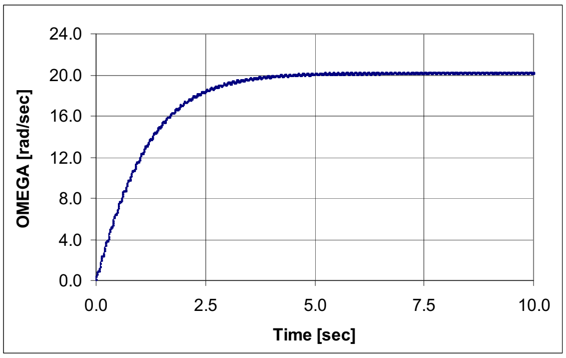

Fig. 3. Transient response of a cylindrical strand to a 1000 Gauss magnetic field rotating at 5 Hz.

This is illustrated in Fig. 3 where the response to a 5 Hz rotating magnetic field is shown. In the steady state, the 10 Hz (double frequency) component of the forcing function has relatively little impact due to the filtering effect of inertia. Only when the supply frequency ω is sufficiently low (below at least 3 Hz) will **Ω** exhibit a time variation. Unfortunately, under normal circumstances, low ω also means low force and thus little effective stirring of any sort. Because of these inertial effects, any attempt to introduce low frequency forcing to enhance stirring and/or turbulence must use something more than a simple conventional single stator RMF-EMS system.

3. *The Impact of Frequency on the Lorentz Force*

The standard low frequency approximation for EMS systems is that the flux density within a cylindrical strand will be uniform over the cross section and the current density will increase linearly with increasing radius. Similarly, the magnitude of the current density is proportional to the applied magnetic flux density B_0 and the supply frequency ω. These approximations are valid within a strand of radius R provided:

$$\mu_0 \omega \sigma R^2 \leq 4 \qquad (3)$$

In the case of a 200 mm diameter strand of molten steel, for example, this inequality is satisfied for frequencies of up to 70 Hz. Thus, below the mold, the supply frequency can be easily increased to 10X the value used in conventional RMF-EMS in-mold applications, thus achieving up to a 10X increase in the stirring force.

4. Force Modulation with a Dual Stator System

Useful low frequency forces, having sufficient magnitude to modulate the stirring in the advanced solidification stage, can be achieved by supplying different frequencies to two axially displaced stirrers, of the type shown previously in Fig. 1. The two stirrers can be termed the upper and the lower stirrer, respectively. At any point within the strand, the Lorentz force will be the vector (i.e. cross) product of the total current density with the total magnetic flux density:

$$\bar{f} = (\bar{J}_U + \bar{J}_L) \times (\bar{B}_U + \bar{B}_L) \qquad (4)$$

Letting ω_U and ω_L be the angular frequency applied to the upper and lower stirrers, respectively, it can be shown that each component of the Lorentz force consists of several constant and time varying components. The general form for each Lorentz force component is:

$$f = f_{DC,U} + f_{DC,L} + f_1[(\omega_U - \omega_L)t] + f_2[(\omega_U + \omega_L)t] + f_3[2\omega_U t] + f_4[2\omega_L t] \qquad (5)$$

where $f_3[2\omega_U t]$, for example, is a term that varies sinusoidally in time at twice the frequency that is supplied to the upper stirrer. In view of the low pass filtering action due to inertia, the force that effectively has an impact on stirring has the form:

$$f \cong f_{DC,U} + f_{DC,L} + f_1[(\omega_U - \omega_L)t] \qquad (6)$$

It is important to note that the magnitude of the force $f_1[(\omega_U - \omega_L)t]$ is essentially proportional to the average of ω_U and ω_L and thus can be made arbitrarily large. However, the time variation of this component can be made arbitrarily small by setting $\omega_U \approx \omega_L$.

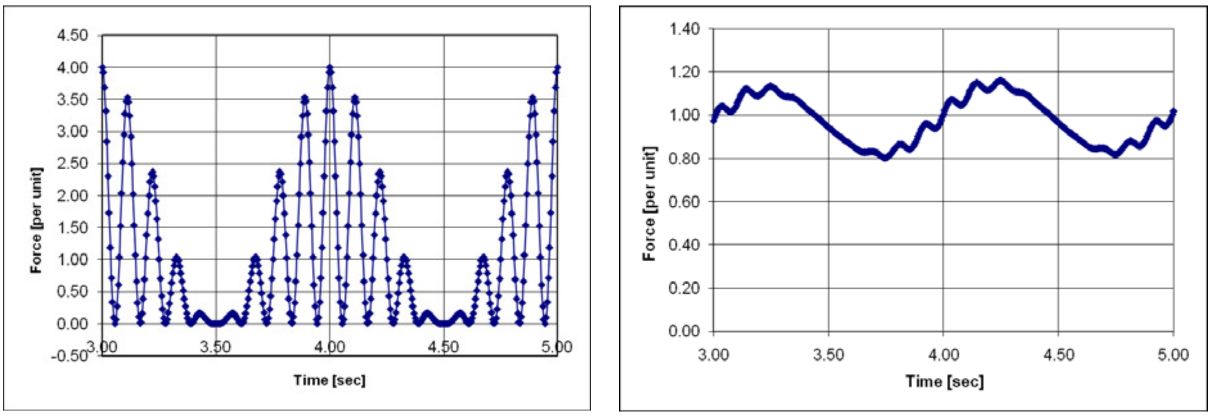

Fig. 4a (left). Actual modulated force due to the interaction of two adjacent stirrers, including DC, low frequency and high frequency terms.
Fig. 4b (right). Force that effectively acts on the molten metal strand because of inertial filtering.

The effective filtering action of inertia is illustrated above in Fig. 4a where a modulated force, containing both high frequency and low frequency terms is shown. The resultant, after passing through a low pass filter having properties similar to those of a column of liquid steel, is shown in Fig. 4b. Note that frequencies of 4 Hz and 5 Hz, respectively, were used in order to better illustrate the filtering action. Due to the low frequencies used, some ripple does appear in the effective force.

3-D Electromagnetic Modelling of Proposed Stirrer

Simple models prove to be extremely useful when developing conceptual EMS designs. On the other hand, proof of concept will require the application of more sophisticated modelling methods, both to evaluate the electromagnetic aspects of the device, as well as to assess the effectiveness of the device for EMS. The electromagnetic and fluid flow modelling of conventional in-mold RMF-EMS have previously been treated in a sequence of papers [4-6] in which it has been shown that considerable care must be exercised when modelling the turbulent flow of molten metal in an EMS system. Electromagnetically, the system must be treated in 3-D and quite simple methods have been developed to treat the motion of the liquid metal relative to the rotating magnetic fields.

For the purpose of the present paper, only the electromagnetic aspects of the proposed stirring arrangement will be addressed, and only for the purpose of presenting representative results. From an electromagnetic perspective, the dual stator system has been modelled by treating the stator steel as being linear and the molten metal core has been assumed to have a variable width relative to the solidified shell. A representative model is shown in Fig. 1 where the solid shell is 50% of the billet cross section. The excitation of the two stators is assumed to be time harmonic. The upper and lower stators are treated separately when excited at different frequencies. The composite fields and forces are then assembled using the two single frequency solutions.

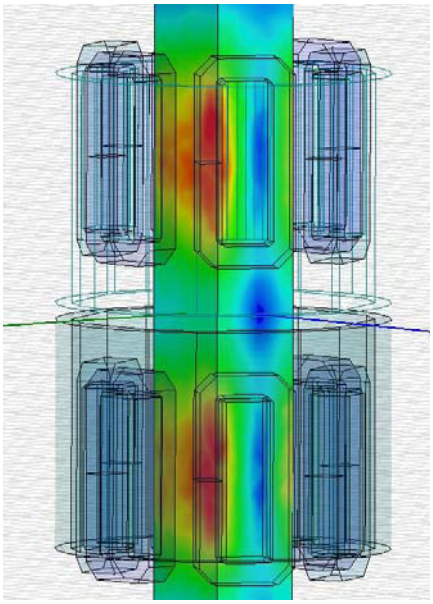

Fig. 5. Typical current distribution on strand surface.

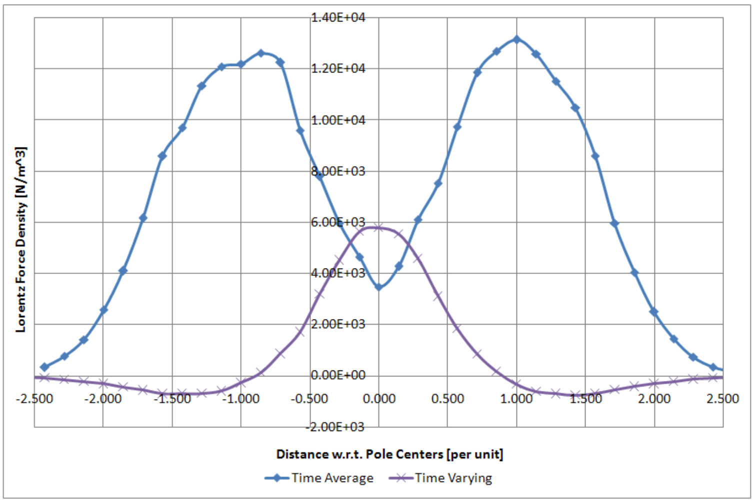

Fig. 6. Representative Lorentz force distributions within molten core - time average plus low frequency time varying.

Fig. 5 shows the current distribution on the surface of the solidified shell. In this case, both stirrers were excited at 18 Hz. The asymmetry due to the orientation of the strand relative to the 6-pole stirrer is apparent. Fig. 6 shows a representative distribution of the Lorentz force density within the melt, with the upper and lower stirrers operating at 18 Hz and 17.5 Hz, respectively. The distribution is taken along an axial line extending the length of the stirrer system. The forces have been separated into the time average component, comprising the first two terms in (6), together with the low frequency 0.5 Hz time varying component, the third term in (6). The extent to which the system parameters can be selected to enhance the low frequency term is obvious.

Conclusions

This paper has introduced a dual stirrer arrangement that has the potential to effectively provide stirring at the advanced solidification stage for continuously cast billets and blooms. It has been shown that very simply modelling methods can be used to significant advantage in order to develop the initial design of systems such as this. On the other hand, numerical modelling methods are the only option when refining the design, or when details of system operation are to be understood.

Recently, preliminary trials have been completed using this system while casting aluminum alloy A357 within a laboratory environment. Tests were run with a conventional single coil stirring system as well as with the proposed system. A 22 kg ingot was cast and with the new system, it was found that the alpha phase globules within the central region of the solidification structure were reduced, on average, from 142 µm to 127 µm.

References

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