Abstract
The paper is devoted to verification of parameter-setting of a numerical simulation of filling and solidification of a 90-ton heavy steel ingot in the ProCAST simulation programme. The aim of numerical modelling realized under the conditions of the Department of Metallurgy and Foundry and Regional Materials Science and Technology Centre (RMSTC) at VSB-TU Ostrava is the optimization of the production of heavy steel ingots produced in VÍTKOVICE HEAVY MACHINERY a.s. (VHM). Input parameters of computation were determined by the real conditions of parallel experimental casting of a 90-ton steel ingot. Material properties of the individual components of the ingot casting system were defined by the COMPUTHERM calculating module, by selection from own database of ProCAST, using datasheets of refractory materials of the manufacturer, and finally checked by calculation of the equations generally used to determine liquidus and solidus temperatures. To obtain more complete information about the temperature fields of the ingot casting system, the process of filling and solidification was monitored using thermal imaging cameras. Primary results of the numerical simulations were compared with the results of thermography measurement and with the real time of filling and solidification. Based on the comparison of the results, the initial temperatures of the casting system and heat transfer coefficients were modified. The character of the filling and the RUN PARAMETERS were also changed. Now, the attention is also focused on the verification of liquids and solidus temperatures of steel, and heat capacity of mould material using methods of thermal analysis.

Keywords: heavy steel ingot, macro-segregation, numerical modelling, heat transfer coefficient, ProCAST

INTRODUCTION
The paper follows the works of authors [1, 2], which are devoted to verification of filling and solidification of 90-ton steel ingot using numerical modelling in the ProCAST simulation programme. The primary aim of the numerical simulations is the minimization of the volume defects in heavy steel ingots, especially macrosegregation, depending on boundary conditions of the casting. Based on available literature [e.g. 3,4], it was confirmed that the macrosegregation is a function of chemical composition of the steel, of the method and time of solidification. This means that in order to minimize the extent of the segregation it is not sufficient to change only the geometry of the mould, but it is also necessary to optimize the regime of the casting and primarily the control of solidification. In order for the default version of the numerical model of the filling and solidification of the steel ingot aimed to predict the extent of the macrosegregation to correspond to real solidification conditions as accurately as possible, it was important to define the parameters of the calculation correctly.

Determination of some boundary, operating and initial conditions is usually not relatively difficult. In our case, the modelled area was clearly defined by the geometry of the casting system of the 90-ton ingot [2]. The character of the filling, or the casting temperature of the steel were defined according to real casting
conditions of the experimentally cast ingot in VHM. The properties of refractory materials were determined as indicated in the data sheets provided by the manufacturer. The quality of the results of the numerical simulation of the volume defects in ingots, especially macrosegregation of elements, is mainly determined by the quality of the thermodynamic properties of steel and of mould material, respectively by the applied conditions of heat transfer among the individual parts of the casting system and by the definition method of the heat losses. And here is where the first difficulties can be encountered. First, the grade of the steel or the cast iron of the mould may not be included in the basic material database of the ProCAST software. To solve this issue the Computherm above-standard module needs to be used. Based on the definition of chemical composition of the steel, the thermodynamic database Computherm, allows the user to calculate thermodynamic parameters for any new material, or to follow the changes of the thermo-physical data relating to changes of chemical composition [5]. Another way is to use the experimental method of thermal analysis [6, 7], or it is also possible to use information from literature. Also, the definition of the heat transfer coefficients among the individual components of the casting system is not simple. The constant values in the range of 100 to 1,000 Wm⁻².K⁻¹ are usually given in literature. To be sure that the heat transfer conditions are set correctly, the thermography measurement of temperature fields and heat flux of the individual parts of the casting system during the experimental casting of 90-ton ingot was ensured.

THERMOGRAPHY MEASUREMENT

The conditions of thermography measurement have been published in the paper [2]. During the thermography measurements, images were taken at 10-minute intervals from the moment of casting system preheating, through the casting itself until the moment when it was found that the temperature does not change. After this, the intervals of the sampling were extended to about half to one hour. The temperature was monitored for 24 hours at selected points (see Fig. 1) on the surface of the head (hot top), of the mould, of the stool and of the sprue.

Thermography measurement results were processed by software GORATEC Thermography Studio version 4.5 [8]. In Figure 2 there is an example of the processing of the selected image of thermography measurement on a mould surface. As shown in Figure 2, the temperature scale is adjusted with regard to the range of measured values. The proper surface temperature can be calculated only when the right emissivity value is known. It must take into account that in most cases an infrared imaged contains objects with different emissivity values. The ambient (background) temperature also affects scanned temperature value. As further shown in Figure 2, SW offers the possibility to analyse the point, line or selected area. During the point analysis the software evaluates the expected temperature on the surface at the selected location. In our case we analysed 8 points - four temperatures in the concave and four temperatures in the convex part of the mould wall.
If we choose evaluation of the temperature on the surface using the line analysis, then we can obtain the temperature profile in the selected horizontal (or vertical) plane. The example of the temperature profile for the selected planes 1 and 2 (note: in Figure 2 plane 1 is closer to a stool of mould) is shown in Figure 3. Another option is a thermal analysis of a selected area of the examined surface. Again, as shown in both previous cases, both the emissivity and ambient temperature can be individually adjusted during the analysis. In Figure 3 two rectangular fields were selected (left - area 1 and then area 2).

Fig.2 Temperature field image with marked points, lines and areas

Fig.3 Temperature profile in the horizontal plane 1 and 2 (see Fig.2) on the surface of the mould

Thermal data of selected areas are generated in the form of a histogram (see Figure 4). From the histogram in Figure 4, the information about temperature distribution in a selected area can be received, but we also can find the density of heat flux. The values are automatically exported into a table – see Table 1.

Fig.4 Histograms of selected areas on the mould surface

<table>
<thead>
<tr>
<th>Area</th>
<th>Min °C</th>
<th>Max °C</th>
<th>Avr °C</th>
<th>Emiss.</th>
<th>Ta °C</th>
<th>Area mm</th>
<th>P2 Joule/sec</th>
<th>&lt;P2&gt; Joule/(sec m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77,6°C</td>
<td>96,6°C</td>
<td>90,9°C</td>
<td>0,65</td>
<td>26,10</td>
<td>459449</td>
<td>460</td>
<td>211</td>
</tr>
<tr>
<td>2</td>
<td>80,2°C</td>
<td>95,5°C</td>
<td>91,0°C</td>
<td>0,65</td>
<td>26,10</td>
<td>459449</td>
<td>461</td>
<td>212</td>
</tr>
</tbody>
</table>

For each area, in Table 1 the determined minimum and maximum values of the temperatures, the average temperature, the used emissivity, the ambient temperature, the size of the analysed surface and heat flux of the radiations (P2) as well as heat flux of the radiation in the specific selected area <P2> are listed. Heat flux of the radiation P2 is defined as:

$$ P_2 = \frac{c\varepsilon(T^4 - T_0^4)}{s} $$

(1)
where \( \sigma \) is Stephan Boltzmann constant, \( \varepsilon \) emissivity, \( T \) – determined temperature on the analysed surface, \( T_0 \) - ambient temperature, \( S \) - selected area. And the heat flux by radiation of the specific selected area \(<P2>\) is defined as:

\[
<P2> = S \cdot P2
\]  

(2)

In this way, all images of surface of mould taken during the thermography measurement from the start of casting up to the actual stripping were processed. In the case of evaluation of thermal images of the head, and of the stool and casting sprue, and eventually the temperature of the wall of the casting pit, the evaluation was simplified to obtain information regarding the temperature distribution on the surface and the character of the temperature profiles in the horizontal planes of individual elements of the casting system.

DISCUSSION OF RESULTS - INTERFACE OF NUMERICAL MODEL

The obtained information about the heat fluxes was then used to refine the settings of the heat transfer coefficients of the numerical model of the filling and solidification of a 90-ton steel ingot in SW ProCAST. Heat transfer coefficients are defined individually for each of the contact interfaces of components in the INTERFACE menu, i.e. such as heat transfer coefficient between the ingot and ingot mould, between the ingot and insulation, etc., as shown in Figure 5.

Figure 6 shows the comparison of the temperature field on the surface of the mould in the selected time a) with the original setting of heat transfer coefficients of numerical simulation b) measured during the thermography measurement c) and temperature field obtained from numerical simulations with adjusting of the coefficient of heat transfer according to the results of thermography measurement. Both, the temperature scale and colour scale of the results of the numerical modelling of the temperature field were adapted to display the results of thermography measurement. As it is obvious from Figure 6, the adjustment of the coefficients contributed to obtaining the more realistic results of the temperature fields on the surface of the mould. Because even the post-processor ProCAST called Visual Viewer offers a possibility of analysis of the temperature changes over time at a selected point or the analysis of the temperature profile of the analysed area, the specific temperatures at selected points and planes in the mould wall were detected, similar to thermography measurements. But there is a difference between the point analysis of results obtained from thermography measurements and numerical simulation in the method of scanning the temperature. While the results of thermography measurements are based on the detection of temperature on the surface of 2D images of the temperature field (not considering curvature geometry or analysis of the temperature in the volume), for the results of numerical modelling the analysis of a point or line is carried out directly at a given point or defined segment. This means that if the chosen point or line extends to the volume of mould wall, then the temperature change is plotted on a graph in exactly the same place, thus possibly in the volume, as shown on the wire-frame view of mould of the selected segment in the wall of the mould in Figure 7. It was also a reason why the lines ultimately selected in the results of numerical modelling intersect a shorter part of the mould wall, and therefore show only a limited section of the temperature profile in the selected plane. Because if a longer part was selected, then the profile intruded into the volume of the mould wall, where the temperature was already influenced by the temperature of the filled metal (the wall of the mould warms up) and therefore it was higher. Further difference between the analysis of the temperature from the numerical modelling and from the thermography measurement is the definition of a position of the point or profile in the plane. As for the images from thermography measurement, the
location of point is "random" – providing no information about the location of the point or line. Whereas, the results of numerical modelling show the position of the point or line accurately defined. Therefore, the temperature can be repeatedly detected in the same point especially if we simulate different boundary conditions. Figure 6 d, e, and f show the temperature profiles obtained in the selected planes. Table 2 shows a summary of observed temperatures at selected points on the surface of the mould wall.

Table 2: Temperatures using the point analysis [in °C] (points from the bottom up: 1, 2, 3, 4 – concave; 5, 6, 7, 8 – convex)

<table>
<thead>
<tr>
<th>Point</th>
<th>NM_initial</th>
<th>T</th>
<th>NM_new</th>
<th>Point</th>
<th>NM_initial</th>
<th>T</th>
<th>NM_new</th>
</tr>
</thead>
<tbody>
<tr>
<td>4th</td>
<td>93</td>
<td>302</td>
<td>295</td>
<td>8th</td>
<td>87</td>
<td>209</td>
<td>208</td>
</tr>
<tr>
<td>3th</td>
<td>94</td>
<td>325</td>
<td>302</td>
<td>7th</td>
<td>87</td>
<td>227</td>
<td>230</td>
</tr>
<tr>
<td>2nd</td>
<td>102</td>
<td>353</td>
<td>343</td>
<td>6th</td>
<td>85</td>
<td>244</td>
<td>237</td>
</tr>
<tr>
<td>1st</td>
<td>76</td>
<td>262</td>
<td>185</td>
<td>5th</td>
<td>83</td>
<td>249</td>
<td>223</td>
</tr>
</tbody>
</table>

Fig.6 Comparison of the temperature field on the surface of the mould and temperature profiles in a selected time step between the variants a), e) numerical simulations with the original setting of heat transfer coefficients; b) image of thermovision measurements; c) numerical simulations after adjusting the heat transfer coefficients according to the results of thermovision measurements.

Fig.7 Example of the mould wall intersection during the temperature analysis of the profile
CONCLUSION
The paper deals with the comparison of the results of temperature field on the surface of the mould obtained from the numerical simulation of filling and solidification of a 90-ton ingot produced in VÍTKOVICE HEAVY MACHINERY a.s. with the results of the thermography measurement. The numerical simulations are performed in the ProCAST software at the Department of Metallurgy and Foundry under the auspices of the Regional Material Science Centre and Technology of the VŠB - Technical University of Ostrava. The aim of the simulations is to optimize the conditions of casting and solidification of heavy forging ingots with an emphasis on minimizing the macrosegregations. In order for the default version of the numerical model of filling and solidification of the steel ingot to correspond with the real solidification conditions as accurately as possible, the temperature on the surface of the mould was verified using the thermography measurement during parallel experimental casting of the real 90-ton steel ingot in VHM a.s. From the comparison of the temperature profiles of the numerical modelling and thermography measurements in individual time steps it was found that the profiles agree until approximately 4 hours after the end of the casting. But then the results begin to diverge. While the real temperature on the surface of mould stabilized until the stripping, in the results of the numerical modelling the gradual decline of the temperature was identified. This can be explained by either inappropriately defined dependencies of the change of the heat transfer coefficient over time, or it can be justified by improperly defined heat capacity of the cast iron mould. For this reason, additional attention will be focused on verifying the heat capacity of a sample of the mould material and its thermal conductivity.

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REFERENCES