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Numerical Modeling of Cold Crucible Induction Melting

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Abstract: This paper describes a numerical solution method for the simulation of a cold crucible induction melting process involving the coupling of electromagnetic, temperature and turbulent velocity fields. The cold crucible induction melting (CCIM) is a process to melt extremely reactive alloys when purity is required. An example of such an alloy is titanium, which can be used for the manufacturing of medical implants, turbine blades and turbocharger rotors. During the CCIM process, the metal charge is contained on a water cooled segmented cooper crucible, and the energy necessary to heat, melt, and overheat the charge is generated by an electromagnetic field induced by a solenoidal coil surrounding the crucible. Once the charge is melted, the induced electromagnetic forces push the metal away from the wall. Hence, the electromagnetic field and the associated force fields are strongly coupled to the free surface dynamics of the liquid metal, the turbulent fluid flow within it, and the heat mass transfer. In order to understand how each parameter of the process affects in the overheating of the liquid, a computer simulation model has been developed using the software COMSOL Multiphysics. The electromagnetic field is solved in the frequency domain, while temperature and fluid flow phenomena are solved in the time domain.

Keywords: cold crucible induction melting, titanium, multiphysics.

1. Introduction

The cold crucible induction melting (CCIM) is an innovative process to melt high temperature reactive materials like titanium alloys. The melting and casting of the material is performed in vacuum or in a protective atmosphere in order to prevent any contamination of the charge. Moreover, a water cooled segmented crucible is used instead of a ceramic crucible to avoid any kind of reaction among the charge and the crucible (Figure 1). The magnetic field generated by an external coil penetrates through the slits of the crucible and generates induced currents which are responsible of melting the charge due to Joule heating.

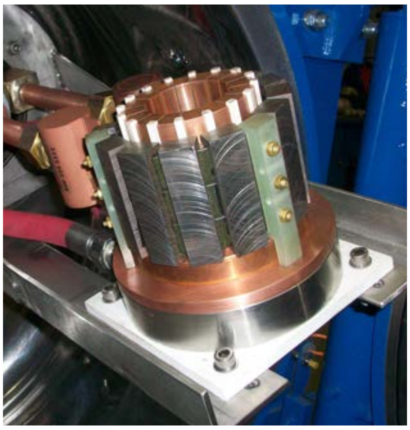

Figure 1. Induction cold crucible furnace.

The main advantage of the cold crucible process is that no contamination of the charge occurs, because there is no interaction between the target material and the cooper crucible [1, 2]. Thus, CCIM is used mainly for metallurgic, medical, and aeronautic applications [3, 4]. However, the energetic efficiency is quite low, which is a disadvantage for its application in a wide industrial range. Another fundamental limitation is the poor overheating that the molten liquid achieves with this process. If the overheating of the charge is small when the molten liquid is tilted to the mold, the probability of appearance of casting defects in the final parts is high. In case of titanium alloys, temperatures above 1600ºC are necessary to melt the metal and obtain enough superheat for casting thin section parts. There are several parameters that play a fundamental role in the overheating and the efficiency of the process. The most important ones are the inductor current that passes through the coil, the frequency of the current, the design of the crucible, the design of the coil, and the crucible filling level. The experimental analysis of some of these parameters, such as the design of the crucible or frequency, is complicated because it is necessary to consider different crucible geometries and different inductor generators, respectively. Even if this is a well-known process, it has never been really optimized. The numerical modeling is a way to easily study the influence of these parameters. Industrial metallurgical processes like melting of alloys in induction furnaces have become a subject of numerical modeling since many years ago [5-7]. A wide range of different modeling approaches for the simulation of the melt flow and heat transfer processes have been developed. In this paper, a 3D electromagnetic-fluid-heat transfer coupled model is presented. The remaining part of the paper contains the mathematical description of the numerical model, including the governing equations and boundary conditions, and the numerical simulation results.

2. Numerical model

The CCIM is a complex process where different physical fields are strongly coupled. The magnetic field generated by the coil creates induced currents in the charge. These induced currents heat and melt the material by Joule heating. Once the charge temperature increases, its electrical properties change, varying the values of the induced currents and the temperature gradient in the charge. Once the material has started to melt, the electromagnetic forces push the material away from the wall, modifying the geometry of the initial billet. As a consequence of this new geometry, the induced currents generated in the charge change again, as well as the corresponding electromagnetic forces. Finally, when the billet is entirely melted, the electromagnetic forces have stirring effect in the molten liquid, homogenizing the temperature due to flow motion. These couplings are summarized in Figure 2.

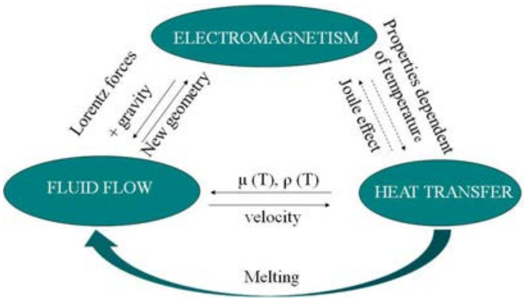

Figure 2. Couplings of different fields.

In this work, some of these couplings have been implemented in the model. The charge is considered to be in a molten state from the beginning ignoring the melting process. We also ignore the deformation of the charge.

2.1. Geometry

The modeled cold cooper crucible has the same dimensions as the crucible of the CCIM installation at the University of Mondragon, which is able to melt 1kg. of titanium (Figure 3). Its inner diameter is 65 mm, and its height 105 mm. The crucible has 16 sectors and the slits are 0.5 mm thick.

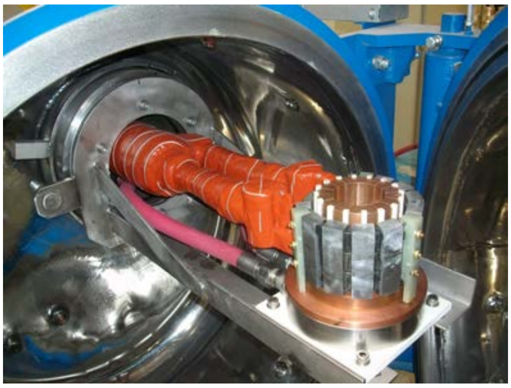

Figure 3. Crucible of the CCIM installation at University of Mondragon.

2.2. Main features of the model

The numerical modeling developed is divided into two steps: in the first step, the heat source generated by induced currents and the electromagnetic forces due to the magnetic field are calculated in the frequency-domain.

In the second step, these values are introduced as input data in the numerical modeling and the variables of the heat transfer (temperature) and fluid flow (velocity components and pressure) fields are calculated.

For the CCIM numerical modeling, it is not possible to properly approximate it as a 2D axisymmetric geometry due to the slits of the crucible. In order to accurately model the CCIM process, it is necessary to consider a 3D numerical model, which is computationally intensive. However, it is possible to model only a sixteenth part of the real problem due to the periodicity of the problem. As it can be observed in Figure 4, the model has four different domains: the charge, the crucible, three turn coil, and the air.

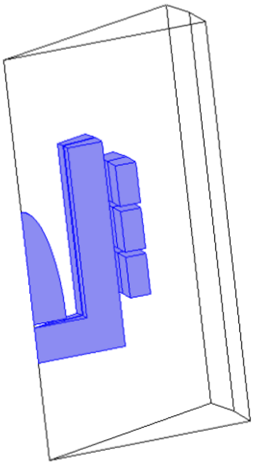

Figure 4. Sixteenth part of the real problem.

2.3. Governing equations

Maxwell´s equations govern the electromagnetic fields, and are solved by COMSOL Multiphysics using the following formulation:

$$(j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)A + \nabla\times(\mu_0^{-1}\mu_r^{-1}B) = J_e$$

where B is magnetic flux density, Je is external current density, ω is the frequency, ε_0 is the permittivity of vacuum, ε_r is the relative permeability, and A is the magnetic vector potential.

These equations are solved in the entire computational domain (including the air, crucible, coil, and charge). The input data is a 1000A external current that crosses through the 3 turn coil with a working frequency of 9 kHz. An important feature in any electromagnetic analysis is the concept of skin depth. For a working frequency of 9 kHz and titanium conductivity of 7.407e5 S/m, the skin depth is equal to 3.4 mm. Thus, 3.4 mm boundary layers have been used to mesh the charge. In the outer boundaries of the computational domain, the magnetic insulation boundary condition has been used, which imposes that the normal component of the magnetic field has to be zero.

The fluid mechanics model consists of the Navier-Stokes equation combined with the flow rate conservation:

$$\rho\frac{\partial v}{\partial t} + \rho v\cdot\nabla v = -\nabla p + \nabla\cdot\left[\mu\left(\nabla v + (\nabla v)^T\right)\right] + F$$

$$\nabla\cdot(\rho v) = 0$$

where ρ is the density, v is velocity vector, p is the pressure, μ is dynamic viscosity, and F is the volume force. In this case, the forces are the electromagnetic forces calculated in the first step. In order to consider the turbulent melt flow, it has been used the well known k-ε model.

These equations are only activated in the charge. The boundary conditions used for the fluid flow problem are a periodic flow condition for the exterior boundaries, and a slip condition at the free surfaces.

For the heat transfer analysis, the following equation has been used:

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p v\cdot\nabla T = \nabla\cdot(k\nabla T) + Q$$

where ρ is the density, C_p is the specific heat capacity at constant pressure, T is absolute temperature, v is the velocity vector, k is thermal conductivity, and Q is heat source. In this case, the heat is generated by the induced currents calculated in the first step. As in the fluid flow analysis, this equation is only activated in the charge.

For the temperature boundary conditions, it has been adopted the periodic heat condition for exterior boundaries. At free surface, the radiation condition has been used, and at the bottom boundaries a temperature of 300ºC has been imposed.

3. Numerical results

Figure 5 shows the magnetic flux density that generates the coil. This figure shows the magnetic field crossing the crucible trough the slit and penetrating in the charge until the skin depth.

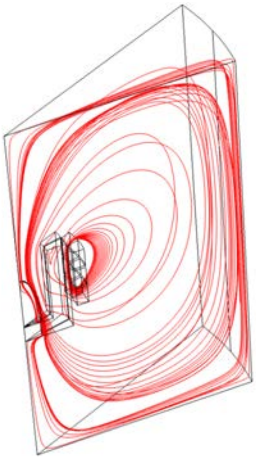

Figure 5. Magnetic flux density.

Figure 6 displays the charge temperature after 10 minutes.

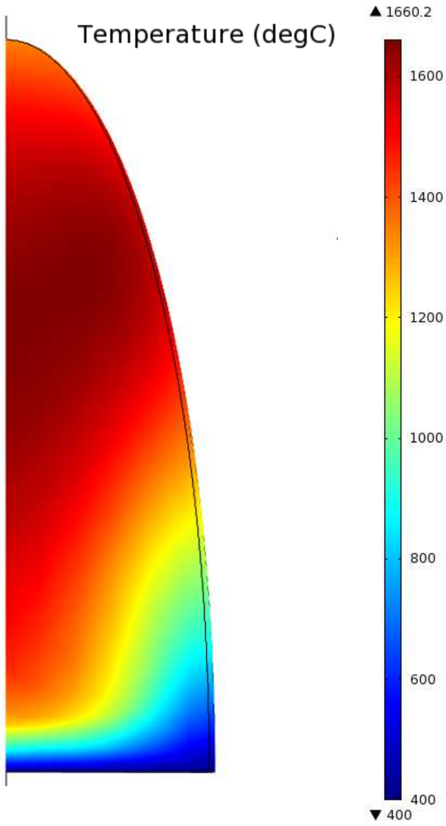

Figure 6. Charge temperature after 10 minutes.

Figure 7 describes the flow pattern due to electromagnetic stirring.

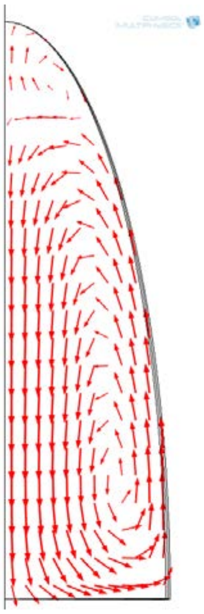

Figure 7. Flow pattern.

4. Conclusions

The numerical modeling is an interest tool for optimizing emerging technologies like CCIM. In this first approximation, the numerical modeling developed involves the sequential coupling of electromagnetic, temperature, and turbulent velocity fields. The results obtained are in good agreement with the theory. The next stage is to perform strong coupling rather than one-way coupling.

5. References

1. Mühlbauer, A., “Innovative Induction Melting Technologies: A Historical Review”, International Scientific Colloquium, Modelling for Material Processing, pp. 13-20 (2006).
2. Harding, R.A., "Temperature Measurements during Induction Skull Melting of Titanium Aluminide", *Materials Science and Technology*, vol. 19, pp. 1235-1246 (2003).
3. Broihanne, G., "Cold Crucible Melting Gets a New Spin", *Materials World*, vol. 8, pp. 21-23 (2000).
4. Nacke, B., "Induction Skull Melting of Oxides and Glasses in Cold Crucible", *International Scientific Colloquium Modelling for Material Processing* (2006).
5. Umbrasko, A., "Numerical Studies of the Melting Process in the Induction Furnace with Cold Crucible", *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 27, pp. 359-368 (2008).
6. Bojarevics, V., "Modeling the Dynamics of Magnetic Semilevitation Melting", *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*, vol. 31, pp. 179-189 (2000).
7. Ernst, R., "Numerical Modeling of a Levitated Liquid in a Cold Crucible", *Proceedings of the COMSOL Users Conference 2007 Grenoble* (2007).

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