Effect of configuration on magnetic field in cold crucible using for continuous melting and directional solidification

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Abstract: To improve the power efficiency and optimize the configuration of cold crucible using for continuous melting and directional solidification (DS), based on experimental verification, 3D finite element (FE) models with various configuration-elements were developed to investigate the magnetic field in cold crucible. Magnetic flux density ($B$) was measured and calculated under different configuration parameters. These parameters include the inner diameter ($D_2$), the slit width ($d$), the thickness of crucible wall, the section shape of the slit and the shield ring. The results show that the magnetic flux density in $z$ direction ($B_z$) both at the slit and at the midpoint of segment will increase with the decrease of $D_2$ or with the increase of the width of the slit and the section area of wedge slit or removing the shield ring. In addition, there is a worst wall thickness that can induce the minimum $B_z$ for a cold crucible with a certain outer diameter.

Key words: cold crucible; magnetic flux density; configuration design; directional solidification

1 Introduction

Electromagnetic cold crucible (EMCC) designed for continuous melting and directional solidification (DS) is an advanced technology for preparing refractory and reactive materials [1, 2]. One of its advantages is free or low contamination. EMCC is composed of a segmented copper crucible and an induction coil. In the process of continuous melting and directional solidification, the metal in cold crucible is heated to the liquid by an induction coil, and the new solidified ingot at the bottom continuously immerses into Ga–In liquid alloys for cooling, thus a high temperature gradient in perpendicular direction forms, which meets the requirement of DS.

In continuous melting and DS with EMCC, due to nonuniform distribution of electromagnetic force on the melt, the solid/liquid (S/L) interface is always curved [3], and thus the grain growth will be disturbed. Moreover, a low power efficiency of EMCC often results in an insufficient superheat degree of the melt, which will deteriorate the continuous growth of the grains. For these reasons, the main aims in designing the EMCC are to improve the distribution of the magnetic field and improve the power efficiency. Numerical method is exclusively applied to the EM simulation of cold crucible, and previous investigations showed that the electromagnetic transparency and the power efficiency are determined by the cold crucible configuration [4–12]. However, the distribution of magnetic field in EMCC has not been fully comprehended, especially the magnetic flux density ($B$) at different positions at the same height. In addition, the 2D numerical model was adopted to calculate the magnetic flux density [13, 14]. However, there are some differences for the calculating results and experimental results. This shows that 2D numerical model is not ideal to investigate the effect of the configuration of cold crucible on the magnetic field. Therefore, in this study, based on experimental verification, a series of 3D FE models were systematically developed to calculate $B$ to explore the effect of the configuration of cold crucible on the magnetic field. The commercial ANSYS program (distributed by ANSYS HIT) and self-developed FEM codes were applied.

2 Numerical tools and research method

2.1 FE model of cold crucible

The EMCC used for continuous melting and DS is cylindrical, with the height of 150 mm and 8 segments,
which was designed and fabricated by our group, as presented in Figs. 1(a) and (b). Based on this EMCC, the configuration parameters were changed, such as the inner diameter \((D_2)\), the slit shape, the existence of shield ring \((h_1, h_3)\), to calculate magnetic flux density in \(z\) direction \((B_z)\) in EMCC using a 3D nodal-based method. The FE model of EMCC and its FE grids generation are shown in Fig. 2.

### 2.2 Governing equations in electromagnetic field

The cold crucible and the induction coil in EMCC system are considered the conductor, the eddy current mainly distributes in the skin layer, and the permeability of all materials is 1.0. Therefore, in the time-varying EM field under a lower frequency, Maxwell’s equations are given as follows:

\[
\nabla \times H = J \quad (1) \\
\n\nabla \times E = -\frac{\partial B}{\partial t} \quad (2) \\
\n\nabla \cdot B = \nabla \cdot (\nabla \times A) = 0 \quad (3)
\]

where \(H\) is the magnetic field intensity; \(E\) is the electric field intensity; \(B\) is the magnetic flux density; \(A\) is the magnetic vector potential [15]. The magnetic field is a curl field, therefore the function of scalar potential cannot be used. However, no current exists in the free space (air), so \(H\) can be stated as a gradient of a scalar quantity:

\[
H = -\nabla \cdot \Phi_m \quad (4)
\]

The magnetic scalar potential \(\Phi_m\) has been adopted to save calculating memory and time. To solve \(A\) and \(\Phi_m\), the Alembert equation with dynamic potential function can be written as follows:

![Fig.1 Bottomless type cold crucible (a) and its section (b)](image1)

![Fig. 2 Calculation model: (a) FE model; (b) FE grid](image2)
\[ \nabla^2 \cdot \mathbf{A} - \varepsilon \mu \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu \mathbf{J} \quad (5) \]
\[ \nabla^2 \cdot \Phi - \varepsilon \rho \frac{\partial^2 \Phi}{\partial t^2} = -\frac{\rho}{\varepsilon} \quad (6) \]

where \( \varepsilon \) is the permittivity. When the field sources \( \mathbf{J} \) and \( \rho \) are given, \( \mathbf{A} \) and \( \Phi \) can be solved and then substituting the solution into equations (2) and (3), \( B \) and \( E \) can be consequently solved [16].

### 2.3 Parameters of models

A standard crucible model is set and its geometry dimension is listed in Table 1, which includes the height of the nether and the upper shield rings (\( h_1 \) and \( h_3 \)), the length of the slit (\( h_2 \)), the height of the cold crucible (\( H \)), the outer and inner diameters of the cold crucible (\( D_1 \) and \( D_2 \)), the induction coil position (\( h_1 + h_4 \)), the width (\( d \)) of the rectangular slit and the power parameters. In this study, each configuration element is individually changed, which is shown in Table 2, and the physical properties of the materials calculated in FE models are shown in Table 3.

#### Table 1 Dimensions and power parameters in standard crucible model

<table>
<thead>
<tr>
<th>Configuration dimension/mm</th>
<th>Power parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_1 )</td>
<td>( h_2 )</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
</tr>
</tbody>
</table>

#### Table 2 Different levels of influence factors on magnetic field

<table>
<thead>
<tr>
<th>Influence factor (variable) (variable)</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter, ( D_2 )/mm</td>
<td>24, 30, 48</td>
</tr>
<tr>
<td>Wall thickness/mm</td>
<td>7, 9, 11, 13, 15, 17</td>
</tr>
<tr>
<td>Width of rectangular slit, ( d )/mm</td>
<td>0.4, 0.8, 1.0, 1.2, 1.6</td>
</tr>
</tbody>
</table>

#### Table 3 Physical properties of materials used in FE models

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity/ (10^8Ωm)</th>
<th>Relative permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induction coil</td>
<td>1.673</td>
<td>1</td>
</tr>
<tr>
<td>Cold crucible</td>
<td>1.8</td>
<td>1</td>
</tr>
<tr>
<td>Air</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

During induction heating process, the induced current on the metal mainly distributes in the skin layer due to skin effect, thus the magnetic field in EMCC which can be effectively utilized is near the crucible inner wall. For this reason, \( B_z \) at the slit and the midpoint of the segment on the inner wall are selected to explore the magnetic field distribution, which are noted in Fig. 1.

### 3 Results and discussion

#### 3.1 Comparison between measured and calculated results

Considering the simplicity and the accuracy of experimental measurement, \( B_z \) at the cold crucible centre was measured in experiment and was calculated with 2D and 3D models respectively, the results are shown in Fig. 3 [17]. From this figure, the \( B_z \) calculated using a 2D model is slightly higher than that measured because the slit configuration and the shielding effect of the copper segment are omitted in this model. Whereas, the \( B_z \) calculated using a 3D model is in good agreement with the measured result. Therefore, the 3D numerical model can produce more accuracy result to reveal the distribution of the magnetic field in cold crucible. \( B_z \) under different configuration elements was calculated with 3D FE models.

#### Fig. 3 Measured and calculated \( B_z \) at crucible center

#### 3.2 Effect of configuration elements

##### 3.2.1 Inner diameter of cold crucible

The inner diameter (\( D_2 \)) of the crucible varies from 24 to 48 mm, and the thickness of the crucible wall keeps constant (15 mm). The results calculated under different \( D_2 \) are shown in Fig. 4. It can be seen from Fig. 4 that \( B_z \) increases with the decrease of \( D_2 \) in the height range of induction coil. This means that the reduced inner space of EMCC can increase the density of magnetic lines. Whereas, the results in Ref. [5] indicated that there is an optimal diameter with the maximum power efficiency. Therefore, undersized \( D_2 \) may cause lower energy utilization. By comparing \( B_z \) at the slit (Fig. 4(a)) with that at the segment midpoint (Fig. 4(b)) at the same height, \( B_z \) at slit is obviously higher than that at the segment midpoint, because the EM penetration is the strongest at the slit. The maximum of \( B_z \) appears near the half height of the induction coil. In addition, \( B_z \) will dramatically decrease when the position is out of the coil region.
3.2.2 Thickness of crucible wall

To investigate the effect of the wall thickness on $B_z$, the outer diameter $D_1$ (60 mm) keeps constant while the inner diameter $D_2$ is changed, the calculation results of $B_z$ distribution at the slit and at the segment midpoint are shown in Figs. 5(a) and (b) and the maximum $B_z$ at the slit and the segment midpoint are shown in Fig. 5(c).

When the wall thickness is changed from 7 to 17 mm, the maximum $B_z$ both at the slit and the segment midpoint decreases initially till reaching the minimum value, and then increases, which are clearly presented in Fig. 5(c). A thinner copper wall can reduce the shielding effect caused by the crucible wall, which results in a higher $B_z$ in EMCC, thus $B_z$ decreases due to the slightly thickening of the crucible wall. Further, the crucible inner space reduces with the thickening of the crucible wall. As a consequence, the slit density on the crucible inner wall increases, therefore, $B_z$ at the slit and at the segment will increase.

3.2.3 Width of rectangular slit

$B_z$ was calculated when the slit width varied from 0.4 to 1.6 mm, the results are shown in Figs. 6(a) and (b) and the maximum values of them are shown in Fig. 6(c). It can be obviously seen from Figs. 6(a) and (b) that $B_z$ increases with the extending of the slit width. $B_z$ reaches the maximum value when the crucible height is about 55 mm, the maximum $B_z$ and the slit width have a near linear relation, as shown in Fig. 6(c). Moreover, the extending of the slit width would improve the EM transparency, especially at the slit. Therefore, with the extending of the rectangular slit, the gap between the maximum $B_z$ at the slit and that at the segment midpoint presents an expanding tendency.
Fig. 6 $B_z$ distribution (a, b) and the maximum $B_z$ (c) under different $d$: (a) At slit; (b) At segment midpoint; (c) Maximum $B_z$

3.2.4 Section shape of wedgy slit

The section shape and the geometry dimension of the wedge slit are presented in Fig. 7(a), where $W$ is the variable. With the widening of $W$ from 1 to 15 mm, $B_z$ both at the slit and at the segment midpoint increase; the maximum $B_z$ increases over 25%, which varies from 407 to 532 mT at the slit and from 326 to 406 mT at the segment midpoint, respectively, as illustrated in Figs. 7(b) and (c). FELIACHI et al [14] indicated that the segment with a triangle section shape possesses the best EM transparency, which coincides with the results in this investigation. The curves in Fig. 7(d) show that the climbing tendency of the maximum $B_z$ gradually slows down with the increase of $W$. On one hand, the extending section area of the slit improves the crucible transparency. On the other hand, the sharp section shape of the segment is not beneficial to increase of the induced
current on the segment regardless of the extending section area of the slit.

Further, the dimension of $L$ is treated as a variable to calculate the magnetic field, as shown in Fig. 8(a). Calculated results reveal that a shorter $L$ is beneficial to enhancing $B_z$ at the slit (Fig. 8(b)) and at the segment midpoint (Fig. 8(c)). Increasing $L$ from 1 to 9 mm will cause the maximum $B_z$ to reduce (Fig. 8(d)), which indicates that a larger area of the slit section can obviously improve the EM transparency. In addition, from the comparison of the curves in Fig. 7(d) and Fig. 8(d), broadening $W$ is a more effective way to improve the EM transparency comparing with shortening $L$.

3.2.5 Shielding cooper ring

The effects of $h_1$, $h_2$ and $h_3$ are evaluated to explore the influence of the shield ring on the $B_z$ at segment midpoint. The results are shown in Fig. 9. It can be clearly seen form Fig. 9 that the shield ring can strongly impair the $B_z$, and the $B_z$ will sharply decrease when there is a shield ring close to the induction coil, which can be partly explained by the shielding effect caused by shield ring. Due to a far gap between the induction coil and the upper shield ring, the $B_z$ hardly reduces in the region of the coil.

4 Conclusions

1) $B_z$ increases with the decrease of inner diameter and the extending of the slit width in the height range of the induction coil. Under the same height, $B_z$ at the slit is obviously higher than that at the segment midpoint.

2) The maximum $B_z$ decreases initially till reaching the minimum value, and then increases with the increase of the wall thickness.

3) For the wedge slit, broadening $W$ is a more effectively way to improve $B_z$ comparing with shortening $L$.

4) A shield ring close to the induction coil will strongly decrease $B_z$ in the cold crucible.

Appendix

$B$ — Magnetic flux density (T);

$B_z$ — Magnetic flux density in z direction (T);
结构对连续熔化与定向凝固用冷坩埚磁场的影响

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摘要：为了提高连续熔铸与定向凝固用冷坩埚的工作效率和优化结构设计，基于实验验证，建立了不同结构的电磁冷坩埚的 3D 有限元模型，并研究了坩埚结构对其内部磁场的影响规律。电磁冷坩埚的结构变量包括坩埚内径、坩埚壁厚、开缝形状以及水冷铜环。结果表明：随着坩埚内径的减小、开缝宽度和横截面积的增大以及水冷铜环的去除，坩埚内部磁场值最低。此外，当外径一定时，存在一个最差的坩埚壁厚使得坩埚内部磁场值最低。

关键词：冷坩埚；磁感应强度；结构设计；定向凝固