Electromagnetic-thermal-deformed-fluid Coupled Simulation for Levitation Melting of Titanium

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A numerical simulation considering electromagnetic-thermal-deformation-fluid of levitation melting is performed by using the finite element method (FEM).The simulation is conducted by considering the two-way interactions of multiphysics field. Material properties in melting area is nonlinear. Surface-to-surface radiation, phase change, deformation in the melting process and fluid flow are also considered. The arbitrary Lagrangian-Eulerian formulation is adopted to track the shape of the melting metal. Dependence of excitation power parameters of coils and melting metal's temperature, lifting force exerted on sample, deformation and velocity magnitude are assessed. Through this simulation, the relationships between different physics fields are obtained so that it is helpful for smelting high pure metals.

***Index Terms*—coupled simulation, electromagnetic-thermal-deformation-fluid, levitation melting, Titanium**

I. INTRODUCTION

THE electromagnetic levitation (EML) method provides a good way for high temperature processing of active materials, like Titanium studied in this paper, so that they would not be contaminated. The interactions between electromagnetic field, thermal field and fluid field are quite close. Yoshikawa, Gaku *et al* carried out a numerical analysis to study the molten metal by adopting the finite element method to simulate electromagnetic field and moving particle semi-implicit method to calculate the fluid field [1]. JONGHYUN LEE observed the performance by adopting the magneto hydrodynamic theory to study the convection inside the levitated Co-Cu droplets [2].A. Kermanpur used the FEM to analyze the interactions between the electromagnetic field and thermal field [3]. V. Bojarevics and K. Pericleous conducted a serials numerical simulations on the dynamic melting process for small samples in the cold crucible by adopting the pseudo-spectral solution method and the Lagrangian tracking method implemented for tracking the arbitrary shape of the melting metal, which combined the turbulent fluid flow, thermal and electromagnetic fields [4]-[6].

In this paper, the surface-to-surface radiation of the melting metals to the coils, which is neglected by the researchers above and they just consider the radiation to the ambient, is considered when considering the heat transfer. What is more, the electromagnetic, thermal and fluid flow fields are considered and the deformation of the melting metal during the smelting process is also conducted. The arbitrary Lagrangian-Eulerian formulation is adopted to track the shape of the melting metal. By taking the numerical simulation of multiphysics field of EML, it is helpful for high active materials' processing.

II. PRINCIPLE OF EML

Fig.1 gives the schematic diagram of electromagnetic levitation. The upper coil is used to stabilize the melting metal, while the down coil is used to generate the lifting force and the Joule heat that used to heat to metal. The current directions in the upper coil and the down coil are opposite.

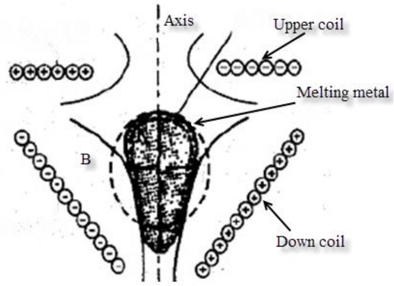


Fig.1.Schematic diagram of EML

A. Magnetic field equations

The harmonic electromagnetic field equations of an electromagnetic levitation device observe the Maxwell equations. In order to solve the Maxwell equations, a magnetic vector potential, $\boldsymbol{A}$, and an electric scalar potential, φ, are defined:

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \tag{1}$$

$$\boldsymbol{E} = -\partial \boldsymbol{A} / \partial t - \nabla \phi \tag{2}$$

The Coulomb gauge condition is employed to ensure a unique solution. The final governing equation is:

$$\nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{A} - \nabla \frac{1}{\mu} (\nabla \cdot \boldsymbol{A}) + \sigma \frac{\partial \boldsymbol{A}}{\partial t} + \sigma \nabla \varphi = 0 \tag{3}$$

Where, μ is the relative permeability; σ is the conductivity.

The Lorentz forces and Joule heat generated would be used in the thermal field and fluid field analysis. The Lorentz force and Joule heat could be calculated by the following equations:

$$\boldsymbol{F}_{\mathrm{m}} = \int_V (\boldsymbol{J} \times \boldsymbol{B}) \mathrm{d}V \tag{4}$$

$$\boldsymbol{Q}_{\mathrm{m}} = \int_V \boldsymbol{J} \cdot \boldsymbol{E} \mathrm{d}V \tag{5}$$

B. Thermal-fluid field equations

The governing equations of thermal and fluid fields (incompressible and Newtonian flow) of transient analysis are described as follows:

$$\rho \nabla \cdot \boldsymbol{u} = 0 \qquad (6)$$

$$\rho\, \partial \boldsymbol{u}/\partial t + \rho \boldsymbol{u} \cdot (\nabla \boldsymbol{u}) = \nabla \cdot \left\{ -p\mathbf{I} + \mu \left[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^{\mathrm{T}} \right] \right\} + \boldsymbol{F} \qquad (7)$$

$$\rho C_p \left[\partial T/\partial t + (\boldsymbol{u} \cdot \nabla) T \right] = \nabla \cdot (k \nabla T) + Q \qquad (8)$$

$$Q_{ij} = A_i \sigma (T_i^4 - T_j^4) F_{ij} \qquad (9)$$

Where, ρ is the density of the Titanium; k is the thermal conductivity; $\boldsymbol{u}$ is the velocity vector; $\mathbf{I}$ is the unit diagonal matrix; $\boldsymbol{F}$ is the volume force; T is the temperature; p is the pressure; Q is the heat source term; Q_{ij} is the heat transferred from face i to face j; A_i is the area of surface i; σ is the Stephan-Boltzmann constant; T_i, T_j are the temperature of surface i,j, respectively; F_{ij} is the view factor of surface i,j.

The fluid field inside the liquid Titanium is turbulent flow which can be described by $\kappa - \varepsilon$ equations:

$$\rho\, \partial \kappa/\partial t + \rho \boldsymbol{u} \cdot \nabla \kappa = \nabla \cdot \left[(\mu + \mu_{\mathrm{T}}/\sigma_\kappa) \nabla \kappa \right] + P_\kappa - \rho \varepsilon \qquad (10)$$

$$\rho\, \partial \varepsilon/\partial t + \rho \boldsymbol{u} \cdot \nabla \varepsilon = \nabla \cdot \left[(\mu + \mu_{\mathrm{T}}/\sigma_\varepsilon) \nabla \varepsilon \right] + \left(\varepsilon C_{\varepsilon 1} P_\kappa - C_{\varepsilon 2} \rho \varepsilon^2 \right) / \kappa \qquad (11)$$

Where,

$$\mu_{\mathrm{T}} = \rho C_\mu \kappa^2 / \varepsilon$$

$$P_\kappa = \mu_T \left\{ \nabla \boldsymbol{u} : \left[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T \right] - 2(\nabla \cdot \boldsymbol{u})^2/3 \right\} - 2\rho\kappa (\nabla \cdot \boldsymbol{u})/3$$

The operator "**:**" in the above equation is defined as:

$$\boldsymbol{a} : \boldsymbol{b} = \sum_n \sum_m a_{nm} b_{nm}$$

Where, κ is the turbulence kinetic energy per unit mass; ε is the dissipation rate of the turbulent kinetic energy; μ is the turbulent viscosity; C_{ε_1}, C_{ε_2}, C_μ, σ_κ, σ_ε are the constant.

III. COUPLED SIMULATION METHOD

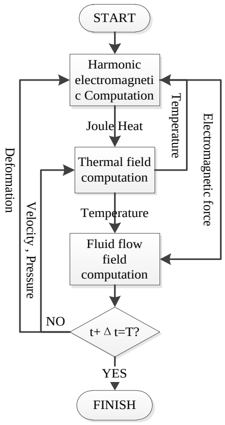


Fig. 2. Flow chat of multi-physics filed simulation

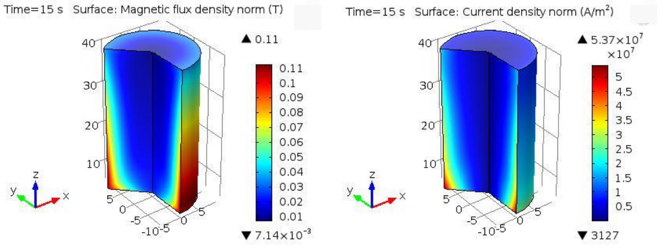
Fig.2 gives the way to the numerical simulation of electromagnetics, thermal and fluid flow fields. The Joule heat and Lorentz force generated in harmonic electromagnetic field are transferred to thermal field and fluid field respectively. While the temperature calculated in the thermal field and the deformation generated in fluid flow are transferred to the electromagnetic field analysis to revise the material properties which depend on the temperature. As for the fluid flow and thermal fields, the temperature influences the thermal fields, the temperature influences the velocity and pressure and their changes would otherwise influence the distribution of the temperature. When the time meet the prescribed time settings, the simulation is finished.

V. PERFORMANCE ANALYSIS AND DISCUSSION

A part of the work, mainly relevant of electromagnetic and thermal field simulation, done is shown as followings.

A. *Electromagnetic field analysis*

Fig.3(a) and (b) are the magnetic flux density and eddy current density in the Titanium respectively, at t=15s when Titanium reaches its melting temperature.

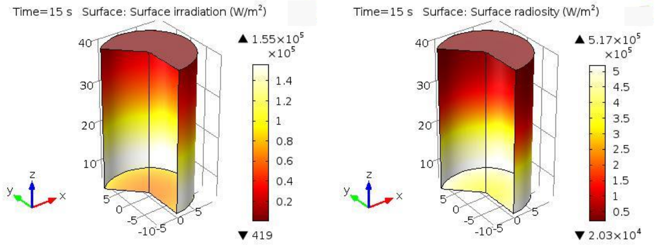


(a) Magnetic flux density norm (b) Current density norm

Fig. 3. Magnetic flux density and current density norm of Titanium at t=15s

B. *Thermal field analysis*

Fig.4 (a) and (b) are the surface irradiation and the radiosity of the Titanium surfaces to the coils surface at t=15s respectively.



(a)Surface irradiation (b) Surface radiosity

Fig. 4. Surface irradiation and radiosity of Titanium at t=15s

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