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Melt Flow and Skull Formation Modelling Possibilities for TiAl Melting Process in Induction Furnace With Cold Crucible

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Abstract

Numerical investigations of the melting process are carried out for the induction furnace with cold crucible (IFCC). The studies, presented in this paper, contain the numerical simulation of electromagnetic setup and turbulent melt flow of experimental IFCC. The results of the three-dimensional transient LES modelling of heat and mass transfer processes in metallurgical applications are shown together with the possibilities of skull formation modelling.

Introduction

Melting of high-purity cast products is often carried out in induction furnace with cold crucible (IFCC), which offers various technological and economical advantages like melting, alloying and casting in one process-step. Due to its importance for modern industry, it has become the subject for numerical modeling [1-3]. The main distinguishing feature is that the melt is kept in the water-cooled crucible and, therefore, high-purity of material is assured by solid skull layer at the melt-crucible contact zone. Practical experiences show that the overheating temperature of the entire melt, which is determined by the electromagnetic, hydrodynamic and thermal process factors, is one of the key parameters of this technological process. The task of optimising melt overheating faces the challenge of finding optimal combination of crucible height to diameter ratio, number of inductor turns and crucible sections, current strength and frequency. Changing of any mentioned factor influences the shape of melt meniscus and, as a result, flow pattern and energy balance. Therefore, solving of this problem should be based on determination of main tendencies for given direction of parameter change. This could be done performing numerical calculations for series of process configurations, with only one of parameters being varied.

Former experimental investigations have shown, that rotational flow structures driven by electromagnetic forces are often unstable. Resulting intensive flow oscillations are thought to be responsible for improved heat and mass transfer between different flow regions. Commonly used two-dimensional numerical models based on the Reynolds-Averaged Navier-Stokes (RANS) equations cannot describe this phenomenon and therefore usually predict temperature distribution, which deviates from measurement results. Major reason of imprecision of 2D models is the three-dimensional character of real flow oscillations. Logically, if we would like to avoid developing of empirical parameter set in order to adjust our 2D model for particular flow case, using of 3D modeling approach is obligatory. The Large Eddy Simulation method, which is receiving growing attention now and is actually being used for practical applications [4-6], was chosen for our numerical studies of cold crucible melting process. Our model experiments in crucible induction furnace have shown applicability of LES to the discussed flow category, not only providing good agreement in terms of calculated flow pattern, but also confirming experimentally determined characteristics of flow oscillations [7].

1. Numerical modelling

The experimental IFCC used for the simulations consists of 5-turn inductor and copper crucible, which has slit water-cooled walls Fig. 1. The melt in the crucible is usually pushed away from the walls by electromagnetic forces and forms meniscus shape. Because of gaps in the crucible wall the geometry is not fully axis-symmetric and 2D model is not able to display the electromagnetic field distribution taking this into account. Therefore, electromagnetic part of cold crucible modelling was resolved with commercial software ANSYS using 3D model. The finite-element model represents a one-sector-wide cut of the complete geometry. Because of acceptable run-times of these calculations, it was possible to couple them with the self-developed code, which calculates free-surface shape of the melt. The 3D approach allows to simulate directly currents which are induced in the copper walls surrounding the melt Fig. 2. The use of 3D electromagnetic model also is advantageous since it gives the non-symmetrical Lorentz force and Joule heat distribution in the melt. There are pronounced periodical changes in the current density and, consequently, Joule heat sources on the surface Fig. 3. They appear because some current is flowing through the crucible bottom, being pushed out back to the melt only in the gap regions. Therefore, there are slight increasing in Joule heat and Lorentz force density opposite of the gaps between the segments.

For the numerical investigations of the turbulent melt flow as well as the heat and mass transfer two turbulence models were applied. The first was the well-known k-ε model, which has relatively low mesh requirements and is widely used and verified in various numerical engineering applications. This model usually produces fast good quantitative results for the time-averaged velocity distribution in case of

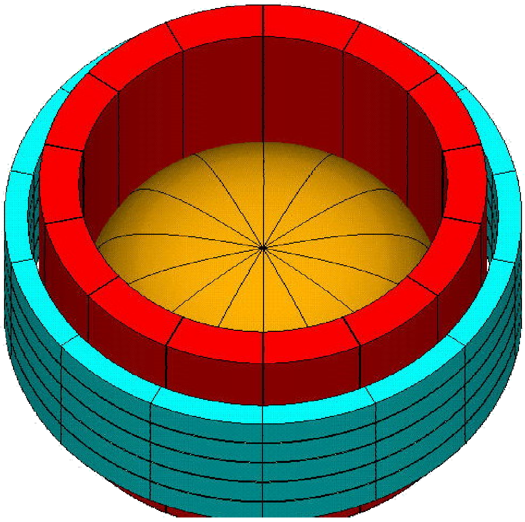

Fig. 1. Model of induction furnace with cold crucible (IFCC).

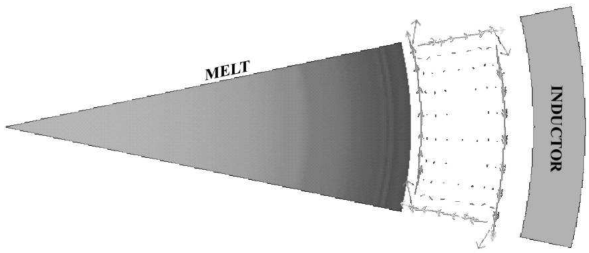

Fig. 2. View from above on the model’s geometry with currents shown in the wall sector.

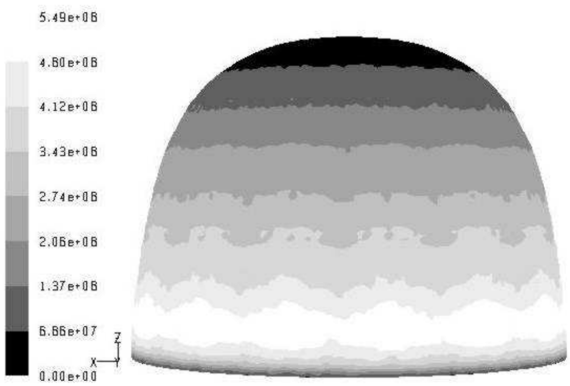

Fig. 3. Joule heat sources distribution in surface elements calculated with 3D electromagnetic model.

stationary two dimensional calculations, but fails to describe correctly the heat and mass transfer quantities in the melt when the system contains at least two dominating recirculating flow eddies.

3D calculations were based on Large Eddy Simulation (LES) turbulence modelling method, which can be described as a compromise between the solving of RANS equations and Direct Numerical Simulation (DNS). Main flow structure is resolved directly like in the DNS approach, but small eddies, which size is comparable with grid size, are modelled additionally. Therefore, finer meshing and, as result, more computational resources are required in order to get an advantage over two-equation models, e.g. k-ε turbulence model, but still less than it is necessary for the application of the DNS.

The Samgorinsky-Lilly sub-grid viscosity model was set for LES simulation, because it provides good stability and has shown good agreement of the results with experimental data. The thermal boundary conditions for CFD analysis included constant temperature setting (corresponding the melting point of TiAl) on the surfaces, which are in the contact with the water-cooled crucible walls, and radiation from the free surface of the melt. More flexible thermal boundaries, based on estimated heat flux, were applied for the further simulations of the skull formation.

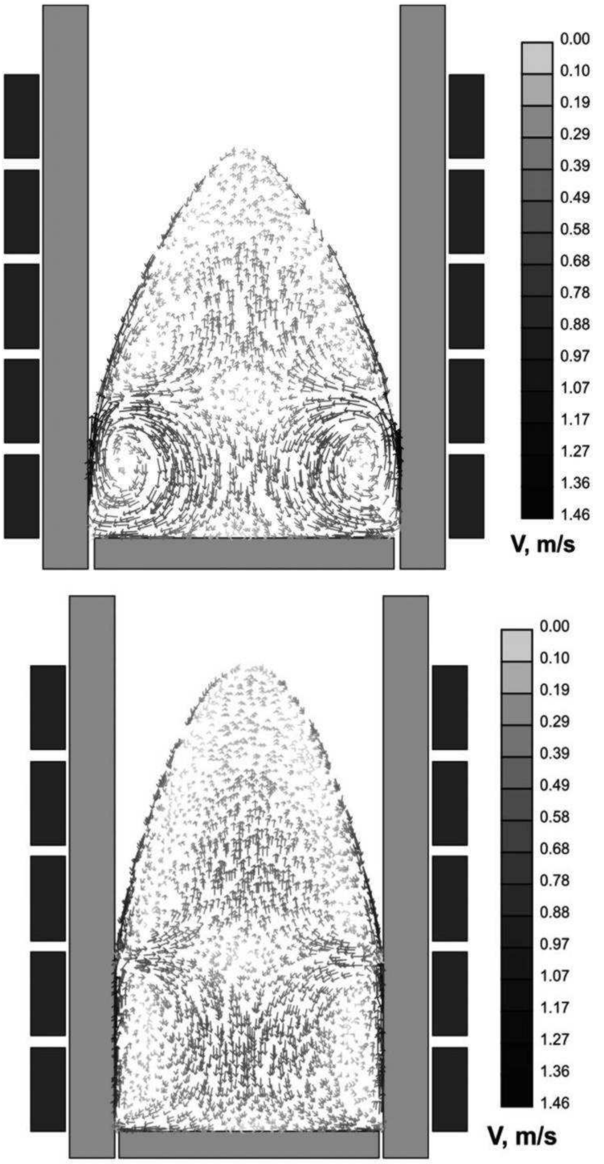

Fig. 4. Velocity vectors with melt H/D ratios 1.20 (top) and 1.67 (bottom).

2. Parameter studies for TiAl melt

There were performed 3D transient LES calculations for the three different height/diameter ratios, but the power induced in the melt was kept the same. The Fig. 4 shows the results for two ratios: 1.20 (left) and 1.67 (right). As it can be seen, the flow is more intensive near the central axis in case of crucible with smaller diameter. This can improve temperature homogenisation and also prevent the formation of the thick layer of the solidified material at the bottom. But, at the same time, the melt has larger contact area with the crucible walls, which can lead to the changes in the electromagnetic forces and Joule heat sources distribution in the melt, as well as to increased heat losses to the water-cooled slits. The comparison of electrical efficiency of these systems shows (see Table 1), that only about 18% of the full power are induced in the melt in case of H/D=0.84, while for the larger ratio it is ~36%. Therefore, the same amount of Joule heat can be generated with significantly lower total energy consumption. However, if the equal amount of induced heat is considered (50 kW in our case) then calculations show no significant difference in resulting average temperature and also in temperature range.

Ratio of the melt H/D	Inductor current, kA	Total power, kW	Power in the melt, kW	Power in the melt, %
0.84	4.6	275.3	50	18.2
1.20	4.0	188.0	50	26.6
1.67	3.7	138.6	50	36.1

Table 1: Calculated electrical parameters for melting process of 6 kg of TiAl in IFCC with frequency 10 kHz and different crucible radii.

Also, the influence of the electromagnetic field frequency was studied. The Fig. 5 demonstrates the melt shape and the time-averaged flows for two cases: 5 and 20 kHz. The melt height decreases at higher frequencies (the induced Joule heat was kept constant). The velocities are noticeably smaller in the 20 kHz case (almost twice on the axis), which may lead to the less intensive mixing. These particular calculations show, that maximum

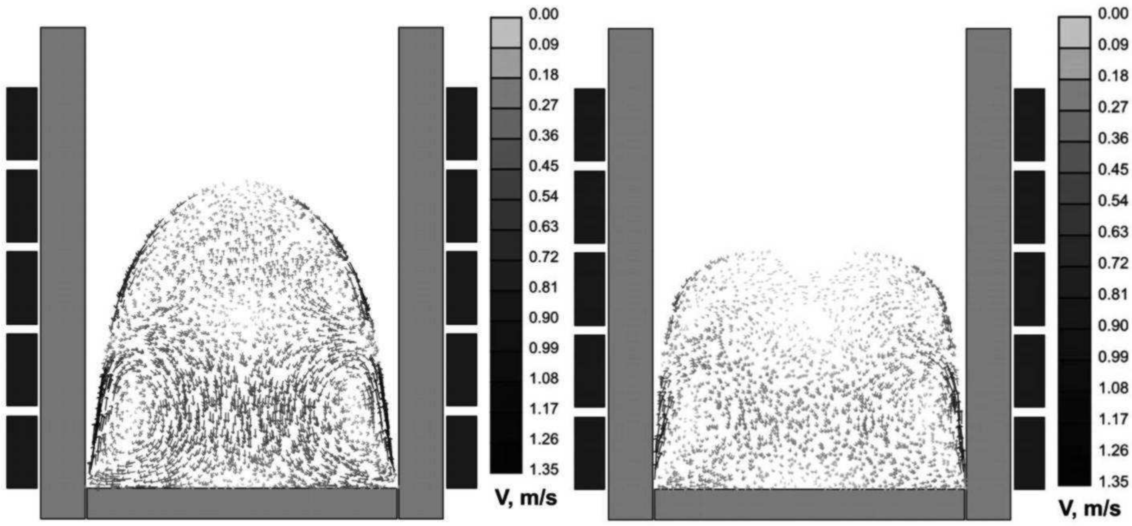

Fig. 5. Velocity vectors with e-m field frequency 5 kHz left, H/D=0.99) and
20 kHz (right, H/D=0.77).

temperature for 20 kHz is by 7 K (or 28% from temperatures range in the melt) higher then for 5 kHz.

Frequency, kHz	Ratio of the melt H/D	Inductor current, kA	Total power, kW	Power in the melt, kW	Power in the melt, %
5	0.96	6.5	171	36	21
10	0.82	5.0	179	39	22
20	0.74	4.0	186	45	24

Table 2: Calculated electrical parameters for melting process of 7 kg of TiAl in IFCC with different frequencies and 8cm crucible radius.

This can be considered advantageous, because increasing of the overheating temperature is useful for practical applications. However, as it will be shown below, less intensive flow in the axial region may lead to the formation of thick skull layer and, therefore, significantly influence final temperature distribution.

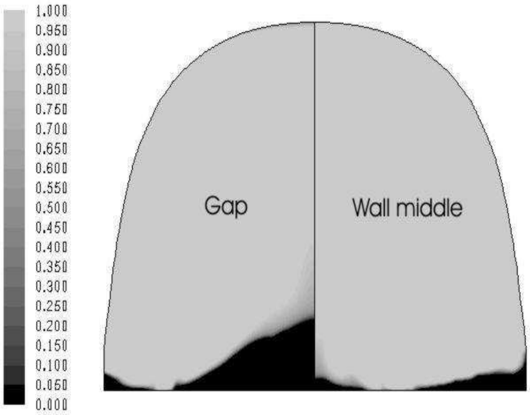

Fig. 6. Liquid fraction simulated with 2D k-ε model. The left side represents results when Joule heat and Lorentz forces are taken from vertical profile opposite of the gap, but on the right side – from the wall middle.

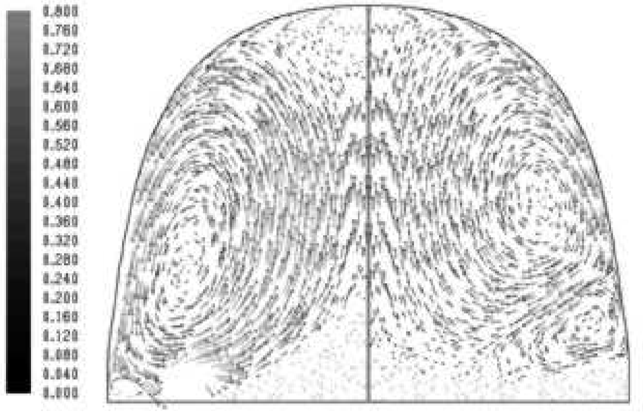

Fig. 7. Velocity distribution (m/s) calculated with 2D k- ε model when skull formation is taken into account. The left side represents results when Joule heat and Lorentz forces are taken from vertical profile opposite of the gap, but on the right side – from the wall middle

3. Skull modelling

The formation of solid layer on the crucible inner surface influences the temperature distribution and also the flow pattern. The 2D steady-state calculations with k-ε model show, that there is noticeable difference in results depending on from which profile the heat sources and Lorentz forces are taken: opposite of the gap or middle of the sector wall Fig. 6. The skull thickness in both cases vary depending on radial coordinate, but in the profile which is opposite of the gap the layer of solidified material grows near the central axis. The Fig. 7 shows that the form of skull layer significantly depends on the flow pattern and, of course, the flow pattern is influenced by the skull form. The important difference between the left and right velocity distributions is that on the left hand side we see only one large vortex, but on the right there is pronounced second one. The thermal behavior of the single- and double-vortex system may differ, but 2D modeling is not able to take into account the 3D character of the cold crucible geometry. It is necessary to choose a profile with sources' distribution, but neither of them will be the correct one. This explains, why 3D approach could be more preferable. There were performed calculations of the skull formation with 3D k-ε model and 3D input data from electromagnetic analysis. The Fig. 8 shows that the skull height changes not only in the radial, but also in azimuthal direction. Also, it is possible to see, that due to intensive there are no large

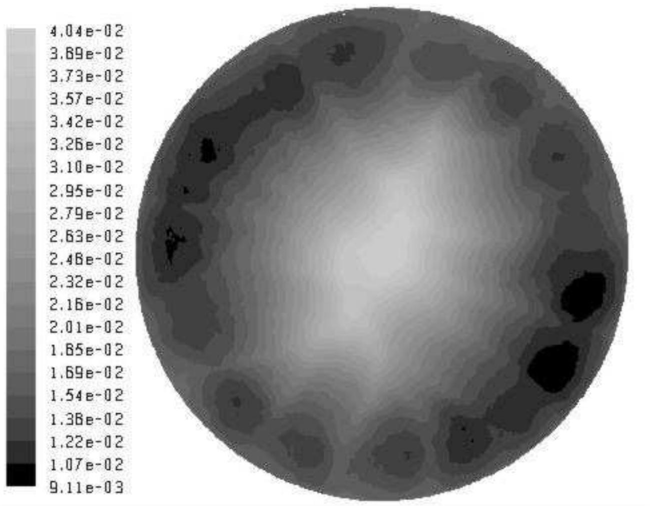

Fig. 8. The skull height (m) distribution calculated with 3D steady-state k-ε model when Joule heat and Lorentz forces are taken from 3D electromagnetic analysis.

differences in the skull layer height on the axis unlike the 2D results (Fig. 7). This shows, that modeling in 3D allows us to get more realistic results.

Conclusions

The comparative modelling results show, that parameters configurations which provide higher H/D ratio of the melt are more efficient when total power consumption is considered, but this advantage is held back by higher heat losses through the crucible walls. Also, calculations reveal that lower frequencies, which are energetically less effective, provide better mixing of the melt. Considering, that change of any parameter (frequency, power, and crucible radius) influences the melt shape and, therefore, the electromagnetic coupling and temperature distribution, further investigations are required to obtain the optimal IFCC configuration.

Skull modelling results show, that 3D approach may be required to take into account the complex geometry of the induction furnace with cold crucible. The future application of transient LES for this problem could face difficulties, because of typically slow convergence of the melting/solidification calculations.

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