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Computer simulation of thermal conditions of mold during the crystallization of blister copper ingots

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The urgency of this work is conditioned by the necessity of introduction of modern technologies of Computer-Aided Design, Computer-Aided Engineering and Computer-Aided Manufacturing (CAD, CAE and CAM) into the daily practice of metallurgical production. The molds, used at Sredneuralsky Copper Smelter for obtaining of blister copper ingots, were analyzed by means of CAE. According to the values of thermal imaging unit, there were formulated and verified the boundary conditions of heat transfer through the following surfaces: “mold – ingot”, “mold – environment”, “ingot – environment”. According to the verified model of non-stationary heat transfer, there was carried out the computer calculation of temperature fields in the mold during the crystallization of blister copper. There was created the algorithm of combined analysis of temperature fields and stress-strain states. The computational model, which estimates the distortion and cracking of mold in operating regime, was realized on the layered finite-element mesh. On the stage of analysis of durability, crack-resistance and distortion of mold, the non-stationary and non-uniform temperature fields, calculated on the first stage, were applied as thermal load, causing the internal stresses and residual strains. Results of computer simulation were used for optimization of the mold design. The part of molds with improved design was produced with following experimental exploitation. Average resistance of experimental molds was increased by 15%. More over, the distortion of walls and bottom was not observed after 200 fillings. Thus, computer simulation of thermal conditions of the mold with crystallization of blister copper ingots is an effective tool of improvement of technological processes.

Key words: computer simulation, finite-element method, WinCAST, mold, blister copper, crystallization.

Introduction

The planned increase of copper production capacity by Ural Mining and Metallurgical Company (UMMC) sets an urgent problem about increasing of strength and operation rate of molds for blister copper casting. Nowadays, the steel molds are exploited at Sredneuralsky Copper Smelter, which is included in UMMC. As a result of thermal cycling, these molds are cracked and plastically deformed. Thermal conditions’ amplitude can be decreased due to the substantiated change of molds design, taking into account the distribution of temperature and crystallization conditions of ingots [1, 2]. The study of operating conditions and directed search of right constructive solutions became less expensive due to the usage of modern methods of computer analysis of digital model in the CAE (Computer-Aided Engineering) programs [3, 4]. However, every specific simulation task needs a creation of computational model, subjected to classical ideas and theories [5, 6]. Correct model enables to obtain the reliable computational results and accurate engineering solution.

The purpose of this work is creation and verification of computational model for the computer research of operating properties of molds.

Computational model and used software

Description of simulated process. The blister copper contains 96.0–99.5% of pure copper and small amount of impurities [7]. Pouring temperature of blister copper is in the range of 1,150–1,210 °C. The molds for copper ingots production are made of carbon steel AISI 1015 (or 1020) and are heated to 100 °C before the pouring. These molds are moving on a closed trailer conveyor and were poured through steel ladle, installed at the nose cone of converter.

Design of the mold takes into account the requirements of state standards [7] for ingot geometry, which should be adapted for mechanical handling and transportation. The weight ratio of the mold (1,210 kg) to the ingot (1,000 kg) is 1.21, which provides the sufficient strength and rigidity of the mold. For the purpose of cooling acceleration, in 15 minutes after pouring, the blister copper ingots in the molds are showered with water. At the same time, water reaches the mold and cools it.

The main cause of mold outage is the formation of high-temperature erosion grid, eventually passing into the through cracks. Other negative factor is distortion, which reduces the service life of the molds. In average, the mold can withstand 200 ingots. Metallurgists associate the development of technological process with increasing of mold durability and its high-temperature rigidity.

Advantage of the chosen software. The specialized software WinCast (RWP GmbH, Germany), applied for simulation of casting technologies, was used in this work [8]. WinCast has the advantage for the tasks, which should be solved. Especially, this advantage consists in multiphysics approach to analysis of cast parts [9], which enables to carry out the sequent solving of two bonded tasks on the common finite-element mesh. In the first stage, the temperature field is calculated in ingot and mold during the crystallization of blister copper. In the second stage, there is analyzed the stress-strain state of the mold. During the analysis of strength, crack-resistance and distortion of the mold, the non-stationary and non-uniform temperature field, calculated on the first stage of the analysis, becomes the load, causing the appearance of internal stresses and residual strains [10].

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Computational model. The temperature distribution in the mold can be determined by the equation of transient heat conduction:

$$\nabla \cdot k(T)\nabla T = \rho(T)c(T)\partial T/\partial t,$$

where: $T = T(t, x, y, z)$ – a desired function of temperature distribution of four coordinates x, y, z, t in space; t – time; x, y, z – spatial values; $\rho(T)$ – density; $c(T)$ – heat capacity; $k(T)$ – thermal conductivity of steel, used for the mold manufacturing.

Heat comes to the mold from ingot during the copper crystallization and following cooling. The temperature distribution in the ingot can be calculated, taking into account the latent heat of crystallization:

$$\nabla \cdot k(T)\nabla T + \dot{q}(T) = \rho(T)c(T)\partial T/\partial t,$$

where: $\dot{q}(T)$ – latent heat of copper crystallization; $\rho(T)$, $c(T)$ and $k(T)$ – thermo-physical properties of copper.

During the proceeding of solution to the computer simulation, the heat conduction equation should be presented in matrix formulation:

$$[K(T)]\{T\} + \{Q(T, t)\} = \rho(T)[C(T)]\{\dot{T}\},$$

where: t – time; $\{T\}$ – vector of temperature field values; $\{\dot{T}\}$ – vector of changing temperature rates in time; $\rho(T)$ – metal density; $[C(T)]$ – matrix of specific heat consumption; $[K(T)]$ – matrix of thermal conductivity; $\{Q(T, t)\}$ – realization of latent heat during the metal cooling in the temperature range from liquidus to solidus.

The dynamic variables – density, specific heat, thermal conductivity and heat of fusion – are the coefficients of the solved equation. They are specified as input data for calculation in the form of temperature dependence. The constitutive equation is non-linear and requires the correlation of dynamic variables in each calculation step, according to the input data on the temperature dependence of thermal properties.

Authors offered the following boundary conditions for the created computational model. This model singles out the heat transfer through the surfaces "mold – ingot", "mold – environment" and "ingot – environment". The following equation is reasonable for the internal boundary "mold – ingot":

$$k(T)\partial T/\partial n = -\alpha(T - T_c),$$

where: n – a normal to the boundary surface; α – coefficient of boundary heat transfer from ingot to mold with the local surface temperature T_c.

Effects of natural convection and radiation to environment with the temperature Tout are taken into account by the heat transfer equation for the external boundaries "mold – environment" and "ingot – environment":

$$k\partial T/\partial n = -[\alpha_{\text{conv}}(T) + A\varepsilon_0[(T/100)^4 - \\ - (T_{\text{out}}/100)^4]/(T - T_{\text{out}})](T - T_{\text{out}}),$$

where: ε_0 – ratio of ideal black body radiation; A – absorption factor of metal.

During the simulation of natural convection, the Nusselt number, characterizing the heat transfer rate, is evaluated by the Grashof and Prandtl criteria function: $\text{Nu} = 1.18(\text{Gr}\cdot\text{Pr})^{0.125}$ [5]. In this function, the Prandtl number takes into account the influence of physical properties of air environment, and the Grashof criterion takes into account the intensity of its movement. Inertial forces can be neglected in the free movement of ambient air with low speeds, considering that physical properties of air and actual temperature drop have the main influence upon the heat exchange. Small values of air movement velocity are observed for free convection. According to this, the Reynolds number, including the air velocity and kinematic viscosity in an explicit form, becomes an inessential factor. Based on the foregoing physical model, the convective component of effective heat transfer coefficient is calculated by the following equation:

$$\alpha_{\text{conv}}(T) = (1.18k(T)/L)((\rho(T)^2C(T)/k(T))L^3\times \\ \times(T - T_{\text{out}})/T))^{0.125},$$

where: L – a typical size, adopted for the mold (1 m).

The calculated convective term is increased by 30% for upper heat-release surface of the mold. On the other hand, this term is reduced by 30% for bottom surface.

The computational model is implemented in the layered finite element mesh [8–10], which allows to switch the type of materials after transition from simulation of manufacturing technology to analysis of operating regimes of the mold (Fig. 1). The crystallized metal in 3D model is marked by black color: the steel of mold is crystallized at the manufacturing stage (Fig. 1, *a*) and the blister copper inside the mold is crystallized at the operating stage (Fig. 1, *b*). The bonded analysis of manufacturing technology of the mold and temperature field during copper crystallization in the mold with its stress-strain states was held in a common finite element mesh due to transition of calculated results.

Results of computational experiments and their discussion

The computational model was verified by the test indication of thermal imaging unit (Fig. 2) due to comparison of calculated and measured values of temperature on the mold surface. Coincidence of calculated and measured values of temperature, together with identical overall picture of temperature distribution on the mold surface, confirm that the boundary and initial conditions of computational model were specified correctly. Therefore, the created computational model forecasts the temperature field in observable construction with adequate accuracy.

The calculated transient temperature field was used as the thermal load in quasi-static solution of stress-strain problem of the mold (Fig. 3). Some variations of mold design were

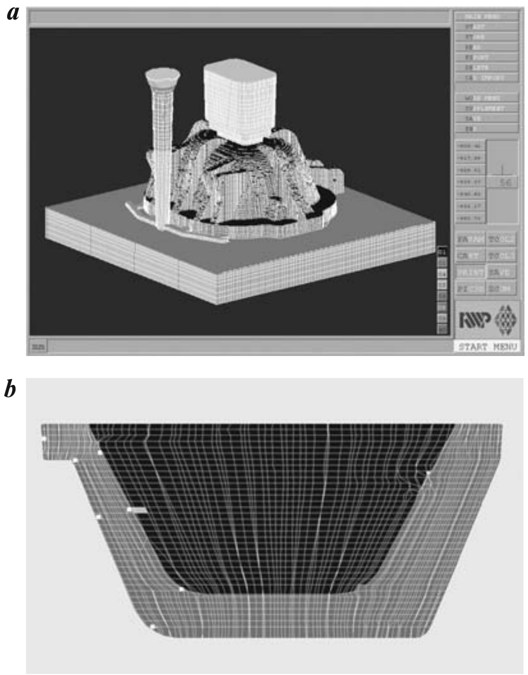

Fig. 1. Finite-element mesh during the simulation of cast technology (*a*) and operating regimes (*b*) of mold

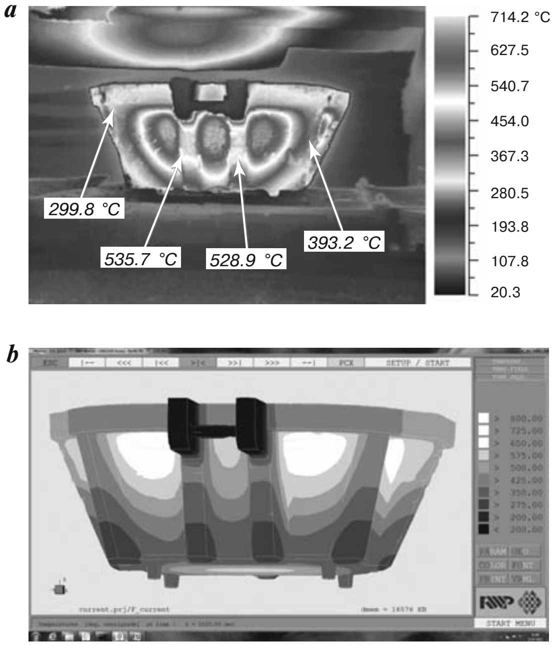

Fig. 2. Measured (*a*) and calculated (*b*) distribution of temperature on the surface of mold before the water cooling process

compared. The chosen variant of design with reinforced ring and bottom zones provides the minimal distortion of the mold under current operating conditions.

A step-by-step computer analysis of ultimate stresses and strains can forecast the location of cracks on the working surface of the mold (Fig. 4, *a*). Using the created computational model, such forecast coincides with visual observation of mold destruction (Fig. 4, *b*).

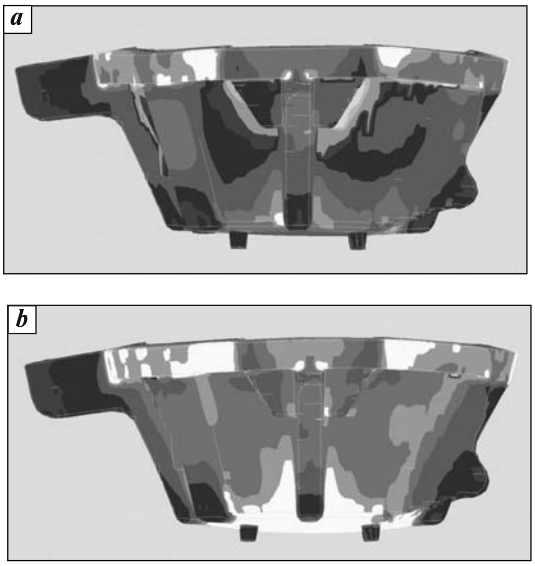

Fig. 3. Stresses and strains in the mold before (*a*) and after (*b*) water cooling of ingot

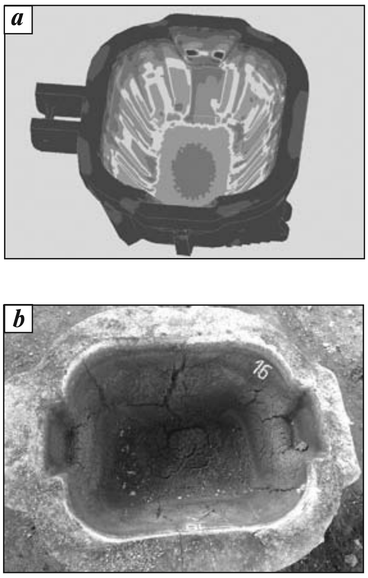

Fig. 4. Forecasted (*a*) and full-scale (*b*) location of cracks on the inner surface of the mold

Practical implementation of simulation results

Pilot batch of molds with developed design was produced from steel AISI 1020 (or AISI 1015) in the number of 10 pieces. The advanced molds successfully passed the test operation in Sredneuralsky Copper Smelter. The average resistance of molds was sufficient for production of 230 ingots for developed design and only 200 ingots for existing design. Despite the increase of the mass of the developed mold by 180 kg, the average specific consumption for pilot batch was 5.81 kg/t, which was lower than average steel consumption (as in October 2012 (6.14 kg/t), when the developed molds were mainly exploited).

After completion of the pilot molds operation, there was no distortion of its walls and bottom. At the moment of outage, the deep erosion grid was observed on the working surface of the mold. Cracking in two zones became the main reason for rejection of exhaust molds. The cracks appeared at the interfaces between bottom and walls (where the copper melt was dropped at the time of pouring) and on shoulders. The through cracks were developed in two molds. Copper melt is poured into the evolved cracks, which leads to formation of combs and makes it difficult to remove the ingot from mold.

Conclusion

There was created a computational model for simulation of temperature fields and stress-strain states of the mold during blister copper crystallization. The created computational model was verified by the measured values of temperature and was used for the mold design optimization. Variations of manufacturing technology and operating regimes of the mold were simulated on the common finite element mesh. According to the results of computer simulation, the pilot batch of molds was produced and successfully tested in the smelting plant. After the completing process of the experimental operation, the pilot molds were practically not distorted.

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