SIMULATION OF MELTING PROCESS IN COLD AND INDUCTOR CRUCIBLE

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Introduction. High frequency (> 200 kHz) skull melting in inductor crucible furnace (ICF) is well suited for treatment of oxide materials. This method enables inductive melting of materials with low electrical conductivity at room temperature and high melting temperature such as ZrO_2, $ZrSiO_4$. The main operational problem is energy transfer to melt at low temperatures that requires special regime of initial heating, e.g.: heating by gas burner or by inserting of Mo-ring.

High frequency (∼ 10 kHz) melting in induction furnace with slitted and water cooled crucible (IFCC) is well suited for treatment of alloys with high melting point such as TiAl. The power requirements depend significantly on the electromagnetically (EM) formed shape and properties of skull layer and layer of solid material in the contact zone with water cooled crucible. The properties of the processed material are well suited for novel applications, e.g., in car industry.

Cold and inductor crucible furnaces have several advantages, e.g., skull layer between the load and cooled inductor ensures high purity of final material and possibility to produce high tech materials in one-step process.

1. Numerical models. Axial-symmetric models for transient simulation of melting of alloys in IFCC and oxides in ICF were described in previous publications [1, 2]. Modelling enables to analyse the melting process in detail and minimise the necessary input energy by appropriate choice of the regime of inductive heating. Distributions of electromagnetic, temperature, and velocity fields are closely related and they are calculated simultaneously, because oxide material has exponential dependence of conductivity on temperature and convective heat transfer is important in final phase. In order to describe the shape of the top surface of metal melt, two-fluid model is used. Gas or another incompressible fluid is placed over the melt. Azimuthally split crucible is modelled by use of effective relative magnetic susceptibility lower than one as suggested in order to escape from 3-dimensional description. The description of phase change in ICF and IFCC is of significant importance, which brings considerable difficulties to the numerical calculations.

Incompressible fluid flow calculations are made by a variant of SIMPLER method. Usually, the velocities in IFCC are quite high reaching around 0.3–0.5 m/s and flow regime is highly turbulent. Therefore, model of turbulent viscosity has to be used. The model describes the complete transition from initial flat shape of the top of metal load to the final one by given power regime. Enthalpy function is used for detailed time dependent description of phase change. The velocities of the glass melt in ICF can be low (< 1 cm), therefore the laminar flow model can be applied.

2. Melting of alloys. Modelling of alloys melting in IFCC enables to insure in which conditions the melt does not contact the cooled crucible walls and minimise the required input energy by required maximal overheating of melt.

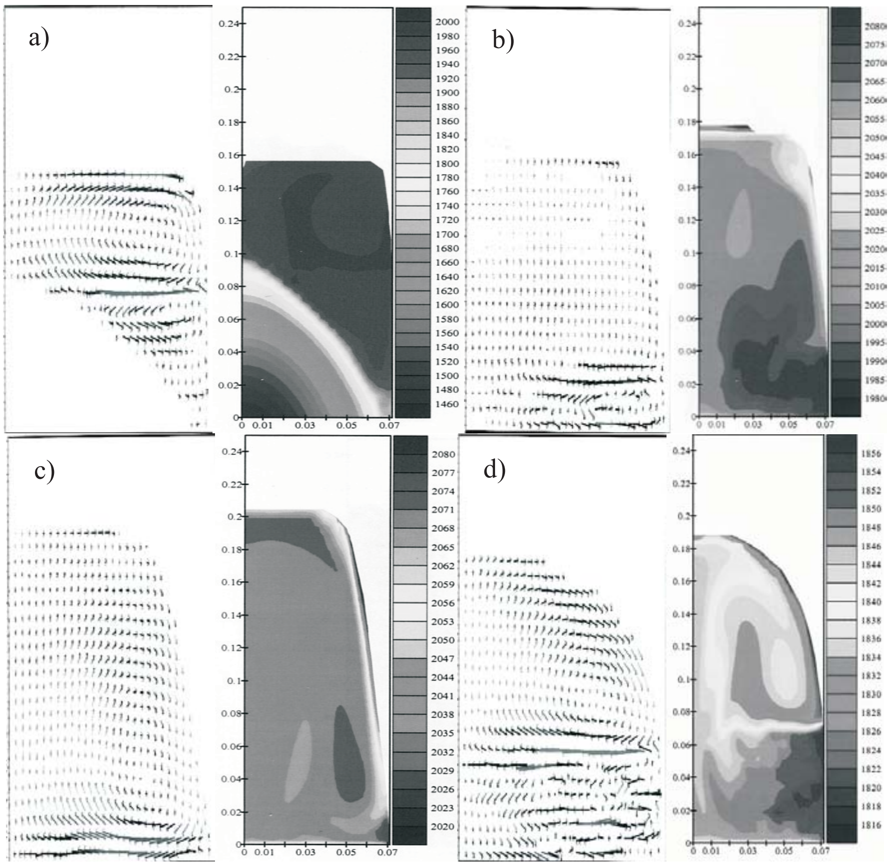

Fig. 1. Distributions of velocity and temperature in the load (TiAl) by IFCC melting at different time moments: a) $t = 5,72$ min ($I = 6500$ A); b) 6,57 min ($I = 6500$ A); c) 7,05 min ($I = 6500$ A); d) 8,6 min ($I = 4000$ A).

Another important point is to obtain the temperature distribution in alloy, because the position of temperature maximum is not clear from just physical reasoning.

As can be seen from Fig. $1(c, d)$, the maximum of temperature in stationary distribution is placed near the inductor, where maximal Joule heat liberated. Below the temperature maximum region the load is quite cold, where the liquid along crystallized interface is flowing. This result of the numerical modeling shows the strong dependence of temperature distribution in the melt on heat exchange

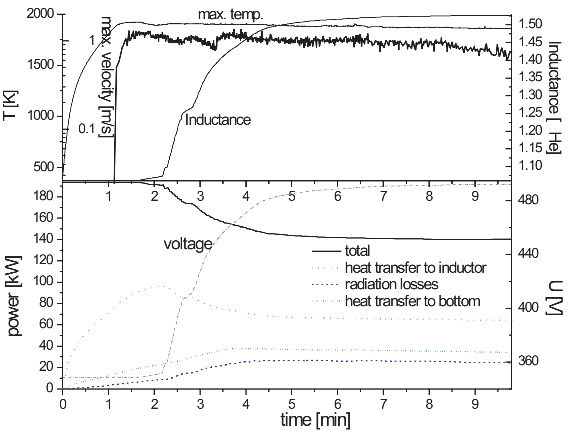

Fig. 2. Changes of power parameters, voltage, maximal temperature, velocity and inductance by inductive heating with 5100 A of 7.9 kg of TiAl melt.

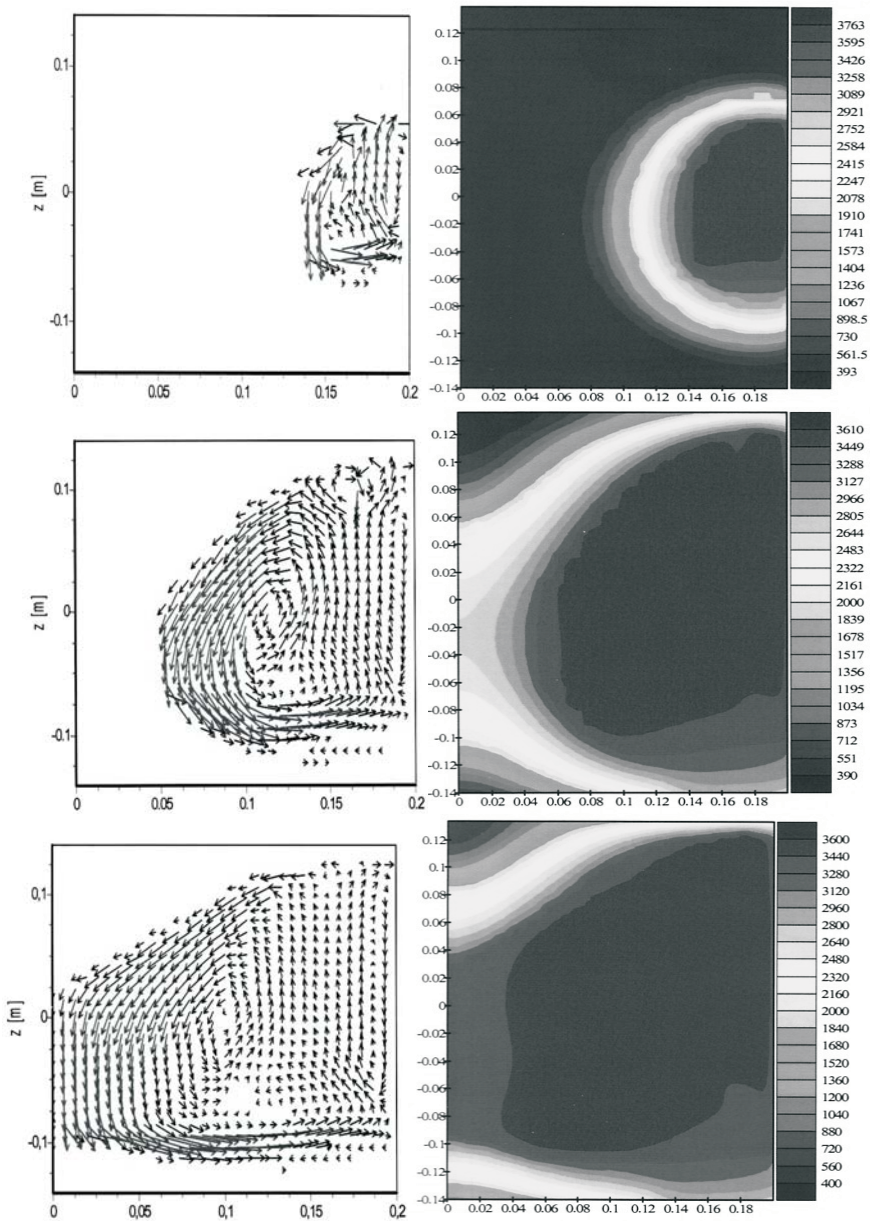

Fig. 3. Distributions of velocity and temperature in ICF by $ZrSiO_4$ melting at different time moments: $t = 29,5$ min; 55,3 min; 59,5 min.

conditions with cold-crucible (heat conductivity and thermal resistance of skull layer in the contact-zone, radiation) and on flow intensity, direction and numbers of flow vortexes, because the correct modelling of turbulent heat exchange in 2D half-empirical turbulent models is practically impossible – more complicated models (LES or DNS) are needed [3]. The flow situation at the bottom and in the contact-zone (especially at the corner of crucible) can be very unstable (Fig. 1*b*, *d*).

Fig. 2 shows characteristic feature that maximal velocity is initially increasing, but it becomes smaller when the melt is forced back from the sidewalls, where the EM force becomes lower. The inductance of the system is a good parameter for characterising of shape development. In the final phase of melting processes the heat transfer losses to cold-crucible walls and bottom are predominant, the ra-

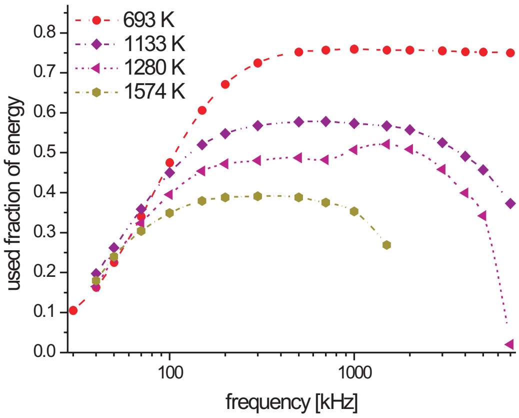

Fig. 4. Optimization of ICF frequency by glass-melting – the average temperature of the load is fixed.

diation and the Joule heat losses in the copper crucible and inductor are relatively low.

3. Melting of oxides. It was found that moderate increasing of power by inductive heating of oxides is necessary in the initial phase to obtain the temperature distribution as homogeneous as possible. Fig. 3 shows example of time-development of temperature and flow fields by $ZrSiO_4$ melting – by temperature and electrical conductivity increasing the melted region is growing in radial and axial directions from initial region with Mo-ring at the crucible wall (Fig. 3) Character of flow is highly influenced by the balance of EM and buoyancy forces.

Characteristic peculiarities in case of glass melting are relevant increase of thermal conductivity with temperature due to radiation and physical quantities varies continuously with temperature without distinct phase transitions. Because of dominating radiation heat transfer, initial heating by gas burner is good choice for glass melting and it can be effectively accompanied with EM heating. As the numerical calculations enable to obtain complete dynamics, numerical constrained optimisation is possible, which suggests the best geometry, heating regime, and frequency [4] (e.g. Fig. 4).

4. Conclusions. Based on the axial- symmetric models of inductive melting in ICF and IFCC, the influence of different parameters of the processes have been studied. The models are based on the time-dependent coupled numerical calculation of EM, temperature, and flow fields taking into account phase changes in the load. The simulations in ICF showed high importance of the pre-heating regime of the load. Correct modeling of heat exchange in IFCC is possible only by using of advanced numerical turbulence models (e.g. LES). The simulations can be used to optimize various furnace parameters and regimes of heating.

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