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Finite Element Analysis of a New Furnace with Travelling Field Inductor for Induction Heating, Electromagnetic Stirring and Levitation of Molten Titanium Alloys

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Abstract. The study based on finite element (FE) models of the electromagnetic field and of the motion inside the volume of the levitated molten titanium alloy of a new induction furnace equipped with a travelling field inductor in this paper is focused on three important effects - induction heating, electromagnetic stirring and charge levitation. The main parameters of this study are the charge weight, the supply frequency and the relative position charge - inductor.

Key words: titanium alloys processing, induction heating, electromagnetic stirring, levitation, FE analysis

Introduction

The motion inside the molten volume of the classical induction furnaces or in the cold crucible furnaces and the levitation of this volume by the action of the Lorentz forces are more or less considered secondary effects of the electromagnetic field presence with respect the main action, represented by the Joule heating effect of induced currents. Instead of the usual inductor that creates a magnetic field only time dependent, this paper considers an inductor of traveling field type, able to generate a wave magnetic field, time and space dependent. This is a new device whose operation regroups the Joule effect of induced currents, respectively the induction furnace function, and the driving effect of Lorentz forces, respectively the linear induction motor function. This last function is the result of the important axial/vertical component of Lorentz forces. Since the spatial structure of the Lorentz force volume density is different in traveling field, the motion inside the molten volume, respectively the electromagnetic stirring, is also different than in a time dependent magnetic field. Consequently, the induction heating (IH), the electromagnetic stirring (ES) and the charge levitation (LEV) are of the same level of practical interest in the new IH-ES-LEV furnace.

Description of the finite element 3D model of the new IH-ES-LEV furnace

This section describes the Flux3D finite element model of the new IH-ES-LEV furnace for induction heating of titanium alloys, in which the Lorentz forces ensure an intense electromagnetic stirring and the levitation of the furnace charge. The inductor of this furnace, Fig. 1, is composed from six helicoidal turns/coils of stranded conductor type, indexed in Fig. 2 phase A1, phase A2, phase A3, …, phase A6. The terminals of the inductor winding are 60 degrees shifted around the furnace axis from one phase to the next one.

Fig. 1: Geometry of the 6-phases travelling field IH-ES-LEV furnace

Fig. 2: Meshing of the regions inductor and charge of the 6-phases travelling field furnace

Supplying the inductor from a power source that consists in a usual 3-phase frequency converter and a 3-phase/6-phase transformer, a travelling magnetic field is generated. If the currents injected in the six phases of the inductor have the following time dependences:
\[ i_{A1}(t) = \sqrt{2} \cdot I \cdot \sin(2\pi ft), \quad i_{A2}(t) = \sqrt{2} \cdot I \cdot \sin(2\pi ft - \pi/6), \quad i_{A3}(t) = \sqrt{2} \cdot I \cdot \sin(2\pi ft - 2\pi/6), \ldots, \quad i_{A6}(t) = \sqrt{2} \cdot I \cdot \sin(2\pi ft - 5\pi/6) \]  

(1)

the wavelength of the travelling field is the double of the inductor axial extension.

The charge of the furnace inside the inductor, Fig. 1, that consists in molten titanium alloy with the resistivity \(2 \, \Omega \cdot \text{mm}^2/\text{m}\), density \(4200 \, \text{kg}/\text{m}^3\) and the viscosity \(4.4 \times 10^{-3} \, \text{Pas}\), is the solid conductor region of the electromagnetic field computation domain. This region has a particular geometry, imposed by the balance between the gravitation, Lorentz forces, viscosity forces and the surface tension. The geometrical parameter \text{CHARGE\_POZ} = 0 defines the position of the charge in Fig. 1 with respect the inductor.

The numerical applications whose results are further analyzed consider two cases - charge 1 and charge 2, with the geometrical data in Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass [kg]</th>
<th>Maximum diameter of charge [mm]</th>
<th>Height of charge [mm]</th>
<th>Inner diameter of the inductor [mm]</th>
<th>Outer diameter of the inductor [mm]</th>
<th>Height of coils cross-section [mm]</th>
<th>Coil - coil gap [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>charge 1</td>
<td>89.08</td>
<td>300</td>
<td>360</td>
<td>360</td>
<td>480</td>
<td>44</td>
<td>4.16</td>
</tr>
<tr>
<td>charge 2</td>
<td>28.03</td>
<td>200</td>
<td>255</td>
<td>260</td>
<td>320</td>
<td>34</td>
<td>3.15</td>
</tr>
</tbody>
</table>

**Main results of the electromagnetic field analysis**

For the case charge 1 in Table 1, supply frequency \(f = 160 \, \text{Hz}\) and phase current \(I = 13.5 \, \text{kA}\) are presented in this section graphical results as support of a better understanding of the new furnace operation. The position of the levitated charge 1 with respect the inductor corresponds to \text{CHARGE\_POZ} = 110.4 \, \text{mm}.

The maximum value 6.17 A/mm\(^2\) of the induced current density, Fig. 3, characterizes a point on the lateral area of the charge surface whose radius is nearly the maximum. As shown in the second image of Fig. 3 related the current density in an axial plane of the charge region, this local quantity, which determines the induction heating efficiency and the electromagnetic stirring intensity, decreases in radial direction.

![Fig. 3: Induced currents density [A/m\(^2\)] maps and arrows](image)

In order to understand the configuration of the magnetic field, the 3D arrows and the 2D arrow representations in the axial plane yOz are presented in Fig. 4 and Fig. 5 respectively. The structure of the magnetic flux density arrows in the second image of Fig. 5, where the legend is lower limited at 100 mT, proves the levitation effect of the magnetic field.

![Fig. 4: Magnetic flux density [T] arrows](image)

**range [0 ... 217] mT**

![Fig. 5: Magnetic flux density in the axial plane yOz](image)

**range [100 ... 217] mT**
The arrows representation of the volume density of Lorentz force in Fig. 6 clearly reflects the levitation effect of the travelling electromagnetic field. The maximum value of this quantity over the charge volume is 513.3 N/m$^3$, while the maximums of the axial/levitation and radial components are 306.7 N/m$^3$ and 429.5 N/m$^3$ respectively.

The structure of the Lorentz force volume density is also reflected by the maps in Fig. 7 related the surface of the furnace charge and a vertical plane that contain the charge axis.

![Fig. 6: Arrows of Lorentz force density [N/m$^3$]](image)

![Fig. 7: Lorentz force density [N/m$^3$]](image)

**Optimum of the levitation effect in the III-ES-LEV furnace**

The influence of the supply frequency on the levitation force that is the integral over the charge volume of the Oz component of the Lorentz force volume density for $I = 14.5$ kA and \(\text{CHARGE}_\text{POZ} = 0\) mm is analyzed in this section. As Fig. 8 shows, \(f_{\text{opt1}} = 160\) Hz represents the value of the frequency for which the maximum of the levitation force is obtained. If the frequency increases over this optimal value, the levitation force slightly decreases. Related the power induced in the charge, Fig. 9, this quantity continuously increase when the value of the supply frequency increases.

Similar results are obtained for charge 2, where the maximum of levitation is obtained for the frequency \(f_{\text{opt2}} = 350\) Hz.

![Fig. 8: Levitation force versus supply frequency - charge 1](image)

![Fig. 9: Power induced in the charge 1 versus frequency](image)

**Identification of the stable equilibrium vertical position of the levitated charge**

The dependence of the levitation force on the relative position charge - inductor in case charge 1, for $I = 13.5$ kA and frequency \(f_{\text{opt1}} = 160\) Hz is represented in Fig. 10. The intersection point to the right of this curve with the horizontal line that corresponds to the charge 1 weight that is 873.9 N, defines the Stable Equilibrium position of the charge for which the levitation force is equal with the charge weight. This position corresponds to \(\text{CHARGE}_\text{POZ} = 110.4\) mm, for which the power induced in the charge, is 124.7 kW.

![Fig. 10: Levitation force versus vertical charge position](image)

For the charge 2, $I = 8.15$ kA and \(f_{\text{opt2}} = 350\) Hz, the equilibrium position corresponds to \(\text{CHARGE}_\text{POZ} = 67.4\) mm.
Increase of the furnace power without alteration of the levitation characteristics

The maximum value of the levitation force with respect to the relative position charge - inductor, Fig. 10, in case charge 1 is 910.5 N for the frequency 160 Hz and the current 13.5 kA. This means a levitation gap 910.5 - 873.9 = 36.6 N between this maximum value and the charge weight. The interest to increase the furnace power should be of practical interest. The results in Table 2, where two increased values of the frequency are considered, contain the values of the current I for which the levitation gap 36.6 N rest unchanged and reflect the increase of the power induced in the charge. The equilibrium position of the charge defined by the result CHARGE_POZ goes up when the frequency increases.

<table>
<thead>
<tr>
<th>f [Hz]</th>
<th>I [kA]</th>
<th>CHARGE_POZ [mm]</th>
<th>P [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>13.5</td>
<td>110.4</td>
<td>124.7</td>
</tr>
<tr>
<td>220</td>
<td>12.96</td>
<td>130.4</td>
<td>180.5</td>
</tr>
<tr>
<td>1000</td>
<td>12.89</td>
<td>152.9</td>
<td>338.1</td>
</tr>
</tbody>
</table>

Electromagnetic stirring / motion inside the molten titanium alloy

The study of the motion inside the volume of molten titanium alloy based on the Fluent model takes into account the field of the Lorentz force density computed with the Flux3D electromagnetic model of the furnace. The computation of the velocity field assumes a fixed boundary of the computation domain and zero value of the normal component of the velocity in all points of this closed surface. The map of the velocity for a time step, i.e., an instantaneous field of velocity and the arrow representation of the average in time of molten alloy velocity are presented in Fig. 11.

Fig. 11. Map of the velocity [m/s] at a given time step and arrows of the average in time velocity

A lateral view and the upside view of the streamlines of the average in time velocity, Fig. 12, clearly reflect electromagnetic stirring effect that consists in the upward motion on the lateral surface of the charge as result of the driving action of Lorentz forces and the downward motion in the charge central volume, region of weak electromagnetic forces.

Fig. 12. Streamlines of the average in time velocity [m/s]

Conclusions

The melting, the levitation and the intense electromagnetic stirring of titanium alloy charges up to 100 kg are processes proved to be feasible by using the new IH-ES-LEC induction furnace, equipped with a multiphase traveling field inductor. A good efficiency of the induction heating and Lorentz forces that ensure the charge levitation and an intense motion inside the molten volume are all obtained in a relatively low frequency traveling magnetic field.

References