M. TKADLEČKOVÁ, K. MICHALEK, K. GRYC, L. SOCHA, P. MACHOVČÁK

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PREDICTION OF QUALITATIVE PARAMETERS OF SLAB STEEL INGOT USING NUMERICAL MODELLING

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The paper describes the verification of casting and solidification of heavy slab ingot weighing 40 t from tool steel by means of numerical modelling with use of a finite element method. The pre-processing, processing and post-processing phases of numerical modelling are outlined. Also, the problems with determination of the thermodynamic properties of materials and with determination of the heat transfer between the individual parts of the casting system are discussed. The final porosity, macrosegregation and the risk of cracks were predicted. The results allowed us to use the slab ingot instead of the conventional heavy steel ingot and to improve the ratio, the chamfer and the external shape of the wall of the new design of the slab ingot.

Key words: steel, numerical modelling, porosity, macrosegregation, cracks

INTRODUCTION

Forged thick steel plates, blocks, and rods are widely used for special machine components for demanding applications. These forgings must be of very high quality, they must be free of shrinkage, porosity, segregation, cracks, etc. Actually, these forgings are obviously produced from conventional forging heavy ingots where we can expect a typical non-uniform cast macrostructure of an ingot, as well as the macrostructure, which is the result of plastic deformation during the subsequent forming process [1].

The main precondition of the competitiveness of any steel plant is production of a consistently high quality. For achievement of the high quality of final steel heavy ingots, the Electro-Slag Remelting (ESR) technology can be used [2], or new unconventional technologies (such as for example the intensive water cooling [3]) can be used. As it is also evidenced by the results of studies performed e.g. by the authors [4], the size of the central defect is strongly dependent on the shape of ingot.

Due to the size of forgings (thick steel plates, blocks, etc.), it would be interesting to produce these forgings from slab ingots. It is possible that production of forgings from slab ingots (which are distinguished by a characteristic aspect ratio A/B) would reduce the occurrence of segregations. One of the ways, how to monitor and optimize the production steps from the casting to the forming process, is use of methods of numerical modelling [5,6].

In this study, casting and solidification of heavy slab ingot weighing 40 Mg from tool steel were numerically simulated with use of a finite element method. When comparing slab ingot with conventional heavy steel ingot, the final porosity, the final macrosegregation and the risk of occurrence of cracks inside the slab ingot were evaluated. Also, the new shape of the slab ingot was designed.

EXPERIMENTAL PROCEDURE

Generally speaking, numerical solution of each task is divided into three stages: 1. Pre-processing: it includes the geometry modelling and process of generation of the computational mesh and definition of calculation. 2. Processing: it involves computation in the solver. 3. Post-processing: it focuses on evaluation of the results.

For achievement of the relevant numerical results, it is necessary to have correctly defined thermo-physical and thermo-dynamic properties of the steel and of the cast iron of the mould. The properties can be determined theoretically with use of empirical equations, or with use of some thermodynamic solver. The phase transformation temperatures should be verified by different methods. For determination of the liquidus and solidus temperature and heat capacity, it is possible to use thermal analysis [7]. The reason for verification of the theoretically defined thermodynamic properties consists in the fact that thermodynamic database obviously can calculate with the equilibrium state during the determination of phase transformation temperatures. The steel is, however, a multi-component heterogeneous material with difficult complex structure and metallurgical production process can lead to evolution of many types of non-metallic phases. These non-metallic phases can have different physical properties than the metal matrix, which influence the values of phase transformation temperatures and also the character of transformation.

M. Tkadlečková, K. Michalek, K. Gryc, L. Socha, Faculty of Metallurgy and Materials Engineering, VSB-TU of Ostrava, Czech Republic
P. Machovčák, Vítkovice heavy machinery, a.s., Czech Republic

Chemical composition of tested tool steel is given in Table 1. Thermo-dynamic properties were determined using the thermodynamic database CompuTherm. The liquidus temperature of the steel was 1 487 ºC, and the solidus temperature was 1 436 ºC. The calculated thermodynamic properties of steel depending on temperature, such as thermal conductivity and enthalpy, are given in Table 2.

Table 1 **Chemical composition of tested tool steel. Content of elements / wt. %.**

C	Mn	Si	P	S
0,39	1,45	0,25	0,010	0,005
Cu	Ni	Cr	Mo	Al
0,15	1,1	1,98	0,23	0,013

Table 2 **Thermo-dynamic properties of tested tool steel in dependence on temperature**

Temperature / °C	Thermal conductivity / W/(m·K)	Enthalpy/ kJ/kg
36	50	0
300	39	150
600	33	349
748	25	544
1 434	32	998
1 487	31	1 275
2 000	39	1 700

Also, definition of the heat transfer coefficients between individual components of the casting system is not simple. The heat transfer coefficients are defined individually for each of the contact interfaces of components. To be sure that the heat transfer coefficients (HTC) are set correctly, it is advisable to make the thermography measurement of temperature fields and heat flux of individual parts of the casting system during the experimental casting of the slab ingot. The HTC is very dependent on the quality of the surface contact between the ingot and mould. Usually, the HTC is described in the literature as a constant. In our case, the HTC were set in dependence on the time or temperature. The validated coefficient was in the range from 150 to 1 000 W/(m^2·K).

The boundary conditions are presented in Table 3. The heat loss through the surface of the mould was defined as a convective cooling. On the surface of the steel an adiabatic condition was defined in a hot top.

Table 3 **List of boundary conditions**

Parameter	Value
Casting temperature/ K	1 828
Total filling time / s	1 860
Ambient temperature / K	293
Emissivity / -	0,85
Temperature of mould preheating / K	323
Gravity acceleration / m/s	9,81

RESULTS AND DISCUSSION

In order to analyse the character of the predicted final internal structure of the slab ingot, or the range of the volume defects, such as porosity and macrosegregation, a comparison with the internal structure of the simulated classical conventional polygonal ingot with the similar weight / steel grade / conditions of the casting was used. Based on the obtained results, the new shape of the slab ingot was also designed.

In the case of prediction of porosity, of macrosegregation and of cracks, it was much better to use only one type of the mesh for computation of filling and solidification and also to compute the processes during these phases in one step. The average size of the tetra elements was approx. 30 mm. Total numbers of tetra elements was approx. 1,5 mil.

The porosity was induced by two mechanisms, solidification shrinkage and gas segregation. The porosity was numerically solved with use of the model developed by Pequet, Gremaud and Rappaz. For further details, please refer to [8,9]. The porosity is shown in numerical results by whole elements (calculation cells) with certain non-filled percent of the metal volume. It means that this does not concern the porosity alone. That’s why porosity may appear at simulations larger than it will be in reality. Comparison of the final porosity in the simulated cases is shown in Figure 1.

If it is computed macrosegregation, it is necessary to consider these limitations: a) no solid movement, b) no grain sedimentation, c) fully equaixed dendrites, no columnar dendrites. The comparison of the macrosegregation of phosphorus is shown in Figure 2.

To calculate the stresses, which can lead to the hot tearing and cracks, the elasto-plastic parameters of steel had to be also generated during the calculation of thermodynamic properties of the steel. The hot tearing criterion, recently derived by Rappaz, Drezet and Gremaud [10], was used. Comparison of the prediction of hot tears is shown in Figure 3.

The classical conventional polygonal ingot solidified during approx. 13 hours, while the total solidification time of the slab ingot was approx. 7,5 hours. Due to the shorter total solidification time, the final macrosegregation of the components in the slab ingot was minor than in the classical ingot, as it is evident from Figure 1. On the other hand, final porosity in the original slab ingot was detected in higher volume range (see Figure 2). Therefore, the new design of the mould shape of the slab ingot was developed. The taper, internal walls and the A/B ratio were changed. The new design of the mould shape led also to a decrease of the risk of occurrence of hot tears (see Figure 3).

CONCLUSIONS

The paper was devoted to verification of production of the slab ingot from tool steel using the numerical modelling with a finite element method. As a result of numerical modelling it was found that:

- the quality of numerical results depends on the accuracy of thermodynamic properties of the steel, or on the defined conditions of the heat transfer;

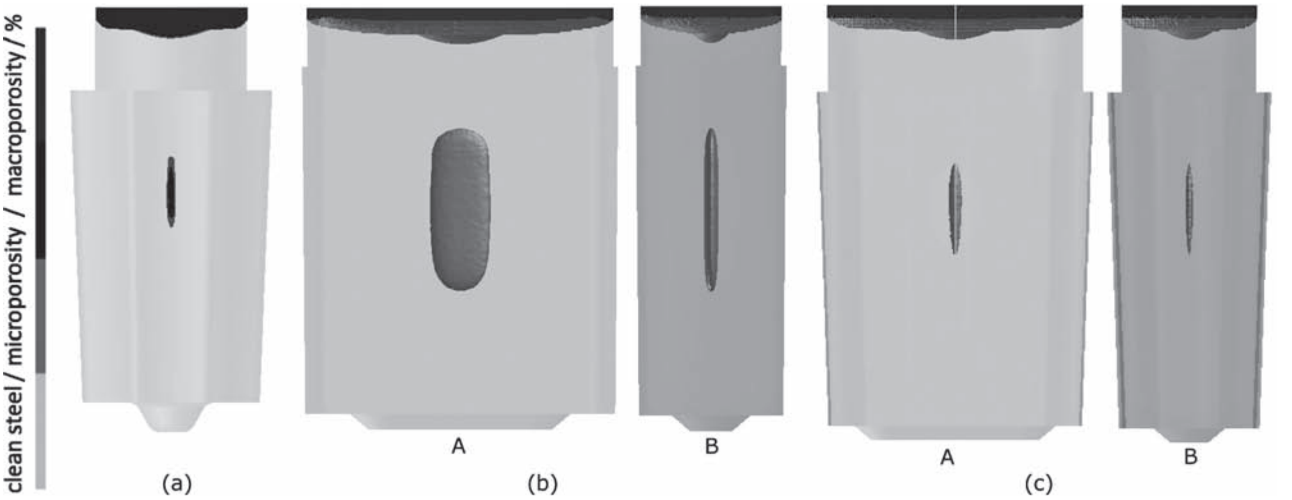

Figure 1 Comparison of the final porosity in (a) conventional classical ingot (b) slab ingot (c) new slab ingot

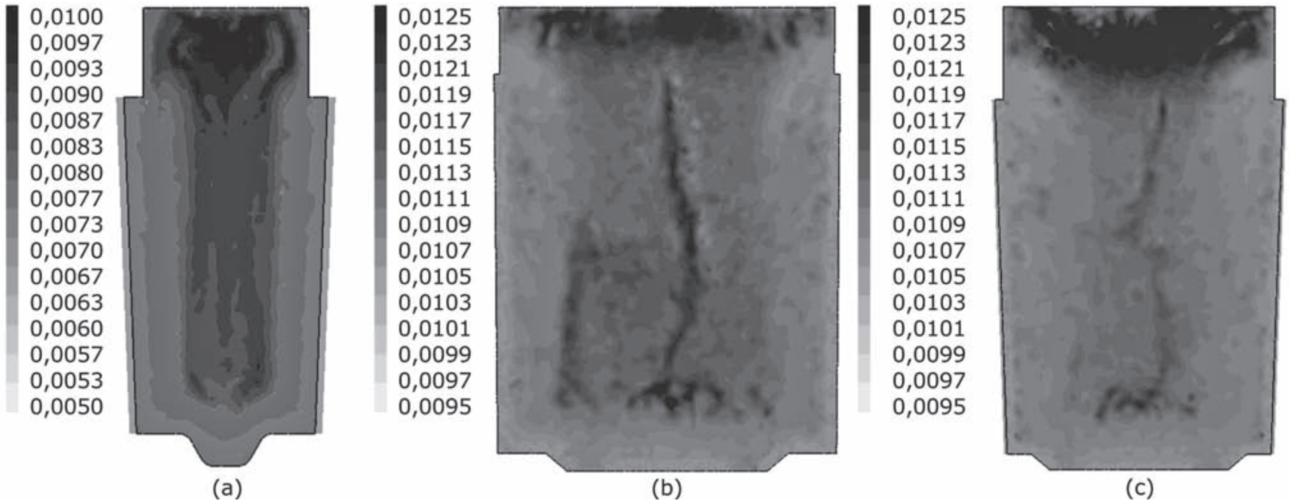

Figure 2 Comparison of the distribution map of macrosegregation of phosphorus in (a) conventional classical ingot (b) slab ingot (c) new slab ingot. The defined content of phosphorus at simulation was for conventional ingot 0,004 wt. %, for slab ingot 0,01 wt. %

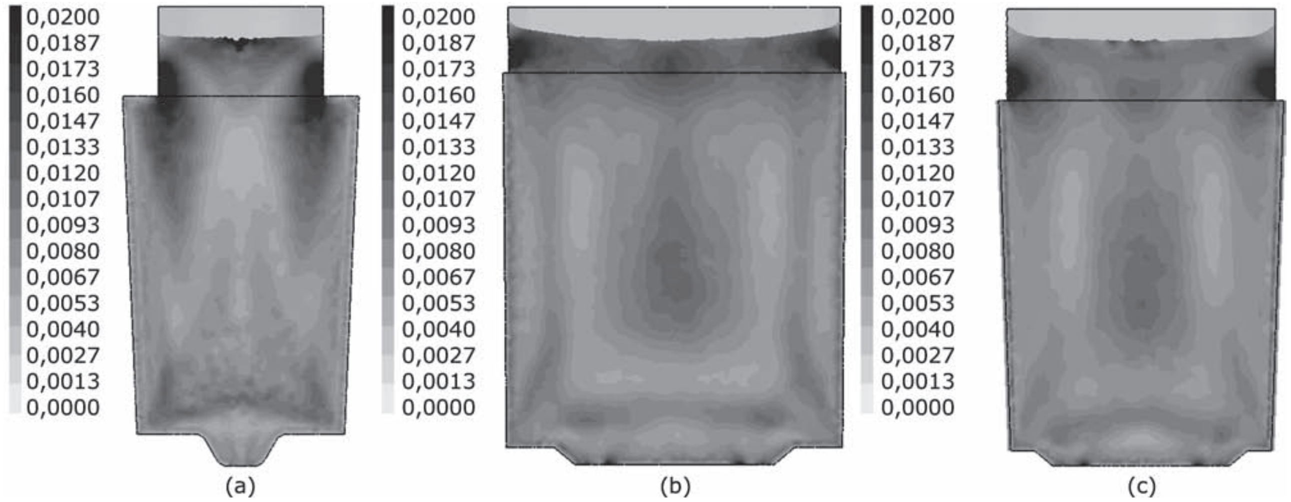

Figure 3 Prediction of the risk of hot tearing using the Hot Tearing Indicator in (a) conventional classical ingot (b) slab ingot (c) new slab ingot

- the range of macrosegregation in the slab ingot is lower than in the case of conventional polygonal heavy forging ingots;
- on the other hand, in the central axis of the ingot body of the slab ingot a large volume of micro-porosity was predicted;

- the risk of hot tears and cracks is mainly at the bottom corner of the ingot and in the central axis of the ingot near the porosity.

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Note: The responsible translator for English language is Boris Škandera, Czech Republic