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COMPUTER MODELING OF COUPLED ELECTROMAGNETIC, TEMPERATURE AND MAGNETOHYDRODYNAMIC FIELDS IN THE INDUCTION HEATING AND MELTING DEVICES

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Abstract. Computer modeling is necessary part of design new induction heating and melting devices [1]. One of the complicated technologies when it is necessary to simulate coupled electromagnetic, temperature and magnetohydrodynamic fields is heating and melting of titanium alloys in the alternating electromagnetic field. Thermal processing of titanium alloys in the inductor has some features that it is necessary to take into account on the designing of the advanced technology and equipment. Low thermal conductivity and high temperature losses at the surface result in maximum temperature inside of the billet that could under appropriate conditions exceed melting point. In this way it is possible to obtain liquid phase of titanium alloy inside of the billet and protect it from the contact with surrounding atmosphere. To get this it is necessary to choose the right regime of processing, frequency of current, power and thermal conditions. At the same time precise heating with very strong execution of the temperature profile during the heating time are essential for thermal processing of titanium alloys in this technology [2]. Mathematical model comprising computation of electromagnetic, temperature, MHD fields after getting melt zone and dynamic of its growth was developed. The calculation of the melting process has been carried out by the method “enthalpy-porosity” with application of models of turbulent currents k-ω SST in a non-static setting. Electromagnetic forces and heat sources have been defined by solving a harmonic task by the method of finite elements on a vector magnetic potential in the system “inductor – load” for each iteration of the hydrodynamic task. Experiments confirmed need in simulation of MHD fields to receive good coincidence. Using of the developed models for simulation of electromagnetic processing billets make it easy to develop and implement optimal heat processing systems for the crucibleless induction melting of titanium alloys.The calculations on the basis of the model and the analysis of physical processes with non-crucible melting of titanium alloys have also been carried out.

1 INTRODUCTION

For the solution of electromagnetic and thermo-hydrodynamic problems, including peculiarities of the MHD flow processes various software solutions for interfacing software products were developed and implemented. In this coupled model the interpolation algorithm and data exchange between software products ANSYS Mechanical APDL to solve the electromagnetic part and Fluent for solution of thermo-hydrodynamic part was modified and adapted. Parametric model of non-crucible melting the cylindrical titanium billet was developed on the basis of these products [3], including the solution of harmonic electromagnetic problem and thermo-hydrodynamic problem taking into account the turbulent flow and the melting process. The main feature of the model is the transfer of the phase boundary in the electromagnetic part of the problem to rebuild the calculated domain. The resulting model is universal and can be applied for the calculation of a similar system with any geometric, physical and energy parameters.

2 MATHEMATICAL MODEL

The initial stage of mathematical modeling of metal melting process in an electromagnetic field is the implementation of the electromagnetic calculation. A sketch of the system "inductor – billet" is shown in figure 1 and consists of inductor 1 and the billet 2. Such systems are usually had low values of magnetic Reynolds number, that allows to solve the electromagnetic problem, excluding the effect of velocities in the metal on the electromagnetic field. Thus, to solve electromagnetic problem the following assumptions: the electromagnetic field in the calculated domain varies harmonically; the influence of the metal movement in the magnetic field is neglected.

System of equations, which describes electromagnetic field, consists of equations on vector and scalar potential, and continuity equations. Not considering bias currents, and also using Coulomb gauge and considering the absence of free electric charges in the region of computation and the assumptions accepted above we can write down the system of equations as follows:

$$\nabla^2 \dot{\mathbf{A}} = -\mu_a \dot{\boldsymbol{\delta}}; \quad (1)$$

$$\nabla \dot{\boldsymbol{\delta}} = 0 \quad (2)$$

$$\dot{\boldsymbol{\delta}} = -\gamma j \omega \dot{\mathbf{A}} \quad (3)$$

where $\mathbf{A}$ – vector potential; $\boldsymbol{\delta}$ – current density vector; μ_a – absolute magnetic permittivity; γ – electric conductivity; $\omega = 2\pi f$ – electromagnetic field cyclic frequency.

In order to determine electromagnetic field in the region of computation explicitly, equations system shall be finalized with (1 – 3) boundary conditions for tangential and normal component of vector potential:

$$\frac{\partial \dot{\mathbf{A}}_\tau}{\partial n} = 0; \ \dot{\mathbf{A}}_n = 0 \quad (4)$$

where n – normal line to the surface of region of computation

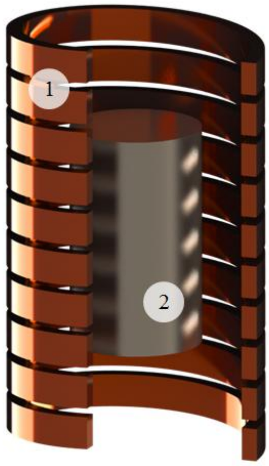

Figure 1. Sketch of the system "inductor-billet"

The next stage of mathematical modelling is the solution of thermo-hydrodynamics problems basing on the results, obtained after electromagnetic calculations. System of equations, which define thermo-hydrodynamic processes, consists of equations of conservation of mass, conservation of motion and conservation of energy. Due to the fact that the appearance of free convective motions and turbulence of flows can be expected, it is necessary to introduce gravitational forces considering density differences and utilization of turbulence model. To allow for free convective motions the Oberbeck–Boussinesq approximation is used. This approximation shows how the dependence of density on temperature linearizes and is taken into account only when there are mass forces. Thus, the fluid can be considered as incompressible. To consider the influence of processes, which happen during melting and solidification stage, thermo-hydrodynamic model is included with melting and solidification model, based on «enthalpy – porosity» method. The influence of electromagnetic field is considered by the introduction of appropriate source elements (which were obtained by electromagnetic calculations) to the equations of motion and energy.

As per the results of analyses of thermo-hydrodynamic calculations correctness, by the example of induction crucible furnace, turbulence model, based on Reynold's averaging of Navier-Stokes equations (RANS), gives temperature distribution results which are not always accurate. Results that are more accurate, in this case, can be obtained by direct numerical simulation of turbulence (DNS – Direct Numerical Simulation). Since turbulence is exceptionally spatial phenomena, the utilization of these models is possible only after the solution of transitional problem in the 3D formulation. The use of complete DNS model for engineering calculations is irrational, because it does not require the discharging of even the smallest vortices. In such cases, they use direct numerical simulation with the usage of large eddy simulation of micro-scale turbulence. (LES – Large Eddy Simulation). Thus, at carrying out the initial calculation for definition of character the system behavior was used LES turbulence method. Taking into account of solidification influence on the character of turbulent flows is implemented by the introduction of additional source elements into the motion quotation, transfer of kinetic energy of turbulent fluctuation and dissipation specific speed.

In this fashion, system of equations, which describe thermos-hydrodynamic process in electromagnetic field, considering solidification process, is as follows:

$$\nabla \mathbf{v} = 0 \tag{5}$$

$$\frac{\partial \rho_0 \mathbf{v}}{\partial t} + \nabla(\rho_0 \mathbf{v}\,\mathbf{v}) = -\nabla p + \nabla \boldsymbol{\tau} + \rho(T)\mathbf{g} + \frac{(1-\beta)^2}{(\beta^3+\xi)} A|\mathbf{v}| + \mathbf{f}_{эм} \tag{6}$$

$$\frac{\partial \rho_0 H}{\partial t} + \nabla(\rho_0 \mathbf{v} H) = \nabla(\lambda \nabla T) + q_{эм} \tag{7}$$

where $\mathbf{v}$ – velocity vector; ρ_0 – fluid density at the temperature T_0; t – time; p – pressure; $\boldsymbol{\tau}$ – viscous stress tensor; T – temperature; $\mathbf{g}$ – free fall acceleration vector; β – liquid phase proportion; ξ = 0.001 – the figure, preventing division by 0; A – the constant of two phase area, which represents the rapidity of speed reduction to zero during solidification; $H=h+\beta L$ – enthalpy; L – material latent heat; λ – heat conductivity.

Walls heat exchange with the environment happens in accordance with Newton-Richmann law Stefan-Boltzman law:

$$q = -\alpha(T_w - T_0) - \varepsilon\sigma\left({T_w}^4 - {T_0}^4\right) \tag{8}$$

where α – heat exchange coefficient, T_w, T_0 – wall temperature and ambient temperature, ε – emissivity, σ – Stefan-Boltzman constant.

3 THE CALCULATION ALGORITHM

Nowadays there are plenty of ways to solve the multiphase MHD problem and ways of their realization [4, 5]. One of such ways based on combination of ANSYS–Fluent and ANSYS–CFX is method, which is represented in papers [6] for the determination of free surface shape of the melt levitating inside the electromagnetic field. The feature of such an approach is that the coordinates of interphase boundary are included in the solution of electromagnetic problem at β = 0.5. Basing on these coordinates the realignment of geometry and electromagnetic problem region of computation happens, whereas hydrodynamics problem is solved by fixed VOF method. This approach allows getting the most accurate results in some cases, especially when there are big gradients of electromagnetic values at interphase boundary. However, the consumption of time resources to realign the geometry at each iteration of hydrodynamics problem can significantly slow down the process of calculation.

That's why, the alternate algorithm of solution of such problems was suggested. It is based on ANSYS and Fluent software [7]. The main feature of it is the transfer of complete distribution of the required value in the region of computation of thermo-hydrodynamics part of the problem. Such an approach can be used for the wide range of MHD problems including various phases distribution, interphase boundaries of which are situated in the area of concentration of electromagnetic field and lead to response distortion.

Numerical solution of thermo-hydrodynamic part of the problem considering phase transition and turbulent phenomena is implemented via Fluent, electromagnetic part of the problem was made via ANSYS Classic. To implement the transfer of source elements of equations of motion and energy, which were obtained by the results of solution of electromagnetic part of the problem, from ANSYS into Fluent the data exchange algorithm was developed. To realize thus algorithm Scheme applicative language, C structural language with User–defined function (UDF) on the bases of integrated Fluent compiler and special Ansys parametric design language (APDL). The algorithm can be separated by two parts: preparatory (Figure 2) and computational (Figure 3).

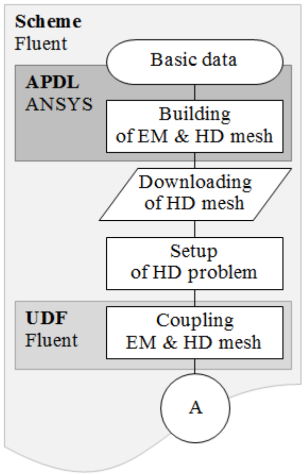

Figure 2. Preparatory part of the algorithm

At the preparatory stage, the following happens: compilation of UDF part of the software; initial data input; construction and uploading of the array of electromagnetic and hydrodynamics problem and their interfacing; adjusting of initial and boundary conditions; materials input; formation of arrays structure for data exchange.

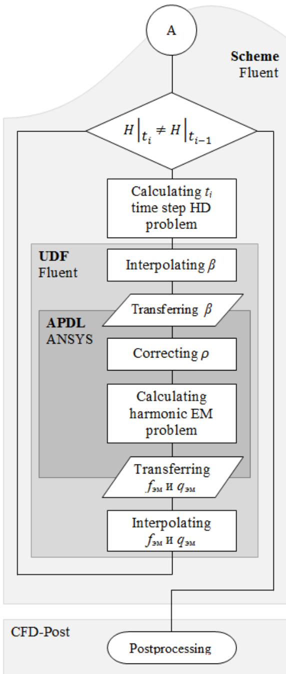

Figure 3. Computational part of the algorithm

After finishing of the preparatory part algorithm goes to implementation of cyclic solution of nonsteady hydrodynamic problem. The first step of cycle is the calculation of "i" iteration of hydrodynamic problem. After results, have been finished β liquid phase distribution is automatically extracted and its interpolation on electromagnetic array, and transfer to ANSYS. Basing on β distribution the correction of ingot electrophysical properties happens. Then harmonic electromagnetic problem is solved in the «inductor – ingot» system. Obtained specific electromagnetic forces and power are transferred as motion and energy source into Fluent. The condition of solution cycle completion is the absence of any changes in the system enthalpy. After cycle completes, all the results are sent to CFD-Post postprocessor for automated and manual processing.

4 ANALYSIS OF THE RESULTS

Basing on the obtained mathematical model there was made the numerical experiment for the liquid phase formation inside of cylindrical ingot made from titanium alloy 6Al-4V in electromagnetic field of 10-turns inductor with the current of 2500 A at the frequency of 4 kHz. Then physical experiment was carried out. The basic geometrical dimensions of the system are shown in Figure 4.

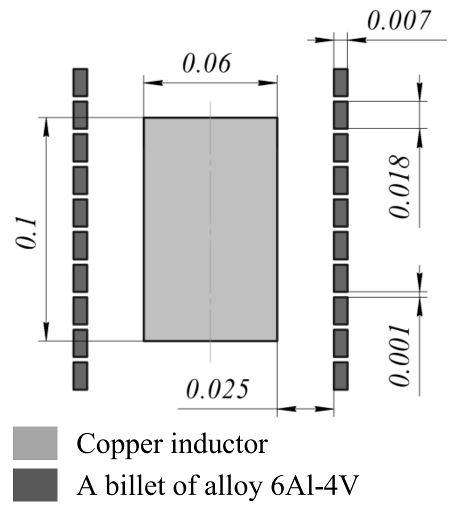

Figure 4. Geometry of induction system

For the imitation of surface constant temperature maintenance the algorithm of supplied power control was used in the model. When the surface gets heated for more than 1407 °C the gradual decrease of the supplied power by 30% happens, up to the temperature of 1644 °C. Function which implements power control is as follows:

$$P(T) = P_0(1 - \frac{k_{fall}}{2}(1 + \tanh(\frac{e}{T_S - T_F}(2 \cdot T_{surf\ max} - T_S - T_F)))), \qquad (9)$$

where P_0 – basic power; k_{fall} = 0.3 – power reduction coefficent; $T_{serf\ max}$ – maximum temperature on the surface; T_S, T_F – temperature of the starting and finishing of power decreasing.

The resulting solution of the problem of liquid phase concentration distribution and temperature field in the volume of billet at different times is presented in Figure 5.

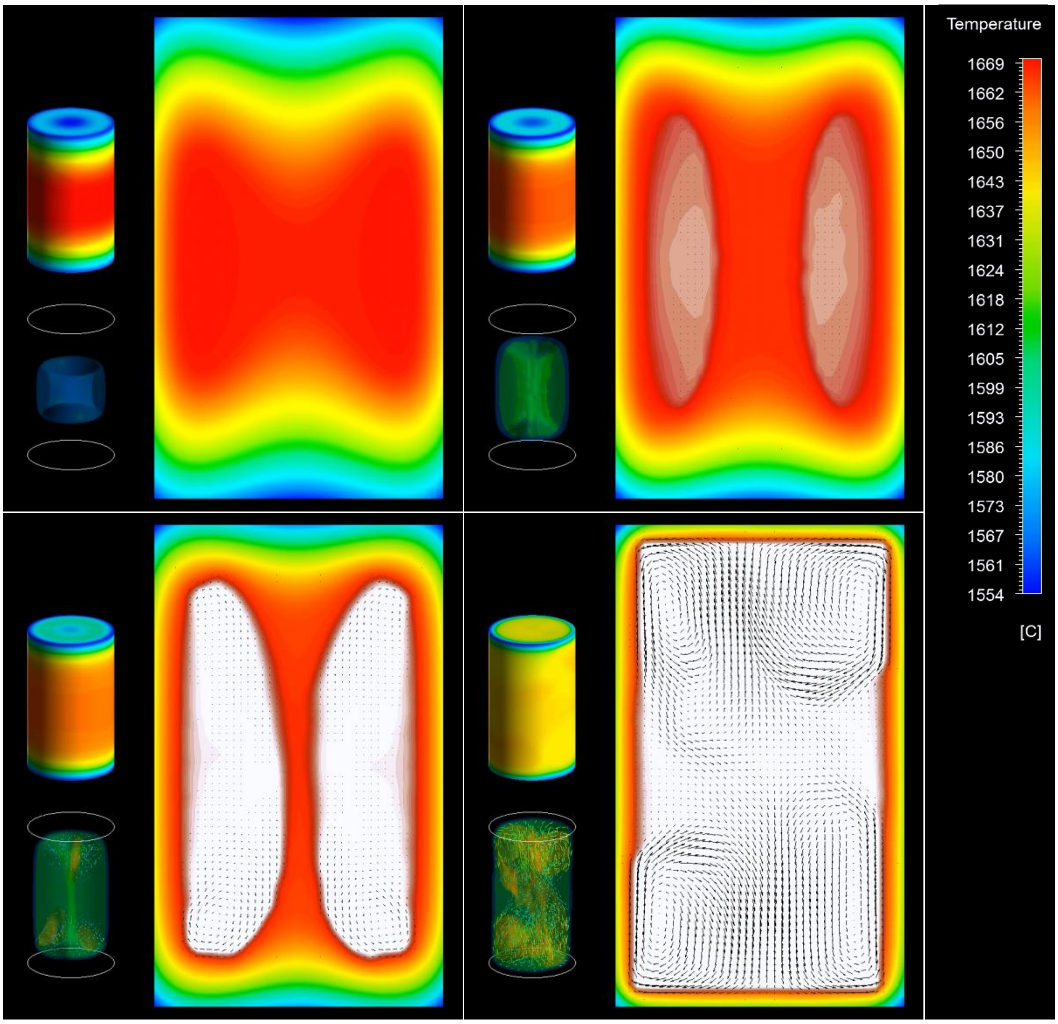

Figure 5. The distribution of the thermal field in the cross section and surface of the billet

The nature of the liquid phase process formation inside of the billet is determined by the distribution of temperature field in cross section of the billet at the moment of reaching the onset temperature of melting. Equalizes of the temperature field to the onset of melting occurs only by conduction in view of heat loss from the surface of the billet and depending on the intensity and distribution of electromagnetic heat sources. In turn, the intensity and distribution of the sources depends on the inductor feeding current (power supplied to the system) and its frequency, respectively. At the same time, a necessary condition is the onset of melting power supply (ΔP) sufficient to raise the temperature to the required value.

5 CONCLUSIONS

There was developed the combined numerical model of the process of 6Al-4V titanium alloy non-vacuum melting considering MHD phenomena and phase transfer processes with the correction of electromagnetic part of the problem. The results of the numerical model solutions similar to the results of physical experiments that shows the correct operation of the coupled model, given minimal assumptions. This model can be used to identify the key parameters and patterns of energy transduction in the system with different geometric parameters and loading materials. At the same time, one should emphasize the importance of solving the problem of stress strain state in a solid phase billet at the steady state of liquid phase formation taking into account volume distribution of the electromagnetic forces in the surface layers of the workpiece and the hydrostatic pressure on the inner surface of the skull. The solution of this problem will determine the permissible wall thickness of billet and take into consideration the effect of electromagnetic forces in the various energy options on its destruction.

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