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Numerical simulation of electromagnetic stirring in continuous casting of wires

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Abstract

Purpose – The purpose of this paper is to describe how electromagnetic stirring during continuous casting of ferrous and non-ferrous metals is applied in order to increase the homogeneity and the material properties by improving the grain refinement in the solidification process. The fluid flow and thermal modeling was performed for studying the metal wire pulling process, where melt is being stirred at the solidification front (SF) by electromagnetic forces. Transient simulation has been carried out in order to investigate the periodical character of the process.

Design/methodology/approach – The numerical analysis was performed in 2D utilizing the rotational symmetry of the problem. First the electromagnetic fields were estimated using FEM and were subsequently exported as source terms in a coupled thermal and flow simulation with FVM.

Findings – The presented numerical model estimated the most suitable position between the stirring coil and the SF to achieve high flow velocities which improve the grain refinement process.

Originality/value – This work enables estimation of the melt solidification in an electromagnetic stirred continuous casting process with oscillating pull velocities.

Keywords Electromagnetic stirring, Continuous wire casting, Modelling, Wires, Electromagnetism

Paper type Research paper

1. Introduction

The process is being developed for continuous casting of metal wires, where the quality of the product is determined by the microstructure of the solidified material. Therefore, homogeneity and fine grain structure are the final properties which are desired. The installation is designed as a graphite mould. A water-cooled tube is placed inside the mould and the metal solidifies while it is being pulled through. A small inductor is placed just before the cooling channel approximately where the solidification front (SF) is situated. The task of the process optimization is to adjust mould geometry and induction parameters in order to receive such a temperature gradient below the SF, which causes the formation of the fine grain structure in the solidified material. An important role is devoted to the melt flow driven by the electromagnetic field from inductor. The right combination of inductor position, electric current and pulling rate ensures optimal wire quality. An additional challenge for the modeling is the oscillating character of the casting process, i.e. the pulling velocity is varied in time. The modeling was done in order to investigate the factors, which may influence the final quality of the cast wire. As the most important were considered such process parameters as pulling rate and the properties of the electromagnetic field, which is used to stir the melt before the SF. The calculations were performed either with stationary and transient k-e turbulence models. The steady-state approach was expected to provide the possibility to adjust the thermal boundary conditions of the model to those of the real process. Further model

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development includes the transient simulation of the process, where the oscillating process is taken into account. This should give the impressions about movement of the SF, which obviously will oscillate. These oscillations will have significant influence on the flow pattern and mushy zone thickness.

2. Grain refinement and fluid flow

The cause for the mechanism of electromagnetic stirring (EMS) is the exploitation of the Lorenz force, which affects moving charges within a magnetic field. Based on this simple principle it is possible to create directed flows in molten metals, which lead to a mixing of the melt. This movement can be computed using the Navier-Stokes equation for incompressible fluids. For laminar flows the equation is given by:

$$\rho \frac{d\mathbf{v}}{dt} = \mu \nabla^2 \mathbf{v} + \rho \mathbf{g} + \mathbf{J} \times \mathbf{B} - \nabla \mathbf{p} \tag{1}$$

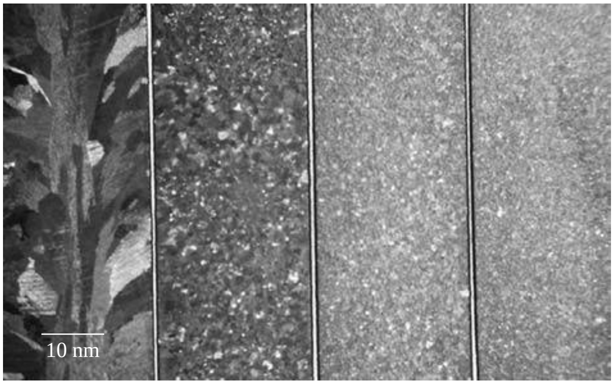
and for turbulent flows it is given by:

$$\rho \frac{d\mathbf{v}}{dt} = \nabla(\mu_{eff} \nabla)\mathbf{v} + \rho \mathbf{g} + \mathbf{J} \times \mathbf{B} - \nabla \mathbf{p} \tag{2}$$

In equations (1) and (2) v is the velocity, ρ is the constant fluid density, μ the cinematic viscosity, $\mathbf{P}$ the total pressure, $\mathbf{J} \times \mathbf{B}$ the Lorenz volume forces and $\mathbf{g}$ the gravitational acceleration constant. Few methods for stirring are described in the literature, which can be mainly distinguished in axial and radial stirring. For a good overview (Mofatt, 1990) is recommended. Former studies revealed two fundamental mechanisms, which explain the grain refinement process by EMS. The flow can break off (this mechanism has a weak effect) or remelt the tips of columnar dendrite arms from the mushy zone, so that they can act as nucleation centers for equiaxed crystals (Campanella *et al.*, 2004; Moore, 1984). For this reason, the stirring equipment has to meet special conditions with regard to the position and the range of the stirrer. A more detailed theoretical background is provided in Moore and Shah (1984). Another very important parameter for the quality of grain refinement is the magnitude of stirring velocity (Moore and Shah, 1984), which, according to equations (1) and (2), is a direct consequence of the Lorenz force and the induced current density in the melt, respectively. For instance, the experimental findings revealed that for the refinement process of pure copper higher current densities are needed than for copper alloys (Figure 1). This effect can be explained with the higher viscosity of the mushy zone which restrains the stirring process and reduces the flow velocity (Campanella *et al.*, 2003).

3. Numerical model

In order to perform a realistic analysis of the flow, it is necessary to start with an electromagnetic simulation of power losses as well as force densities within the melt, the solidified material and the ingot. This part was realized using the commercial software package Ansys™. The casting implements, which are schematically shown in Figure 2, were modeled utilizing the axis and rotation symmetry, which leads to a reduction of the geometry to a two dimensional axis symmetrical problem. The second part, the flow simulation, was performed with the CFD-software Fluent™, which is a part of the Ansys™ package. A realistic electromagnetic simulation requires the consideration all electrically conducting components of the casting device, whereas a flow simulation can



Note: From the left to the right side the flow velocity was increased
Source: Campanella (2003)

Figure 1.
Grinding patterns of a C97 (Cu-1%Ni-1%Pb-0.2%P) alloy, where different stirring intensities were used

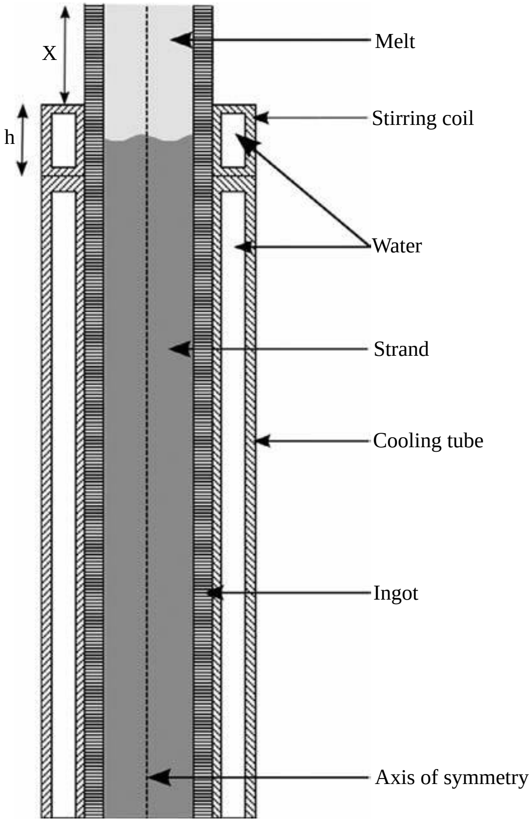


Figure 2.
Sketch of the casting implements

be reduced merely to melt and ingot. Because of the fact that Fluent™ is a separate program, it was necessary to export and couple the results of the electromagnetic and the flow simulation. In this case, the results of the mentioned regions from the electromagnetic simulation were written in an element table. These integral values are to be embedded into the CFD calculation with the requirement that the created mesh has nearly the same quantity and size of elements. Fluent affords to store these values to the user-defined memory deposing a user-defined function (UDF), which has been created for this problem before.

To get valid findings, it is indispensable to take the solidification process into account. This can be realized using an enthalpy-porosity technique (Voller and Prakash, 1987). Therefore, the availability of adequate thermal boundary conditions is assumed. For the sake of simplicity the heat removal by the cooling water can be simulated embedding a linear temperature profile at the outer wall of the ingot utilizing a UDF. The advantage is that the thermal resistances of all components in the system do not have to be known. Moreover, the experiments show a good agreement with a real installation.

In common industrial casting implements the pull velocity is not constant, but rather discontinuous. It can be separated in a repetitive pulling and holding phase. This characteristic also had to be implemented in the calculation. This was realized by a time depending step function, which changed the boundary conditions for the velocity inlet as well as the outlet and patched the pull momentum on the solidified material every time step.

The typical pull velocities cause small Reynold's numbers at the inlet, which has a magnitude of $\mathrm{Re} \approx 260$ in our case (pure copper). In the area close to the stirrer we obtain 10-100 times higher flow velocities with corresponding Reynold's numbers with a magnitude of 10^4, which leads to turbulent flows. To increase the efficiency of EMS, it is essential to adjust the position of the SF with respect to the position of the stirrer. Because of the small geometry of this problem it is necessary to determine the region of solidification accurately, which requires considering of the influence of the turbulent heat transport. For this purpose the k-e turbulence model was used, which combines an adequate accuracy with marginal calculation time.

4. Numerical model results

Comparing the flow simulation results of a configuration without EMS and with the use of EMS, respectively, we obtain quite different pictures of the solidification morphology despite the small geometry of the problem. In general, the three following cases are possible:

(1) SF forms above the stirring coil.
(2) SF forms below the stirring coil.
(3) SF forms near the axis of the stirring coil.

There are several possible ways to regulate the position of the SF relative to the coil axis. In the present work it was done solely by adjusting the pulling velocity.

Starting with the first case, Figure 3 shows the contours of liquid fraction and the flow velocity of pure copper for a low casting speed (because of the discontinuous casting speed it is necessary to pay attention that the position of the SF is slightly oscillating. It has to be mentioned that in the following we only compare upper reversal points with each other). Although the SF is well above the stirrer, a wide extension of the mushy zone can be noticed (Figure 3(b)). Owing to the flow distribution, which is shown in Figure 3(c) the concave solidification morphology in Figure 3(b) is a consequence of the higher flow velocities at the wall and the lower flow velocity at the centre of the melt, which effects a beginning solidification from insight the melt. Figure 4 shows the contour of liquid fraction and flow velocity for SF ideal position $p_1 = x + h/4$ and for SF at the stirring coil axis. The reason for the diverse flow velocities can be explained with Figure 5. The pull velocity coincides with the flow, which is generated by the stirring coil, in the region close to the walls. In the center, both flow directions are opposing and lead to damping action.

In the second case – if the SF is below the stirrer – a second eddy will be generated (Figure 6). Its flow direction is exactly the other way round, which causes a constructive interaction in the center region and a destructive at the walls. In the region near the stirring coil axis the flow magnitude is very low, because of the fact that neither of the eddies can influence the melt. Hence, the melt cannot be stirred and the liquid fraction decreases rapidly, which leads to an increase of viscosity. Therefore, the eddy below the stirrer generates noticeable lower flow velocities, which are additionally damped at the walls and allow the melt to solidify. An increase of the solidification at the walls, as can

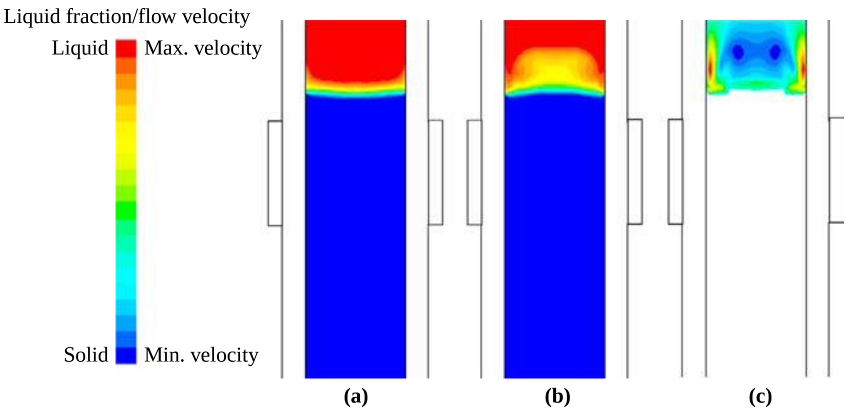


Figure 3.
For low casting velocity contours of: (a) liquid fraction without EMS, (b) liquid fraction with EMS, (c) contours of flow velocity magnitude

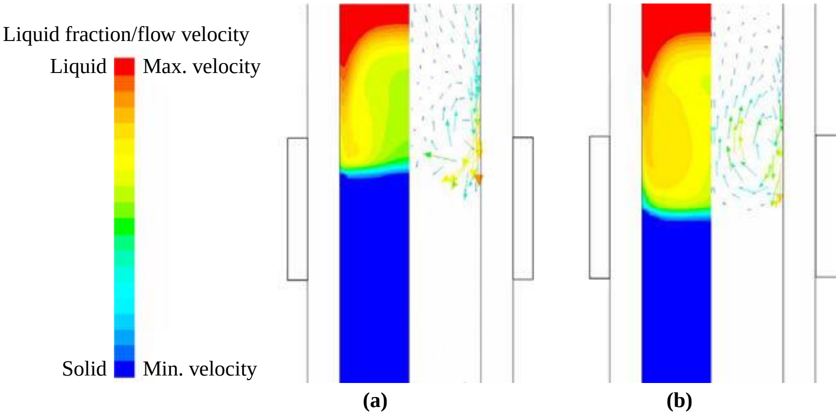


Figure 4.
Contour of liquid fraction and flow velocity (a) For SF ideal position $p_1 = x + h/4$ and (b) for SF at the stirring coil axis

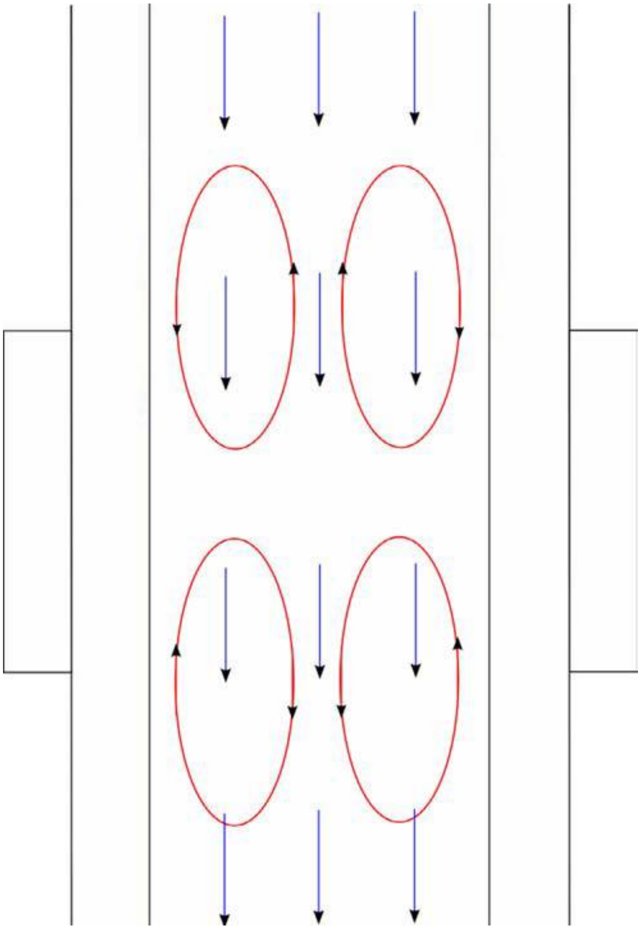
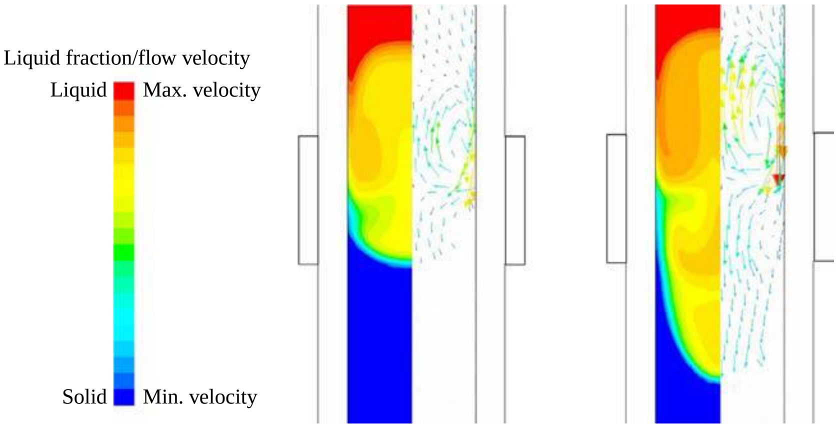


Figure 5.
Flow components

Note: The pulling flow (blue) and stirring flow (red) interfere inside the mould

be seen in Figure 6(b), generates an inhomogeneous solidification structure of the metal and the grain refinement process loses its efficiency.

The third case (Figure 4(b)) is when the SF is located at the coil axis. Figure 7 shows how the melt flow velocity profile depends on the position of the SF. When the latter moves downwards, the velocity magnitude reaches its global maximum near $p_1 = x + h/4$, decreases afterwards until the middle of the coil and increases again up to second maximum (if viscosity of the mushy zone is not too high) near $p_2 = x + 5h/4$. A SF at the stirring coil axis causes a wide mushy zone (Figure 4(b)) a smooth flow velocity gradient to the point of full solidification. It is expected that the lower flow velocity effects a beginning solidification at the walls, which leads combined with the high temperature gradient in this region to a inhomogeneous solidifications texture and a lower material quality as in case 1. Therefore, the highest efficiency can be



(a) (b)

Figure 6. Contour of liquid fraction and flow velocity for (a) a high casting velocity magnitude and (b) very high velocity magnitude

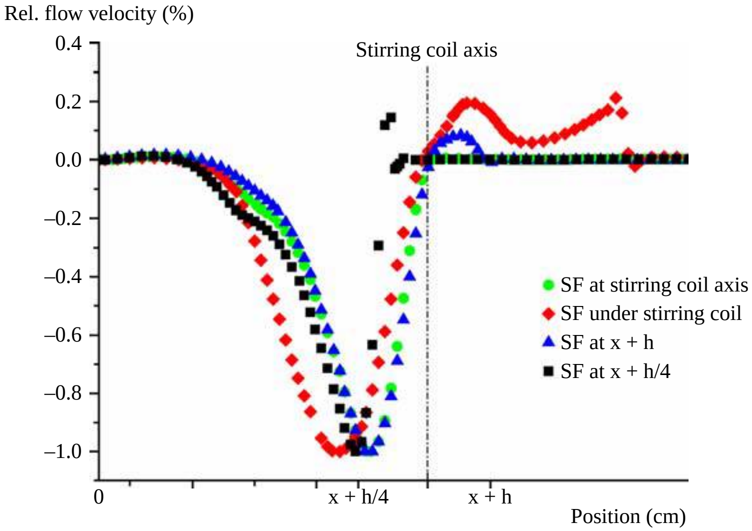


Figure 7. Profiles of the relative axial stirring flow velocities for different positions of the SF

achieved if the SF is positioned at P_1, as it is shown in Figure 4(a), where the highest flow velocity and proper solidification behavior is combined.

5. Conclusion

The use of numerical simulation as a tool for the analysis and optimization of the geometrical (e.g. position of the coil) and electrical (e.g. current, frequency) process parameters in the field of EMS is indispensable because of extremely time and cost consuming character of the experimental investigations. However, it is often complicated to take all necessary factors into account, which may influence the reliability of the numerical modeling.

With the help of the calculations presented in this article it was possible to achieve a detailed picture of the melt behavior. The numerical model of the continuous casting installation includes not only adequate thermal boundary conditions, but also captures the irregular movement of the melt according to the process requirements. The performed numerical investigations allow an evaluation of influences of the electrical and geometrical parameters inside the installation on the melt flow intensity and SF behavior. It has been found that an ideal utilization of the forced flow for grain refinement is achieved, if total SF begins at x + h/4 (Figure 2).

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