PILOT CALCULATION OF THE TEMPERATURE FIELD OF THE CERAMIC MATERIAL EUCOR

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Abstract
EUCOR, a corundum-baddeleyit material, which is not only resistant to wear but also to extremely high temperatures, is seldom discussed in literature. The solidification and cooling of this ceramic material in a non-metallic mold is a very complicated problem of heat and mass transfer.

The investigation into the temperature field, which can be described by the 3D Fourier equation, is not possible without the engagement of a numerical model of the temperature field of the entire system — comprising the casting, the mold and the surroundings.

The temperature field was investigated on a 350x200x400 mm block casting of stone with a riser of 400 mm using an original model with graphical input and output. The computation included the automatic generation of the network, and the successive display of the temperature field using iso-zones or iso-lines. The thermophysical properties of the cast as well as the mold materials were gathered and the initial derivation of the boundary conditions was conducted on all boundaries of the system. The initial measurements were conducted using thermocouples in a limited number of points.

The paper provides results of the initial computation of the temperature field, which prove that the transfer of heat is solvable, and also that using the numerical model it is possible to optimize the technology of production of this ceramic material, which enhances its utilization.

The results are complemented with an approximated measurement of the chemical heterogeneity of EUCOR.

This analysis was conducted using a program devised within the framework of the GA ČR projects no. 106/01/1464, 106/01/1164 and 106/99/0728, of the COST-OC.P3.20 and COST-OC 526.10, of the KONTAKT.

Introduction
Corundum-baddeleyit Material (CBM) is a modern electrically cast heat- and wear-resistant material. It is resistant to corrosion and to wear even at very high temperatures. This material belongs to the not too well known area of the Al\textsubscript{2}O\textsubscript{3}-SiO\textsubscript{2}-ZrO\textsubscript{2} system. This material is produced in several plants throughout the world under different trademarks, in three different types, differing mainly in the ZrO\textsubscript{2} content. EUTIT s.r.o. in Stará Voda, which is the initiator of this grant proposal, produces this material with 32-33% ZrO\textsubscript{2} under the name of EUCOR. During production, mainly the waste from dismantled glass furnaces is processed here.

All customers place the requirements on the properties of CBM which are determined:

a) for the internal walls of glass furnaces: the resistance to liquid glass and the creation of bubbles when in contact with liquid glass.

b) for the production of wear-resistant products: resistance to wear, low porosity, crystalline structure, and resistance to temperature shocks.

CBMs are applied mainly in the construction of glass furnaces, in certain steel-works aggregates, especially within heating furnaces, etc. They have a high resistance to glass as
well as liquid metal, they are also suitable for great temperature changes. Slabs from this material are therefore very suitable for the walls and floors of melting aggregates, linings, pouring filters, isolation plates and for a number of other uses which can be accessible after mastering the optimising of the technology of their production and utility properties.

From the foundry viewpoint it is possible to compare the properties of EUCOR with those of commonly cast metals, especially steels and cast steel. For example, the solidification coefficient of steel when cast into a sand mould is approximately 0.07, here EUCOR is 0.065 and the solidification coefficient of steel when cast into a cast-iron mould is 0.13, here EUCOR is 0.163 [m.h^{1/2}], etc. This relationship can not be assumed generally. The proposed investigation will either confirm or disprove this.

An original numerical model of solidification, cooling, and heating

An original and universal mathematical model of solidification, cooling and heating has been developed in order to be capable of analyzing a one- to three-dimensional steady or unsteady temperature field of a system comprising a casting, the mold and surroundings, namely the system as a whole or any of its parts during any industrial technological processes whose individual sub-processes can be solidification, cooling, heating, refrigerating and others in any sequence or singly. The model enables the simulation of traditional and also non-traditional technologies of casting in foundries, metallurgical plants, forging operations, heat treatment processes, etc.[3,4]

Solidification (crystallization) and cooling rank among the most important technological processes. It is the case of general, up to the 3D (spatial) transfer of not only heat but also mass. In the system of the casting, mold and surroundings, all three kinds of heat transfer take place. In such a case, the problem is unable to be solved accurately. It is not exactly solvable in the case when mass transfer is not under consideration and from the three kinds of heat transfer in the system the conduction is considered decisive. Thus neither the Fourier equation (1) (the melt does not flow) nor the Fourier-Kirchhoff equation (2) (the flowing melt) is exactly solvable. Both are partial differential equations of the 2nd order. The chance of their successful solution lies in the outdated analogue and numerical methods.

\[
\frac{dt}{d\tau} = \frac{\lambda}{\rho \cdot c} \left( \frac{\delta^2 t}{\delta x^2} + \frac{\delta^2 t}{\delta y^2} + \frac{\delta^2 t}{\delta z^2} \right) + \frac{Q \text{ SOURCE}}{\rho \cdot c} \quad (1)
\]

\[
\frac{dt}{d\tau} = a \cdot \Delta t + \left( w_x \frac{\partial t}{\partial x} + w_y \frac{\partial t}{\partial y} + w_z \frac{\partial t}{\partial z} \right) + \frac{Q \text{ SOURCE}}{\rho \cdot c} \quad (2)
\]

From these the explicit difference method has been chosen. It will allow the most elegant way of simulation of the development of latent heat of the phase or structural changes that in both of the mentioned equations appear as a member of the so-called heat flow from the internal source. For the proper simulation of latent heat development the thermodynamic function of enthalpy is introduced. The entalphy function and its dependence on temperature must be known for relevant metallic material (Fig.1). The authors of this paper have used it in the Czech Republic as the first.

The assignment and preparation for simulation

The aim of the research was to investigate a 3D transient temperature field of a EUCOR casting, solidifying in a mold made from a CT mixture. The final layer of the bottom of the mold comprises a CT mixture of crushed magnesite. Figure 2 illustrates the assembled mold.
The riser comprises an oblique four-sided prism, where the upper end is 150 x 270 mm, the base is 123 x 250 mm and the height 300 mm. The actual EUCOR casting has a size of 400 x 350 x 200 mm. Three frames are used during the molding procedure—two being 690 x 600 x 400 mm and one 690 x 600 x 200 mm. The method of casting, which is being considered, therefore, is vertical pouring. It is also possible to use the horizontal arrangement, where it is necessary to design the circular riser mounted in the geometrical center within the upper, i.e. larger, wall of the casting.

This approach ties on to experimental research into the temperature field of the same material—EUCOR—mentioned at last year’s METAL 2000 Symposium [1].

The pouring temperature is 2300 °C, the initial mold temperature is 20 °C. The liquidus temperature is estimated to be 1775 °C and the solidus 1765 °C. The dependence of the heat capacity $c$, heat conductivity $\lambda$ and density $\rho$ of EUCOR on temperature is illustrated in Figures 3-5. The values of the same properties for the mold material are taken from other literature and exacted via measurement [2]. The mean density of the discretization network is 20 mm. A scheme of the 3-D computational network of the solved systemted casting(riser) - mold - surroundings can be see in Figure 6. The selected time step is 10 s.

Heat transfer by convection and radiation is considered in the direction from the upper base of the mold and casting (from the level) and from the surface of the frame of the mold to the surroundings $\alpha_{total} = \alpha_{convection} + \alpha_{radiation}$. Heat transfer coefficients on these boundaries were estimated. It was presumed that there is ideal physical contact between the casting and mold, and the riser and mold.

It is necessary to state that this is merely a preliminary calculation of the temperature field of a solidifying casting of EUCOR.

Results of numerical analysis

The results attained from the analysis of the temperature field of a solidifying casting and the heating of the mold represent only one quadrant of the system in question. The thermokinetics of the phenomenon was monitored over a five-day period when the casting was kept inside the mold in order to cool completely.

Figures 7-10 display the temperature field after periods of 5 minutes; 2 hours; 4 and 9,9 hours. Figure 9 shows the system after 4 hours—shortly before complete solidification. Figure 11 shows the temperature curves of the points along the heat and geometrical axis of the system illustrated in Figure 6.

Conclusion

The algorithm of the calculation of the temperature field should aim to achieve two goals: Directed solidification as the primary condition for a healthy casting. Optimisation of the technology of casting together with the preservation of optimum utility properties of the product. The achievement of these goals depends on the ability to analyse and, successively, control the effect of the main factors which characterise the solidification process or accompany it.

The analysis of the quantities should be aimed mainly at the analysis of the causes of heterogeneities in the casting with respect to phase and structural changes. It should also be aimed at thermokinetics of the creation of shrinkage porosities and cavities and at the prediction of their creation and, therefore, to control the optimisation of the shape and sizes of the risers, the method of isolation, the treatment of the level, etc. The main economic criteria to be observed are the saving of liquid material, mould and isolation materials, the saving of energy and the optimisation of casting process and the properties of the cast product.
The paper provides results of the initial computation of the temperature field, which prove that the transfer of heat is solvable, and also that using the numerical model it is possible to optimize the technology of production of this ceramic material, which enhances its utilization. The mastering of an advanced technology for the casting of EUCOR will contribute to the optimisation of a number of industries, namely the glass, energy, foundry, metallurgical, etc.

Nomenclature

I enthalpy [J.kg\(^{-1}\)]
L latent heat [J.kg\(^{-1}\)]
t temperature [K]
\(\tau\) time [s]
a thermal conductivity \(a=\lambda/\rho\cdot c\) [m\(^2\).s\(^{-1}\)]
\(\lambda\) heat conductivity [W.m\(^{-1}\).K\(^{-1}\)]
\(\rho\) density [kg.m\(^{-3}\)]
c specific heat capacity [J.kg\(^{-1}\).K\(^{-1}\)]
\(\Delta\) Laplace operator [-]
Q\(_{\text{source}}\) heat flow from internal source [W.m\(^{-3}\)]
V volume [m\(^3\)]
x, y, z axis in given direction
w\(_x\), w\(_y\), w\(_z\) shift rate [m.s\(^{-1}\)]

References

Fig. 1: Influence diagram enthalpy-temperature

Fig. 2: Scheme of the system casting-mold
Fig. 3: Influence diagram specific heat capacity-temperature

Fig. 4: Influence diagram heat conductivity-temperature

Fig. 5: Influence diagram density-temperature
Fig. 6: Diagram of 3-D computational network

Fig. 7: 3-D temperature field of the system in time 5 min
Fig. 8: 3-D temperature field of the system in time 2 hours

Fig. 9: 3-D temperature field of the system in time 4 hours
Fig. 10: 3-D temperature field of the system in time 9.9 hours

Fig. 11: Influence temperature-time of 3 points on the heat axis (see Fig. 6)