Electromagnetic Mould Stirring with Higher Supply Frequency

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The use of mould stirring in the continuous casting of steel yields a better surface quality of the cast strands.1–3) On the one side, a more uniform thickness of the initial solidified shell is realized by homogenizing the temperature of the molten steel.1,2) On the other side, due to the “washing effect” non-metallic inclusions like larger alumina particles and Ar bubbles are removed from the surface layer of the cast strand,1–5) where their presence can generate cracks and slivers in the subsequent processes.1–3)

As the magnetic field of the stirrer must penetrate through the inner copper wall of the mould, just low supply frequencies can be employed. Therefore, large stirrers and frequency converters of high power have to be used (Table 1 and Fig. 1). This paper presents a mould stirring configuration allowing the usage of higher frequencies, e.g. 50 Hz and consequently, of smaller inductors with direct network supply.6)

The mould stirring can be performed with an outer inductor if all mould walls are made of copper (Fig. 2). The electric currents, $i_e$, induced in the exterior mould wall by the inductor’s rotational magnetic field are passed through the interior wall, where the inner currents, $i_i$, appear. These currents produce a second rotational magnetic field inside the mould, which stirs the molten core of the strand.6) If the thickness of the mould walls is smaller than the penetration depth of the electromagnetic field, $d$, an intermediate magnetic core shown in Fig. 2(a) must be used as a return path for both outer and inner rotational magnetic fields. Figure 2(b) shows a mould with vertical walls thicker than $d$, where an intermediate magnetic core is no longer neces-

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**Table 1.** Characteristics of industrial mould stirrers.

| Stirrer type            | Stirrer installation            | Frequency (Hz) | Power (kVA) |
|------------------------|---------------------------------|----------------|-------------|
| Linear of Nippon Steel | inside the mould cooling chamber| 2              | 300 - 600   |
| Linear of Rotelec5     | behind the mould backup plates  | 0.5 - 1.5      | 700 - 1000  |
| Rotational of Rotelec5  | around the mould                | < 10           | 500         |
| Rotational of SMS Elotherm (Fig. 1) | around the mould    | 1.7            | 770         |

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Fig. 1. Mould stirrer of the SMS Elotherm: (a) the three-phase inductor; (b) the stirrer and the frequency converter.

Fig. 2. Mould stirring by an outer inductor inside (a) a thin-wall and (b) a thick-wall mould (schematic): 1, copper mould; 2, laminated core of the inductor; 3, cast strand; 4, intermediate magnetic core.
The electric currents, $i_i$, and their inner magnetic field can be enhanced using a mould of cold crucible type, as in the case of high-frequency electromagnetic casting (EMC), where the mould is divided into segments by axial and radial slits\(^7\) or sheets of a copper alloy with high electric resistivity.\(^8\) The configurations presented can be applied in the slab casting too, to stir inside the mould (EMRS), to slow down/accelerate the meniscus steel flow (EMLS/EMLA)\(^9\) as well as for the multi-mode stirring (MMEMS).\(^4,5\)

Experimental tests were performed using two laboratory models (Fig. 3) described in Table 2 and Fig. 4. Each of them comprises a mould model of an aluminium alloy (Fig. 4), which surrounds an intermediate steel core with a constant thickness, $b$. The inductors of the laboratory models were supplied with constant phase currents of 1.5 A and 3 A, respectively.

In the absence of the aluminium mould model, the measured magnetic flux density in the center of model 1 was 8.1 mT. With the mould model installed inside the inductor (Fig. 3(a)) was measured nearly the same r.m.s. value of 7.9 mT, produced by the inner electric currents, $i_i$.

The inductor height, $h$, of model 2 (Fig. 4 and Table 2) is great in comparison with the radius, $R$. Therefore, the electric currents, $i_e$, induced in the exterior wall of the mould model (Fig. 2) would practically flow only in azimuthal direction through its upper and lower horizontal walls, i.e. without passing through the interior vertical wall. To prevent this, the mould model was slitted into segments shown in Fig. 3(c), by which the induced currents will pass axially through the interior wall.

The electromagnetic field in model 2 was also calculated in cylindrical coordinates $(r, \varphi, z)$ applying the finite difference method. The magnetic field was determined\(^6\) in the domain $r>R$ (Fig. 4) using the magnetic scalar potential and for $r\leq R$ by solving the equations of the complex magnetic vector potential, $A$

$$\begin{align*}
\text{rot} \left( \frac{1}{\mu} \text{rot} A \right) - \text{grad} \left( \frac{1}{\mu} \text{div} A \right) + j \omega \sigma A &= - \sigma \text{grad} V \\
\text{..................................................(1)}
\end{align*}$$

![Fig. 3. Laboratory models: (a) model 1 with a central coil for measurement of the magnetic flux density; (b) the inductor with an outer copper coil for indirect water cooling and the inner mould model with four supporting arms of the laboratory model 2; (c) the slitted mould model of an aluminium alloy with an inner annular steel core of model 2.](image)

![Fig. 4. Laboratory model (schematic): 1, mould model of an aluminium alloy; 2, laminated magnetic core of the inductor; 3, intermediate annular core of steel.](image)

| Type of characteristics              | Model 1                  | Model 2                  |
|--------------------------------------|--------------------------|--------------------------|
| pole pair number, phase number, frequency | 1, 3, 50 Hz              | 1, 3, 50 Hz              |
| inner radius ($R_i$), height of the laminated core ($b$) | 44.5 mm, 23 mm           | 83 mm, 200 mm           |
| thickness of the steel magnetic core ($a$) | 12.5 mm                  | 5 mm                     |
| type of the mould model of an aluminium alloy | non-slitted              | slitted (12 segments)    |
| outer radius ($R$), thickness of the mould model ($b$) | 42.5 mm, 5 mm            | 81 mm, 4 mm             |
| r.m.s. value of the inductor line current density | 8.86 kA/m                | 6.12 kA/m                |

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and of the complex electric potential, $V$,

$$\text{div}(\sigma \text{grad} V) = -j\omega \text{div} (\sigma A)$$

inside the conductors, respectively. The electrical conductivity, $\sigma$, is for the mould model equal to the conductivity of the aluminium alloy in the $r$- and $z$-directions and $\sigma = 0$ was introduced in $\varphi$-direction allowing for the mould model segmentation. The permeability, $\mu$, of the intermediate steel core (Fig. 4) was calculated by the first-harmonic amplitudes characteristic $B=f(H)$ determined for a sinusoidal time variation of the magnetic field strength.\(^{10}\) Field calculations and measurements have yielded distributions of the magnetic flux density inside the mould model, which are also close to the values obtained in the absence of the mould model (Fig. 5).

The presented slitted or non-slitted mould, e.g. with vertical thick-walls (Fig. 2(b)), can be employed between an upper and a lower conventional mould shown in Fig. 6(a), from which it must be electrically insulated as in the case of low-frequency EMC.\(^{11}\) Similarly as for BITTER coils,\(^{12}\) the water cooling is ensured via axial holes. To enhance the electric currents in the inner wall, a mould of a greater height can be subdivided into mould rings shown in Fig. 6(b), which are also reciprocally insulated.

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