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SETTING A NUMERICAL SIMULATION OF FILLING AND SOLIDIFICATION OF HEAVY STEEL INGOTS BASED ON REAL CASTING CONDITIONS

POSTAVITEV NUMERIČNE SIMULACIJE POLNJENJA IN STRJEVANJA VELIKIH JEKLENIH INGOTOV NA PODLAGI REALNIH RAZMER PRI ULIVANJU

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The paper is devoted to new experiences with the setting of a numerical simulation of filling and solidification of a 90-ton steel ingot in the ProCAST simulation programme. The aim of the numerical modelling realized under the conditions of the Department of Metallurgy and Regional Materials Science and Technology Centre (RMSTC) at VSB-TU Ostrava is the verification and optimization of the production technology for the heavy-steel ingots produced in VÍTKOVICE HEAVY MACHINERY a.s. The input parameters of the computation were determined with the real conditions of casting a 90-ton steel ingot. The ingot geometry was created in the CAD system SolidWorks. Before the computational grid generation of finite elements in the Visual-Mesh module, the geometry was subjected to an analysis of the topology. The material properties of the individual components of the ingot-casting system were defined with the Computherm calculating module selecting the materials from its own database of ProCast. In addition, the thermodynamic properties were determined by using the datasheets of the refractory materials of the manufacturer, and finally checked with the equations generally used to determine liquidus and solidus temperatures, density and enthalpy, etc. The boundary conditions and the heat transfer were also defined. In parallel with the numerical simulation, the operational experimental casting of a 90-ton ingot was carried out. To obtain more complete information about the temperature fields of the ingot-casting system and of the data about the values of the heat flow, the process of filling and solidification was monitored by using thermal imaging cameras. The conclusion summarizes the main knowledge obtained on the basis of the primary results of the computation and gives a guideline for further research.

Keywords: numerical simulation, heavy-steel ingot, heat flow, thermal measuring

Članek obravnava nove izkušnje z numerično simulacijo polnjenja in strjevanja 90-tonskega jeklenega ingota s ProCAST-programom za simulacijo. Namen izvršenega numeričnega modeliranja v Department of Metallurgy in Regional Materials Science and Technology Centre (RMSTC) na VSB-TU Ostrava je preverjanje in optimiranje proizvodne tehnologije težkih jeklenih ingotov, proizvedenih v Vítkovice Heavy Machinery, a. s. Vhodni parametri za izračun so bili določeni v realnih razmerah pri ulivanju 90-tonskega jeklenega ingota. Geometrija ingota je bila postavljena v CAD-sistemu SolidWorks. Pred postavitvijo mreže končnih elementov z Visual-Mesh-modulom je bila geometrija obdelana s topološko analizo. Lastnosti materiala posameznih komponent livnega sistema ingota so bile določene z računskim modulom Computherm in z izbiro materiala iz datoteke ProCast. Termodinamske lastnosti so bile določene z uporabo datotek proizvajalcev ognjevzdržnih materialov ter končno preverjene z izračunom po enačbah, ki se uporabljajo za določanje temperature likvidusa in solidusa, gostote, entalpije itd. Določeni so bili robni pogoji in prenos toplote. Vzporedno z numerično simulacijo je bilo izvršeno eksperimentalno ulivanje 90-tonskega ingota. Da bi dobili bolj popolno informacijo o temperaturnih poljih ulivnega sistema ingota in podatke o vrednostih toplotnega toka, je bil postopek polnjenja in strjevanja posnet tudi s termovizijsko kamero. Sklepi povzemajo glavne ugotovitve primarnih rezultatov izračunov in dajejo napotke za nadaljnje raziskave.

Ključne besede: numerična simulacija, težki jekleni ingot, toplotni tok, termografske meritve

1 INTRODUCTION

The numerical modelling of filling and solidification of a steel ingot was performed within the Department of Metallurgy and RMSTC using the ProCAST software. The software allows a 3D fully dimensional numerical simulation of filling and solidification of steel including a prediction of the ingot-volume defects such as porosity and shrinkage. Due to the Flow and Stress modules, it is possible to take into account the effects of natural convection and of the formation of the air gaps between the ingot body and the inner wall of the mould during the calculation, and to predict the emergence of the internal stress that can ultimately lead to cracks and rupture[1].

In general, the numerical solution of each task is divided into three stages:

1. *Pre-processing*: includes the geometric modelling, the computational mesh-generation process, and the definition of the calculation.
2. *Processing*: involves the computation in the solver.
3. *Post-processing*: focuses on the evaluation of the results.

The conditions for the numerical model setting were based on the real conditions of an experimentally cast, 90-ton steel ingot produced in VÍTKOVICE HEAVY MACHINERY, a. s.

2 GEOMETRY AND THE COMPUTATIONAL MESH

The computational-mesh geometry and the generation of the casting system for the 90-ton steel ingot were made in cooperation with MECAS ESI, s. r. o. The comparison between the real and the CAD geometry of the casting system is shown in **Figure 1**[2]. **Figure 2** shows the final computation mesh of the casting system. The volume ingot mesh consists of 348 794 nodes. The total volume of the tetra elements is 1 766 041. The mould has a rough mesh. For a more appropriate description of the geometry, the details, the insulation, and the ceramic parts have a better mesh.

The final mesh of geometry was saved in *. mesh format and subsequently loaded in the ProCAST module for a calculation entry, also called the PreCAST. It was necessary to define:

- the material properties of the individual parts of the casting system,
- the heat-transfer coefficients on the interface of the geometry elements,
- the boundary conditions, such as the casting temperature, the casting speed, the conditions of heat losses through the surface of the ingot,
- the operating conditions (such as gravity),
- the initial conditions for the calculation,
- the calculation parameters – the so-called RUN PARAMETERS.

Among the other things, the RUN PARAMETERS define the conditions for the calculation termination, the so-called STOP criteria. The stop criteria also include the attainment of a certain temperature in the ingot or the termination of the calculation at a particular time after the filling. The number of the steps of the calculation is also specified, as well as the length of the time step and the frequency of storing the results regarding the temperature field and/or the heat flux[2,3].

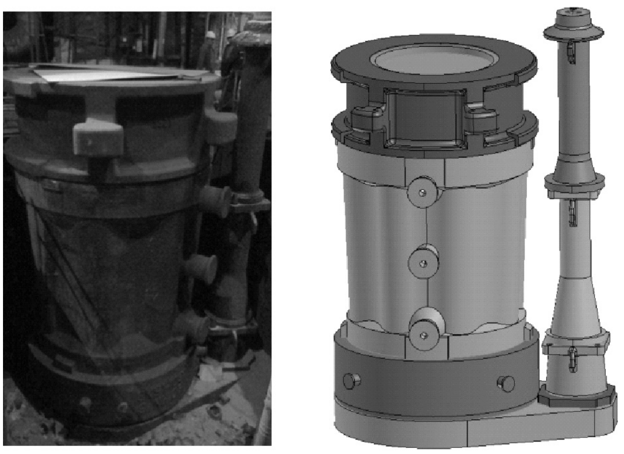

Figure 1: Comparison between the real and the CAD geometry of the casting system for a 90-ton ingot[2]
Slika 1: Primerjava realne in CAD-geometrije ulivnega sistema 90-tonskega ingota[2]

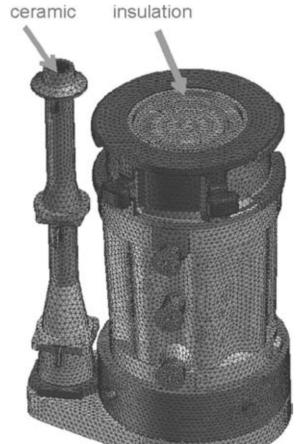

Figure 2: View of the final computational mesh of the casting system
Slika 2: Videz končne računske mreže ulivnega sistema

The computational time of one variant is around 96 h when two processor cores are used. However, the time needed for the preparation of the simulation and for the evaluation of the achieved results has to be added to the time taken by the computation.

3 MONITORING OF THE HEAT FLUX AND OF THE TEMPERATURE DURING THE EXPERIMENTAL CASTING

As mentioned above, the course of the changes in the temperature field on the surface of the casting system during the experimental casting of a 90-ton ingot was also monitored by using the thermal-imaging cameras. The thermography measurements were performed with AVIO TVS 700 cameras. According to the tables of the emission coefficients, the value of emissivity was set at 0.85. At the time of the measurement, an average ambient temperature was 26 °C corresponding to the conditions of the operation of a steel plant. The measurement was not affected by the increased dusting or drafts, and it was done with a tripod from a constant distance of 6.5 m. **Figure 3** shows the workers making the thermography measurements.

During the thermography measurements images were being taken in 10-minute intervals, from the moment when the casting system got preheated, during the casting itself and until after the stripping, therefore for 24 h. The temperatures were monitored on the surface of the head, the mould, the washers, and the casting stake. During the measurements, the temperature of the pit wall, in which the casting system was located, was scanned twice. After the completion of the filling, an image of the temperature-field distribution on the surface of steel, incurred after the addition of the insulation backfill, was recorded. A self-evaluation of images was

Figure 3: View of the workers making the thermography measurements
Slika 3: Delavci med izvajanjem termografskih meritev

performed in the SW GORATEC Thermography Studio v4.5. When evaluating the images, the temperature distribution, the temperature profile and the heat flux in the selected area were monitored. The values of the thermal flow and the temperature information were used to specify the parameters of the setting of the numerical simulation of filling and solidification of the steel ingot.

4 DISCUSSION OF THE ONGOING RESULTS

During the tuning of the setting of the numerical simulation of the filling and solidification of a 90-ton ingot, 9 configurations have been calculated up to now. The difference between the temperature profiles on the surface of the ingot obtained for the first variant and for 9th variant, 20 min after the initiation of the filling and at the end of the filling, when the thermography-measurement results were used, is captured in **Figure 4**.

The software for the image evaluation has different options for setting the displayed scale of temperatures; thus, the authors of the paper used the possibilities of the Visual Viewer of ProCAST and adjusted the scale of the numerical-simulation results to the scale of thermography. The selection and editing of the colours were dependent on the colour sense of the user. The advantage of the Visual-Viewer postprocessor is the display of the temperature in precise contours – changes to the minimum and maximum values can provide accurate information about the temperature in the chosen geometric location. In its first column **Figure 4** shows the temperature evolution on the mould surface for the original setting, where the values of the heat-transfer coefficients ranged from 100 W m^{-2} K^{-1} to 1000 W m^{-2} K^{-1} as is typical in these simulations. However, it is obvious that the temperature values on the mould surface are below the values measured during the thermography measurements (the second column). Therefore, it was necessary to adjust the coefficients according to the measured values depending on time. The third column already captures the evolution of the temperature on the mould surface after the adjustment of the heat-transfer coefficients. The

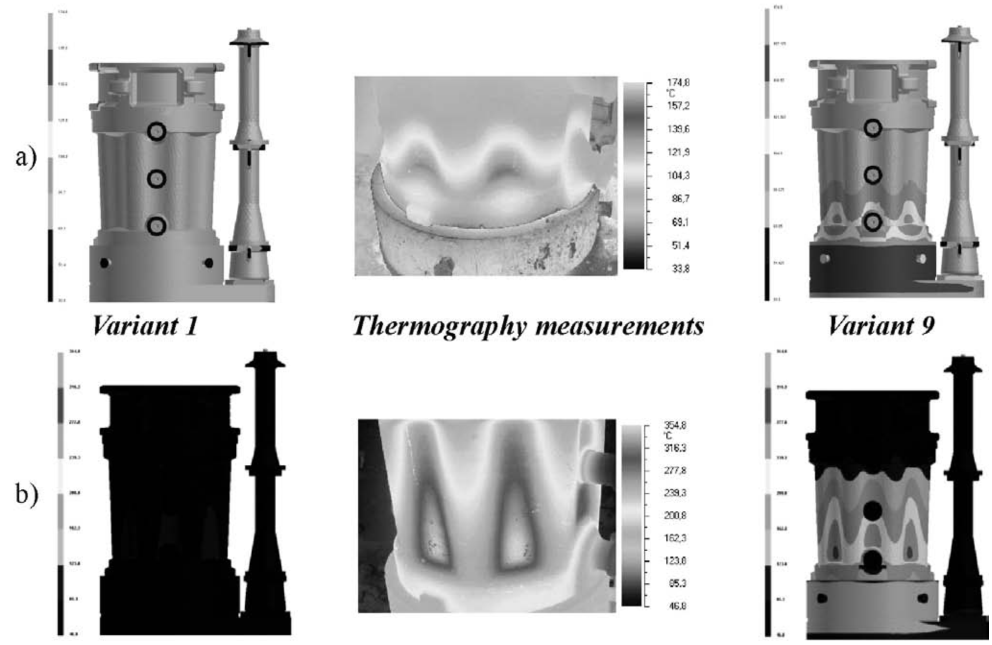

Figure 4: Comparison of the temperatures on the ingot mould surface: a) 20 min after the initiation of the filling, b) after the filling
Slika 4: Primerjava temperature površine kokile: a) 20 min po začetku ulivanja, b) po koncu ulivanja

results of the thermography measurements and the numerical simulation are already converging.

5 CONCLUSION

The setting of the numerical model for filling and solidification of a heavy 90-ton steel ingot was based on real experimental conditions of casting. The numerical modelling was carried out under the conditions of the Department of Metallurgy and RMSTC at VSB-TU Ostrava in ProCAST SW. During the solution, an import of the specific material properties was planned. For example, solidus or liquidus temperatures were determined for the material (steel) using the instrumentation for a thermal analysis (STA 449 Jupiter of NETZSCH Company) placed in the laboratory of RMSTC[4]. During the experimental ingot casting, the temperatures and the heat flows on the surface of the casting system were monitored with a thermal imaging camera. Once the process of the temperature profile on the mould surface of the numerical-simulation results corresponds to the results of the thermography measurements from the start of the filling to the actual stripping, the researchers will proceed to further stages of numerical simulations based on the distribution of the segregation of chemical elements through the cross section of the ingot. At the same time, the analysis of the segregation distribution will be evaluated on the experimental cut ingot. The aim of the numerical simulations will be to test the changes in the boundary conditions of casting that should help us not only to minimize the volume of defects, but also to minimize the occurrence of the segregation in the heavy forging of ingots produced by VÍTKOVICE HEAVY MACHINERY, a. s.

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