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Recent Investigations on LELs for Levitation Melting

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Abstract

In the present paper, the analysis of a new prototype of Longitudinal Electromagnetic Levitator (LEL) for melting non magnetic billets is presented. The purposes of the research here described were to increase the levitation capacity of a previous levitation apparatus and to improve the system performance.

A parametric analysis of the prototype has been carried out by solving the coupled electromagnetic and thermal problems using a commercial finite element solver in order to analyse the influence of the process parameters.

The numerical results have been validated by experimental tests which have shown a fairly good agreement.

Introduction

High frequency electromagnetic levitation melting of metals is a process for achieving high purity melts, where any contact with a crucible is avoided.

The purposes of this investigation were to improve the system performance, i.e. to increase the levitation capacity, to reduce the melting time and to evaluate the levitation stability.

2D and 3D FEM commercial software models have been applied for the solution of the coupled electromagnetic and thermal problems, in order to optimize the process parameters [1]. The electromagnetic problem has been solved by the A-V formulation in order to calculate the induced power density distribution and has been coupled with a thermal model for the calculation of the transient temperature field inside the billet.

The 2D models allowed us to evaluate the optimal equilibrium positions in order to maximize the induced power in the billet to the end of reducing the melting time.

Three-dimensional effects, i.e. the influence of the levitator end connections, have been evaluated by 3D simulations, assuming the billet fixed in the equilibrium position during the thermal transient. Several experiments have been carried out on the prototype, in order to validate the numerical results. Some helpful considerations emerged from the tests.

1. Description of the Problem

During the heating process, the billet is held in an equilibrium position y_e, in a time varying magnetic field H, produced by supplying the inductor with a sinusoidal current of constant amplitude. The equilibrium position of the billet is defined as the distance between the bottom conductors and the billet barycentre. Rotation and translation movements are neglected in a first approximation.

In order to evaluate the temperature at the end of the heating process, a magneto-thermal transient problem has to be solved: the induced current and power density distributions in the billet have been evaluated by solving a time-harmonic eddy current problem at the supply frequency, taking into account skin and proximity effects. Usually, the frequencies involved in levitation processes are between 10 and 500 kHz; in this range, Maxwell equations can be solved in the quasi-stationary case. Finally, the transient thermal analysis has been carried out to evaluate the temperature distribution and the melting time.

2. Formulation

The electromagnetic problem has been solved in terms of the phasor of the magnetic vector potential, $\vec{A}$, and the phasor of the electric scalar potential, V. The magnetic field source consists of eight series connected longitudinal conductors with impressed current. At the domain boundary, infinite boundary conditions are imposed in order to set the magnetic vector potential to zero at infinite distance.

The transient temperature distribution in the billet has been evaluated by solving the Fourier equation in the billet region. Suitable heat exchange conditions are imposed on the billet surface considering convection and radiation. The transient simulation is achieved by considering a convenient number of time steps: at each step, the induced power density distribution is calculated by the electromagnetic problem solution and is used as source for the thermal problem. At each step all the material properties are updated.

The force acting on the billet can be calculated by using Laplace's law:

$$\vec{F} = \int_{\Omega_B} \Re_e(\vec{J} \times \vec{B}^*)\, d\Omega, \qquad (1)$$

where the current density $\vec{J}$ and the magnetic flux density $\vec{B}$ are known from the electromagnetic solution. The instantaneous forces acting on the billet are the sum of a constant component and a component oscillating with double frequency. Considering the low-pass filtering effect of the billet inertia, the periodic component can be reasonably neglected.

In a cartesian coordinate system (x, y, z), representing horizontal, vertical and longitudinal axes respectively, it is possible to calculate the components of the force acting on the billet $\vec{F}_x\ \vec{F}_y\ \vec{F}_z$. $\vec{F}_y$ is the levitating component of force, while $\vec{F}_x$ and $\vec{F}_z$ are the stabilizing ones.

Tab. 1. The electric and thermal characteristics used for the calculations

Material	ρ [Ωm]	λ [W/m·K]	C [J/kg·K]	γ [kg/m^3]	Emissivity	α[W/m^2·K]
Aluminium	2.65 10^{-8} *	237 **	925	2700	-	-
Billet surface	-	-	-	-	0.3	20

Note: * - at 293 K; ** - at 300 K (linear + 0.004 K^{-1})

3. Description of the Model

A sketch of the cross-section and the laboratory prototype of the levitator are shown in figures 1-a) and –b). The system is composed by the inductor and an aluminium cylindrical billet, 250 mm long, 25 mm diameter; the inductor consists of eight square cross-section copper tubes, 8.5x8.5x1 mm, supplied by AC current at 10 kHz. All main conductors are parallel to the longitudinal billet axis, as shown in figure 1-b), and series-connected. The inductor is surrounded by an infinite air region. The thermal model is limited to the billet region, enclosed by a surface describing heat exchange.

The electromagnetic and thermal problems are solved by using a commercial Finite Element Method tool [1]. A first-order mesh, composed by 260000 nodes and 1250000 volume elements, is adopted for the 3D problems.

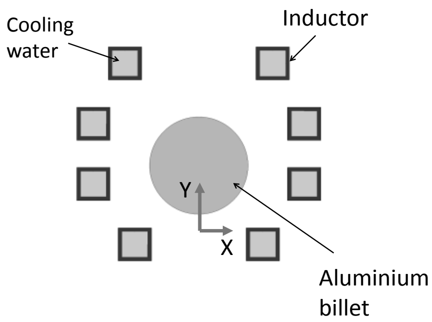


Fig. 1.a) 2D cross-section of levitation system

Fig. 1. b) Laboratory prototype

4. Numerical Results

4. 1. 2D Simulation Results

For the geometry of figure 1-a), a parametric optimization based on 2D electromagnetic simulations has been carried out, in order to find the range of billet equilibrium positions and the corresponding values of the supply current. In particular, the equilibrium positions for the billet are found when the upward total magnetic force is equal to the billet weight, i.e. 3.25 N.

A non-linear relationship for the resulting force acting on the billet can be obtained by applying different supply current values.

An example of the calculation results is shown in figure 2), which gives the resulting force for different vertical positions *y* of the billet as a function of the supply current in the range 1000 to 1800 Arms.

As shown in figure 3, each equilibrium position of the billet along the vertical axis corresponds to a different supply current value. The graph of figure 4) gives the total power induced in the billet as a function of the supply current at the different equilibrium positions. The diagram shows that in order to maximize the total induced power, the equilibrium position must be chosen as close as possible to the bottom conductors; however, in this choice, the risk of collision between the billet and the levitator's conductors, as a consequence of possible billet oscillations, must be taken into account.

To make a preliminary choice of the working equilibrium position (and supply current), some considerations on the heating process have been carried out. In the graph of figure 4, the evaluation of the levitator efficiency for

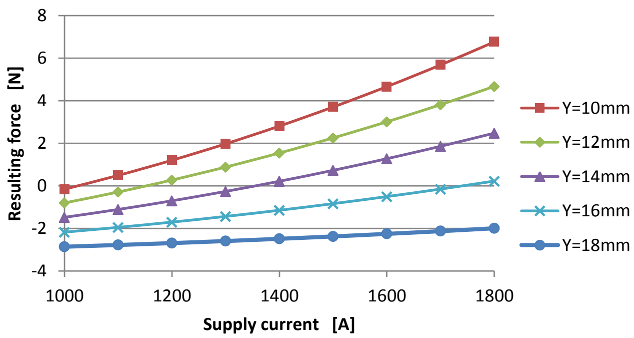


Fig. 2. Resulting force *vs.* supply current at different billet positions *y*

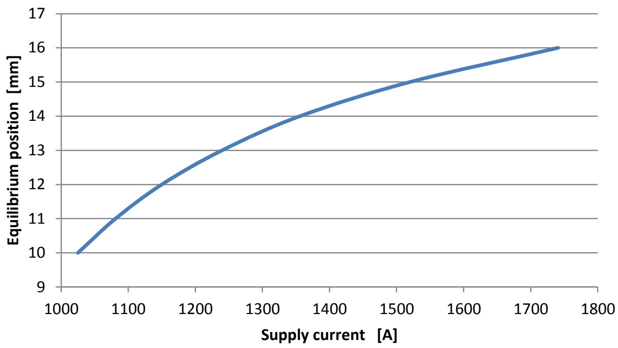


Fig. 3. Equilibrium position *vs.* supply current

different supply current values is also given: the efficiency decreases when the billet distance from the bottom conductors increases.

Moreover, also the value of the total induced power must be considered in the choice of the equilibrium position in order to obtain a fast melting process. Finally, for the laboratory tests, the total input power of the levitator had to be adapted to the available output of the supply. Consequently, our choice was to keep the billet in a range of equilibrium positions between 14 and 16 mm.

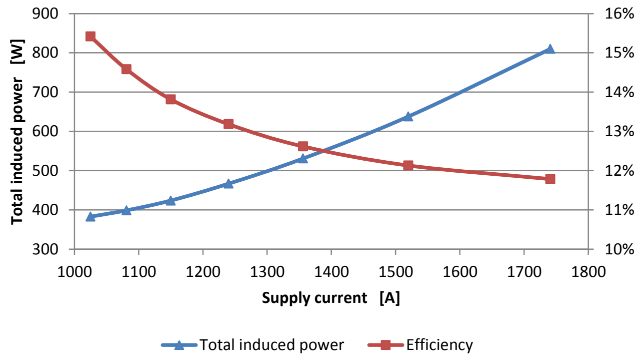


Fig. 4. Power induced in the billet and estimated electrical efficiency *vs.* the exciting current at the equilibrium positions

As shown in figure 5, the induced power density is not uniformly distributed in the billet cross-section; in particular, most part of the power is transferred at the bottom of the billet.

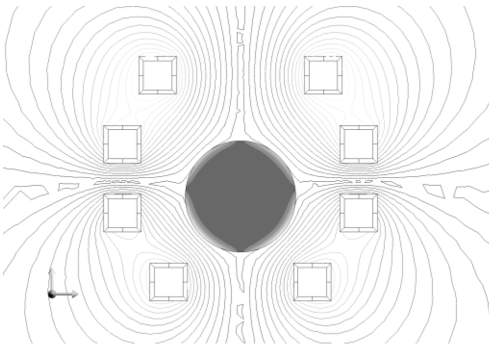


Fig. 5. Induced current density distribution in the billet cross-section and magnetic field lines [at 1500A supply current]

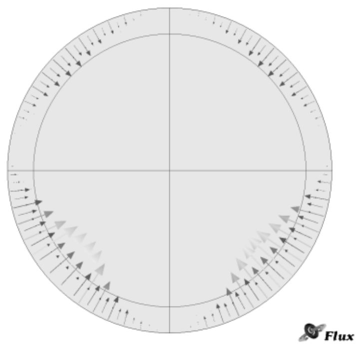


Fig. 6. Force distribution on the billet cross-section [at 1500A supply current]

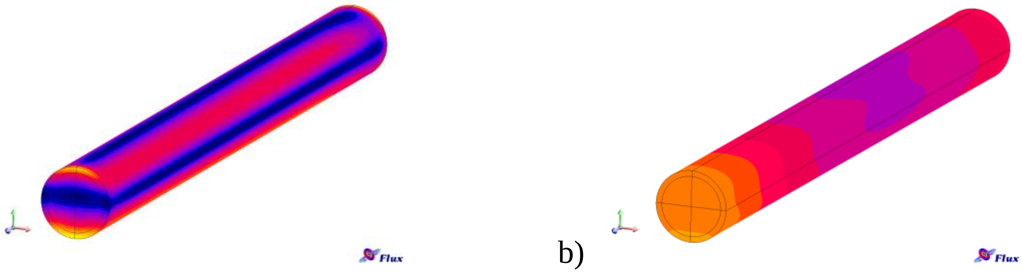
The electromagnetic force distribution acting on the billet is represented in figure 6. It should be noted that the force distribution on the billet traces the induced current distribution, and four stressed zones are present. As a result, a non-uniform force distribution is obtained; in particular, at the bottom of the billet there is a lack of the levitation force, because of the 'magnetic hole' formed by the two lower conductors.

Finally, in order to estimate the melting time, a transient magneto-thermal simulation has been carried out, taking into account the temperature dependence of the material properties.

4. 2. 3D Simulation Results

A three-dimensional electromagnetic and thermal coupled problem has been solved, in order to predict the influence of the coil end effects on the heating process, i.e. the billet stability and the temperature distribution. In figure 7-a) and -b), the current density and temperature distributions at the end of the process are shown. The non-uniform distribution of the induced current density practically does not affect the final temperature distribution, because a fast thermal equalization occurs during the thermal transient due to the high thermal conductivity of aluminium; as a consequence the billet temperature tends to increase nearly homogeneously.

The effect of the levitator end connections is to increase the current density induced at the billet edges, providing an additional induced power, which gives rise to a small temperature gradient from the extremities to the billet centre.



a) b)

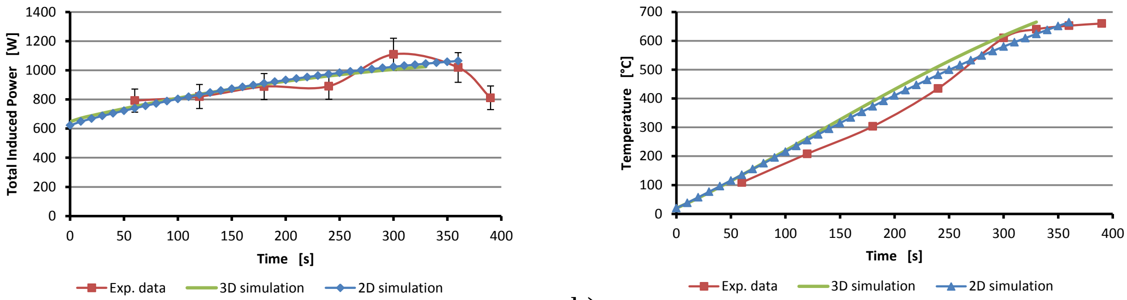
Fig. 7**.** Induced current density (a) and temperature distribution (b) on the billet at the end of the process [I=1500 A; maximum temperature difference Δϑ=13 °C]

5. Experimental Validation of the Results

Several melting tests have been performed on the prototype in order to compare the numerical results with experimental data.

The diagrams of figure 8 show that the total power induced in the billet and temperature variations during the process predicted by 2D and 3D numerical simulations are in good agreement with experimental tests.

It should be noted that the numerical simulations are stopped before reaching the melting temperature, while experimental tests are carried out until the melting of the billet is reached. This explains the lower slope of the increase of measured temperature at the end of the melting process, because a part of the induced power has to provide also the latent heat. The melting temperature is reached in about 390 seconds.



a) b)

Fig. 8. Induced power (a) and billet temperature (b) during the heating process; comparison of 2D and 3D calculations with experimental data [I=1500 A]

Figure 9 shows a thermal image of the billet at the end of the heating process. The predicted force distribution on the billet, shown in figure 6, has been confirmed by experimental observation. At low temperature, the billet behaves as a rigid body and all electromagnetic stresses give rise to a resulting force, acting on the billet barycentre. Moreover, due to the non-symmetric levitator connections at the coil ends, a torque acts on the billet leading to its rotation and possible oscillations.

This situation is no more valid at high temperature, because plastic deformations of the billet take place while approaching the melting temperature.

In particular, once the melting temperature is reached, the electromagnetic stresses act locally on the melted billet surface; considering also the hydrostatic pressure and surface tension effects, the non-uniform force distribution stretches and deforms the billet.

Moreover, a typical drop-shaped cross-section occurs because the levitation forces acting on the bottom part of the billet are weaker, due to the 'magnetic hole' between the two lower conductors (see figure 6), while the hydrostatic pressure reaches the maximum value in this position. A second aspect is that, as in a plastic deformable body, all perturbations act only locally and torque effects and oscillations are no more generated.

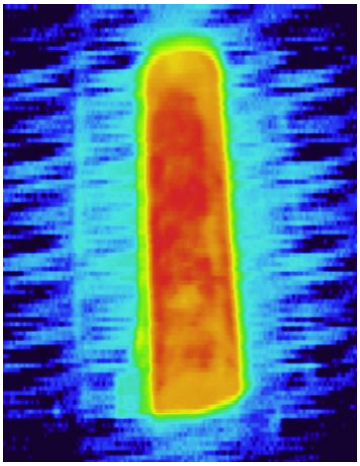


Fig. 9. Thermal image of the heated billet

Conclusions

A new prototype of longitudinal electromagnetic levitator for melting non-magnetic billets has been built and tested. The goals of higher levitation capacity and good levitation stability have been achieved; moreover, the melting of aluminium billet has been obtained in a relatively short time, which can be further reduced with a suitably increased exciting current, not presently available in the laboratory.

The effect of the 'magnetic hole' has been verified; it causes the melted billet to lose some metal drops at the bottom and, finally, to fall down. After the falling of metal drops, the temperature of the levitating melt slightly decreases; a possible explanation is that the coupling with electromagnetic field in this new configuration is not so good as before, because the metal moves away from the inductor and the cross-section of the levitating melt becomes lower, while the heat losses from the billet surface remains approximately the same.

Some oscillations can arise during the first part of the process, when the billet temperature is low. If not damped, these oscillations can be amplified and cause the test failure. This drawback has been faced with the introduction of a damper, placed at one of the billet edges. This consideration will lead to future developments, e.g. optimization of the LEL's geometry, in order to obtain a faster and more stable heating process.

Further researches are programmed for more deeply investigating this problem.

References

[1] CEDRAT, http://www.cedrat.com, FLUX user's guide.

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