PREDICTION OF CASTING AND SOLIDIFICATION OF SLAB STEEL INGOT

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Abstract

The main problem in production of forgings from tool steels, especially in the form of thick plates, blocks, and rods which are used for special machine components for demanding applications, is the inhomogeneous structure with segregations, cracks in segregations or complex type of non-metallic inclusions of MnS and TiCN type. These forgings are actually produced from conventional forging ingots. Due to the size of forgings, 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. The paper presents the verification of the production process of slab steel ingots in particular by means of numerical modelling using finite element method. The paper describes the pre-processing, processing and post-processing phases of numerical modelling. The attention was focused on the prediction of behaviour of hot metal during the mould filling, on verification of the final porosity, of the final segregation and on prediction of risk of cracks depending on the actual geometry of the mould.

Keywords: Steel, slab ingot, macrosegregation, numerical modelling

1. INTRODUCTION

Forged thick steel plates, blocks, pulleys and rods are widely used for special machine components for demanding applications. These forgings must be of very high quality [e.g. 1], 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 [e.g. 2].

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 [e.g. 3].

In this study, casting and solidification of heavy slab ingot weighing 40 t from tool steels were numerically simulated with use of a finite element method. The attention of numerical modelling was focused on prediction of behaviour of hot metal during the mould filling, on verification of the final porosity, of the final segregation and on prediction of the risk of cracks on the actual geometry of the iron mould. The obtained results were compared with the final internal structure of classical conventional ingot of the similar weight.

2. MODEL DESCRIPTION

Generally, numerical solution of each task is divided into three stages: 1. Pre-processing: it includes geometry modelling and the 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.

2.1. Geometry and FEM mesh

The whole 3D ingot geometry was created in the CAD system SolidWorks. The CAD geometry of the casting system is shown in **Fig. 1**. In our case, only one type of computational mesh for calculation of filling and solidification was used and we calculated the whole process in one step. The final surface and volume computational mesh of finite tetra elements used in this study are shown in **Fig. 2**. The average size of the tetra elements was approx. 30 mm. Total numbers of tetra elements was 1 620, 658.
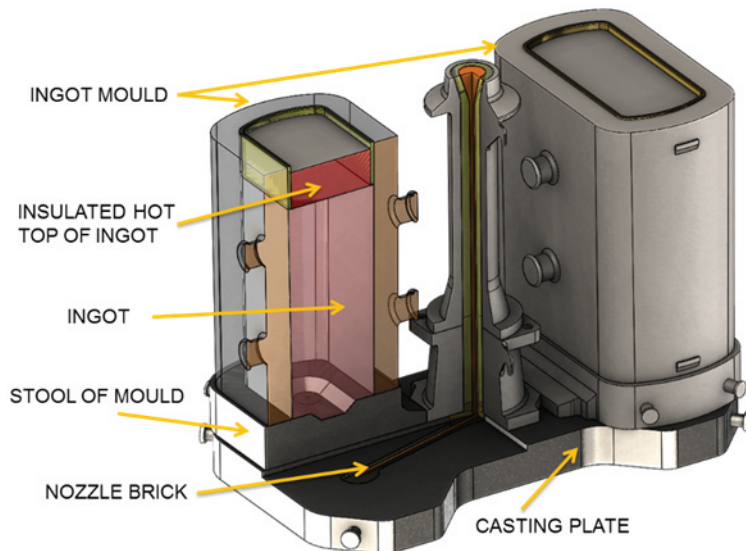

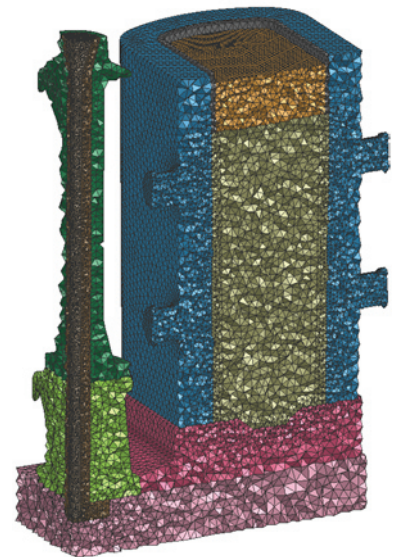**Fig. 1** CAD geometry of the casting system of a 40-ton steel slab ingot

Fig. 2 View of the final computational mesh of the casting system

2.2. Thermo-physical parameters

Composition of the cast tool steel into slab ingot is given in **Table 1**. The mould and others parts of the casting system were made from cast iron. Due to the fact that steel and material of the mould were not included in the basic material database of the simulation programme, the integrated thermodynamic database was used to calculate the thermo-physical properties. The liquidus temperature of steel was 1,487 ºC, and the solidus temperature was 1,436 ºC. For achievement of relevant numerical results, it is necessary to have correctly defined thermo-physical properties of steel. Therefore, the phase transformation temperatures should be verified using several different methods. For determination of liquidus and solidus temperature and heat capacity it is possible to use the thermal analysis [e.g. 4, 5, 6].

Table 1 Composition of steel in wt. %

C	Mn	Si	P	S	Cu	Ni	Cr	Mo	Al
0.385	1.45	0.25	0.01	0.005	0.15	1.1	1.975	0.225	0.0125

2.3. Interface

Definition of the heat transfer coefficients among the individual components of the casting system is not simple. The heat transfer coefficients are defined individually for each of the contact interfaces of components in the INTERFACE menu, such as heat transfer coefficient between the ingot and ingot mould, between the ingot and insulation, etc., as it is shown in **Fig. 3**. The constant values in the range from 100 to 1,000 $W.m^{-2}.K^{-1}$ are usually given in literature. However, the previous research [7, 8], has found that the heat transfer coefficients should be set depending on the time or temperature.
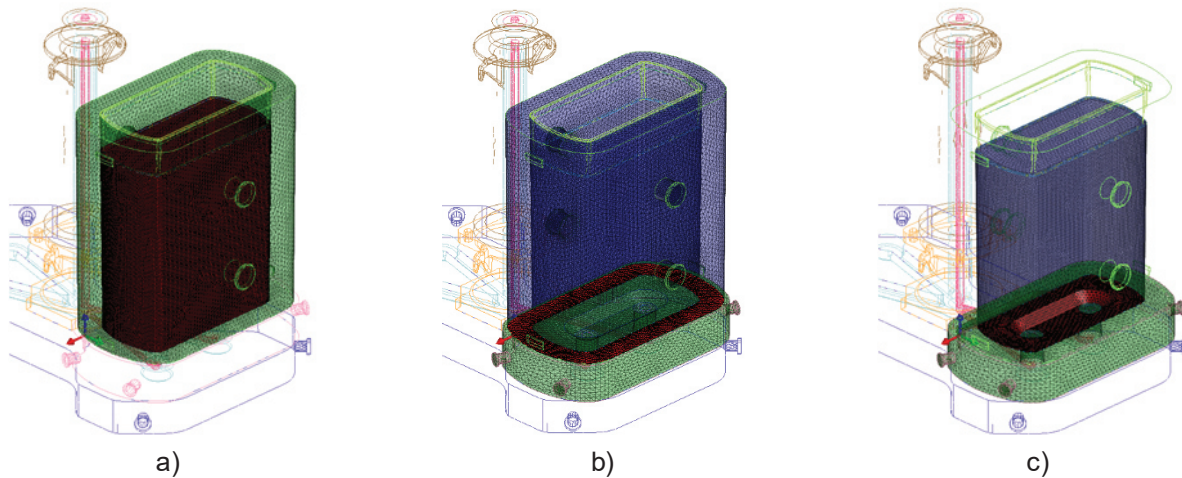
Fig. 3 Examples of definition of interfaces between individual components of the casting system (a) between the ingot and ingot mould (b) between the ingot mould and stool of the mould (c) between the ingot body and stool of the mould

2.4. Boundary conditions

The boundary conditions are presented in **Table 2**. The total filling time was 1,860 seconds. The casting temperature was 1,828 K. In our case, the heat loss through the surface of the mould was defined as a convective cooling. The ambient temperature was 293 K, the emissivity was 0.85. On the surface of the steel an adiabatic condition was defined in a hot top.

Table 2 Boundary conditions

Parameter	Unit	Value
Casting temperature	K (Kelvin)	1,828
Total filling time	s (second)	1,860
Ambient temperature	K (kelvin)	293
Emissivity	-	0.85
Temperature of mould preheating	K	323
Gravity acceleration	$m.s^{-1}$ (meter per second)	9.81

2.5. Simulation parameters - Run parameters

For calculation of the porosity, shrinkage cavity, macro-segregation or cracks, the equations have to be activated using the so called simulation or run parameters. These parameters activate the individual module of the software. For example, the thermal module allows us to perform a heat flow calculation by solving the Fourier heat conduction equation, including the latent heat release during solidification. The fluid flow module allows us to perform a mould filling calculation (free surface), as well as fluid flow computation by solution of the Navier-Stokes equation. The macro-segregation module of the software can calculate automatically the macro-segregations for steels, based on the composition of the alloy. This can be achieved with the link of the module with thermodynamic databases. It has been developed for multi-component alloys and back diffusion is taken into account [9].

Based on the simulation parameters, it is possible to specify also the maximum time step size, which will be used during the filling stage only. Also, the stop criteria and conditions of convergence can be defined. The example of stop criteria and other parameters used in this study are presented in **Table 3**.

Table 3 The example of setting of the simulation parameters

Parameter	Abbreviation	Value
Stop criterion: Maximum number of time steps	NSTEP	5000
Stop criterion: Final temperature	TSTOP	1,690 K
Frequency of temperature results storage	TFREQ	50
Porosity - Critical macro-porosity	MACROFS*	0.7
Porosity - Feeding Length	FEEDLEN**	0.02 m

* MACROFS is the critical solid fraction for macro-porosity and it is equal to 0.7 by default.
** FEEDLEN is defined as the feeding length of liquid steel, which is suggested to be 20 mm

3. RESULTS AND DISCUSSION

In order to analyze the character of the predicted final internal structure of the slab ingot, or the range of the volume defects, such as porosity and macro-segregation, a comparison with the internal structure of the simulated classical conventional polygonal ingot with the similar weight/steel grade/conditions of the casting will be used.

3.1. Temperature field at the end of filling

Since the casting temperature and the filling time was practically the same for both types of ingots, also the temperature field at the end of the filling was in both cases very similar (see the **Fig. 4**).
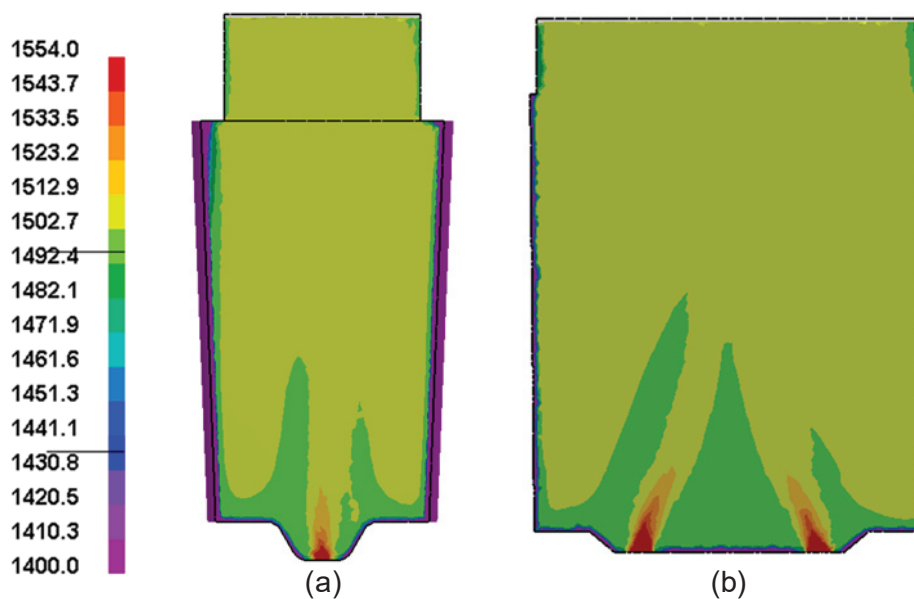

Fig. 4 Comparison of the temperature field (in °C) at the end of filling
in the cross section of the classical conventional polygonal ingot (a) and slab ingot (b)

3.2. Solidification time

Although the temperature field at the end of filling was very similar for both types of ingots, different times of solidification were obtained. The classical conventional polygonal ingot solidified in approx. 13 hours, while the total solidification time of the slab ingot was approx. 7.5 hours, as it is evident from the **Fig. 5**.
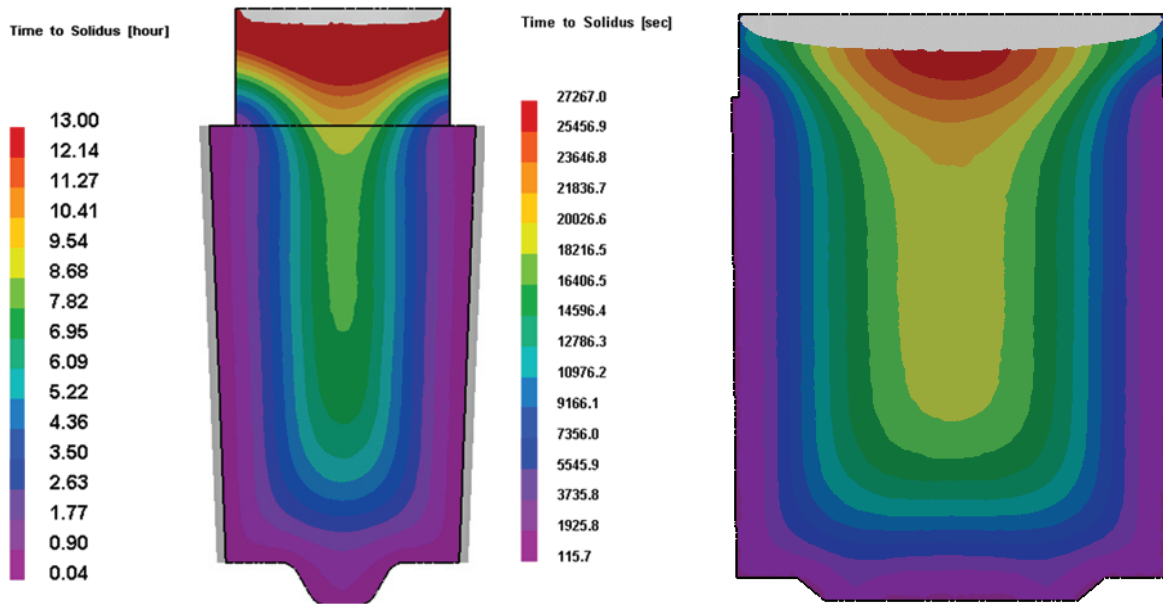
Fig. 5 Comparison of the total solidification times between
the classical conventional polygonal ingot (a) and slab ingot (b)

3.3. Character of final macro-segregation vs. porosity

Due to the shorter total solidification time, the final macro-segregation of the components in the slab ingot was smaller than in the classical ingot. Comparison of macro-segregation of phosphorus is shown in **Fig. 6**. On the other hand, final porosity in the slab ingot was detected in higher volume range, as it is evident from **Fig. 7**. Therefore, in the next step of the research the attention will be focused on the new design of the mould shape. The taper, the internal walls and the ratio of the A/B will be changed.
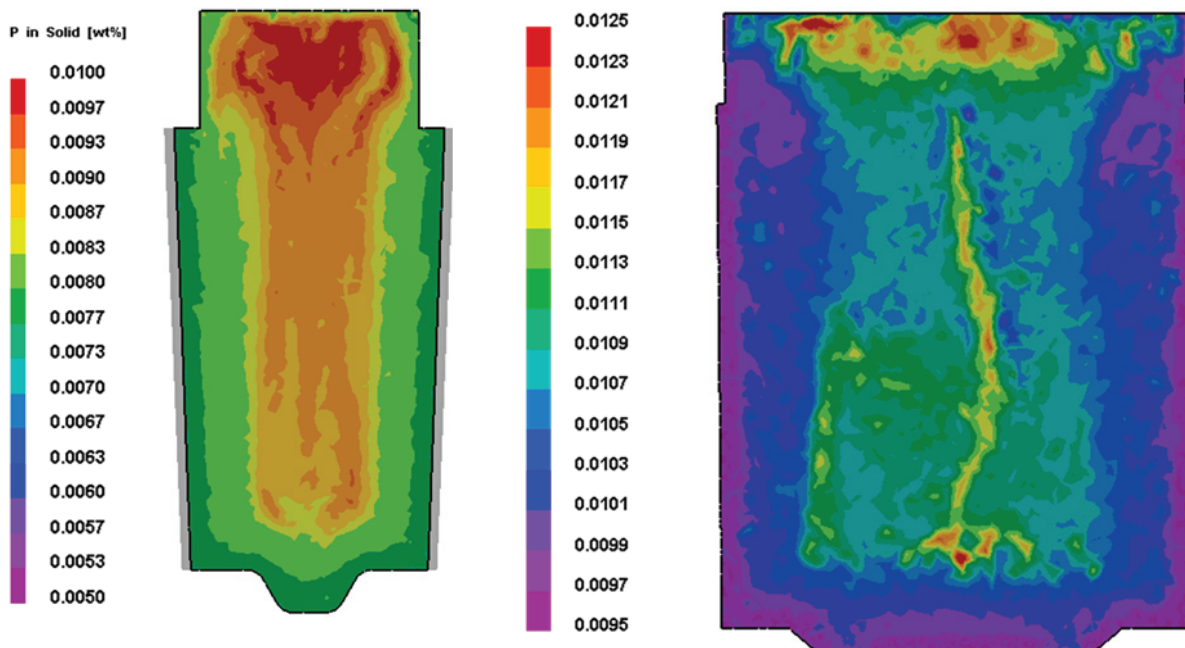

Fig. 6 Comparison of the distribution map of macro-segregation of phosphorus of the 40-ton steel slab ingot (in wt. %) with the macro-segregation of phosphorus in the conventional ingot. The defined content of phosphorus in the simulation was for the conventional ingot 0.004 wt.%, for the slab ingot 0.01 wt. %

4. 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. The main reason of verification of casting and solidification of the 40-ton steel slab ingot was the possibility of replacement of the conventional heavy steel ingot actually used for production of the special forgings. Using the numerical modelling, it was found that:

- the range of macro-segregation is lower than in the case of conventional polygonal heavy forging ingots with the same weight and produced from the same steel grade;

- on the other hand, in the central axis of the ingot body of the slab ingot a large volume of micro-porosity was predicted. This micro-porosity can be, nevertheless, eliminated by the following forging.
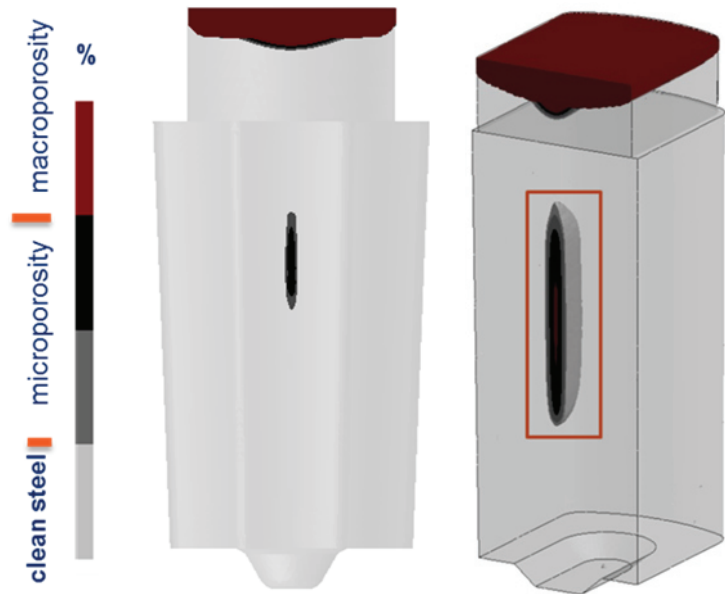

Fig. 7 Comparison of the final porosity in the (a) conventional classical ingot (b) slab ingot

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