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To cite this article: M Tkadleckova *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **179** 012067

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Distribution of porosity and macrosegregation in slab steel ingot

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Abstract. The paper presents a new knowledge and experiences with verification and optimization of production technology of heavy slab ingot weighing 40 t from tool steel using the results of numerical modelling and of operational experiments at a steel plant in the company VÍTKOVICE HEAVY MACHINERY a.s. The final porosity, macrosegregation and the risk of cracks were predicted. Based on the results, the slab ingot can be used instead of the conventional heavy steel ingot. Also, the ratio, the chamfer, and the external shape of the wall of the new design of the slab ingot was improved, which enabled to reduce production costs while the internal quality of steel ingots was still maintained at very high level.

1 Introduction

The company VÍTKOVICE HEAVY MACHINERY a.s. (VHM) focused in recent years on an expansion of production of forgings with higher added value, which definitely includes also the forgings from tool steels finding their application mainly in general engineering, at the construction of machinery and equipment. This concerns e.g. thick steel plates, pulleys, disks, etc. Production of these demanding forgings requires knowledge and experience that can only be obtained through own research and development. However, with regard to the price of material and the weight of the forgings such research is very expensive. For forgings weighing from approx. 15 to approx. 60 tons it is necessary to use high-quality ingots weighing from 20 to 100 tons. The know-how for the production of heavy forgings requires knowledge and experience particularly in the field of metallurgy. It is necessary to observe the required chemical composition with respect to very strict requirements relating to the content of oxygen, sulphur, and other elements. Especially for larger forgings, it is required to obtain homogeneity and isotropy of properties, i.e. the minimum extent of segregations and very low content of non-metallic inclusions. Octagonal polygonal ingots are used most often for the forgings. In the case of tool steels, the ingots with a larger chamfer of the ingot wall with a relatively low ratio of the height of the ingot to its mean diameter (H/D) are recently preferred [1-4]. These ingot parameters ensure better conditions for charging of the molten steel from the ingot hot top to the ingot body during solidification. The result is a very small centerline porosity of the ingot. However, the larger diameter of ingots causes a greater central macrosegregation, and thus in possible non-homogeneity of mechanical properties of the forged product. For certain types of forgings (especially of plates) these macrosegregations can be limited by using slab ingots, which are



distinguished by a characteristic A / B aspect ratio. It is expected that due to the relatively small width of the slab ingot, and thus its faster solidification in comparison to a polygonal ingot of the same mass, the occurrence of macrosegregations in the slab ingot will be smaller than in the polygonal ingot.

One of the ways, how to verify and optimize the production steps from the casting to the forming process, is the use of methods of numerical modelling [5-11]. The numerical modelling allows us to follow the character of the flow of the steel during the filling of the mould, to predict the temperature field during the casting and solidification, or to predict the final volume defects, which may occur in the final solid structure, such as porosity, macrosegregation, and cracks or hot tears.

Due to the huge plant effect from the results of the numerical modelling, in this study, the numerical modelling was also used for verification and optimization of production technology of heavy slab ingot weighing 40 t made from tool steel. The main aim of numerical modelling in ProCAST software realized under the conditions of the Department of Metallurgy and Foundry (DMF) and Regional Materials Science and Technology Centre (RMSTC) at the VSB-TU Ostrava was the optimization of the production of heavy steel ingots produced in VHM, especially focused on minimization of porosity and macrosegregations.

The paper summarizes also the research and development of the new design of the mould for slab steel ingot production. In the paper, the operational experiment and the results from plant experiment are also outlined. Based on the results of evaluation of complete series of numerical simulations, and based on their operational verification, it made it possible to reduce production costs while the internal quality of steel ingots was still maintained at very high level.

2 Operational experiment

The company VÍTKOVICE HEAVY MACHINERY a.s. is a traditional producer of large machine components. The typical products of this company are crankshafts, propeller and connecting shafts, rotor shafts for wind power plants, forged parts for containers of pressurizers, steam generators, heat exchangers and collectors for both conventional and nuclear power engineering. For these products, it is necessary to cast ingots weighing up to 200 tons. Steel plant of the VHM is equipped with EAF, LF, VD and VOD facilities. Ingots from 1.7 up to 200 tons are bottom cast. Typical steel grades for these products are structural carbon-manganese, low alloyed, middle alloyed and tool steels. The EAF capacity is 70 tons so the larger ingots are cumulated from two or three heats.

For the purposes of research, development, verification and optimization of production, an experimental slab ingot weighing 40 t was cast from tool steel at the VHM. The heat chemical composition of cast grade steel is documented in **Table 1**. The steel was produced and cast according to the VHM standard technological procedures valid for this steel grade. After stripping of the ingot from the mould, the ingot was cooled down by controlled cooling in a furnace for reduction of the stresses. Subsequently, the ingot was cut into two halves along the vertical axis. After flame cutting, the affected layer of the centre surface of the cut ingot was milled off for subsequent analysis. For an evaluation of the distribution of porosity, a penetration test was performed (see **Figure 1**). However, the test did not reveal the expected large porosity. It only highlighted the crack on the ingot, which was formed by milling. Similarly, due to the low content of sulphur in steel the Baumann sulphur print did not show the expected zones with its increased concentrations.

Table 1. The heat chemical composition of steel grade of the experimental ingot (wt. %).

C	Mn	Si	P	S	Cu	Ni	Cr	Mo	V	Al	Nb	N
0.37	1.45	0.26	0.011	0.001	0.16	1.03	1.96	0.20	0.007	0.018	0.005	0.0059

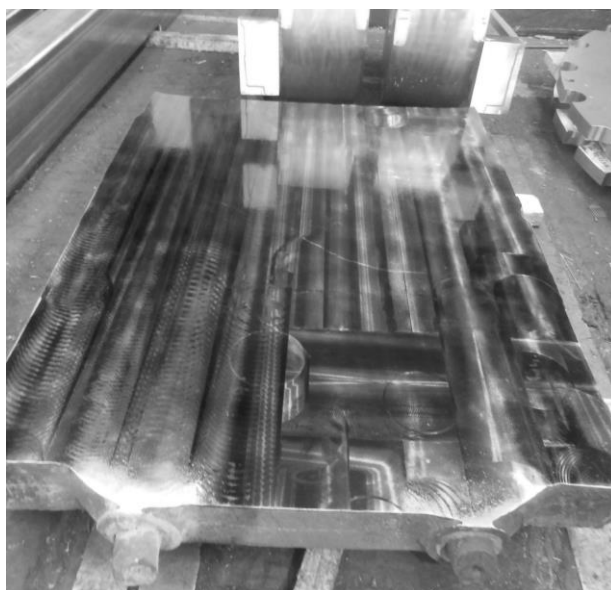


Figure 1. Section cut of the experimental slab ingot during the penetration test.

Due to the number of required chemical analyses, selection of required elements for determination of their concentration levels it was necessary to pay an increased attention to the choice of an optimal method of analyses. The method used in a standard manner for metallurgical analyses - analysis on laboratory optical emission spectrometers, which would ensure the efficiency and accuracy – was not applicable, since it required a sample in the solid state. Taking of the solid samples in the required quantity was technically not feasible. The partial solution consisted in the use of mobile spectrometers, either X-ray or optical emission, for determination of at least some elements. Its obvious advantage is the fact that the analyses can be performed directly on the ingot repeatedly and without taking of the samples.

For all the elements and individual methods, the possible achieved precision was determined experimentally by measurements of the control sample under conditions of repeatability (in the shortest time of repetition). The exception was the determination of phosphorus. The measured values were evaluated using robust procedures of the statistical software QC.Expert. The values presented in **Table 2**, such as "accuracy of the method", were calculated as half of the difference between the upper and lower quartiles (the interval, which contains 50 % of the measured results, the limits of the box in the box plots). Identical statistics was also used for processing the uncertainty of the results of individual measurements directly on the ingot.

Table 2. Average concentration of the elements and the accuracy of individual measurements (wt. %).

Element	Method	Average concentration of the element in the control sample	Method accuracy
C	Analyzer LECO	0.175	± 0.0015
C	OES – Spectrometry	0.175	± 0.01
Mn	Chemically	1.15	± 0.003
Mn	OES – Spectrometry	1.15	± 0.01
Si	OES – Spectrometry	0.26	± 0.01
P	Chemically	0.0087	± 0.0006
S	Analyzer LECO	0.0007	± 0.0001
Cu	OES – Spectrometry	0.11	± 0.01
Ni	OES - Spectrometry	0.18	± 0.01

3 Numerical modelling

In order to analyze the character of the predicted final internal structure of steel ingot, or the range of the volume defects, such as porosity and macrosegregation depending on the shape of the ingot, a comparison of the results of numerical modelling of internal structure of the conventional polygonal ingot with the slab ingot and with the new design of the slab ingot of the similar weight/steel grade/conditions of the casting was done. The numerical results were also confronted with the results of the plant experiment. Generally, numerical solution of each task was divided into three stages: 1. Pre-processing: it included geometry modelling and the process of generation of the computational mesh, and definition of calculation. 2. Processing: it involved computation in the solver. 3. Post-processing: it focused on the evaluation of the results. The conditions of numerical model settings were based on real conditions of the experimentally cast 40 tons steel ingot produced in VHM a.s. The details of the model settings were published in [12].

3.1 Solidification time

Although the temperature field at the end of filling was very similar for all three types of ingots, different times of solidification were obtained. The conventional polygonal ingot solidified in approx. 13 hours, while the total solidification time of the slab ingot was approx. 7.5 hours, or approx. 8.5 hours for a new design of the slab ingot, as it is evident from the **Figure 2**.

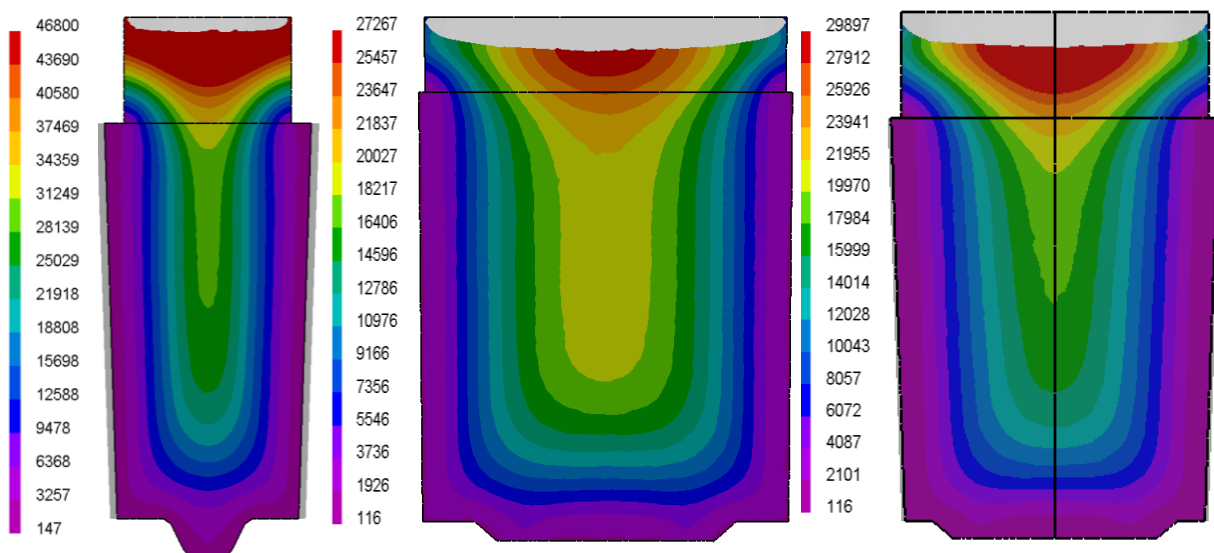


Figure 2. Comparison of the total solidification times (in seconds) between the conventional polygonal ingot (left), original slab ingot (middle) and slab ingot of the new design (right).

3.2 Character of final macrosegregation vs. porosity

Due to the shorter total solidification time, the final macrosegregation of all the elements in the slab ingots was smaller than in the conventional polygonal ingot. An example of a comparison of macrosegregation of phosphorus predicted by numerical modelling is shown in **Figure 3**. From **Figure 3** it is also evident that the macrosegregation of phosphorus in the slab ingot of the new design is minor in comparison with the original shape of the slab ingot. If we compare the content of the phosphorus detected from a real sample of the original slab steel ingot (see **Table 1**) with the numerical results, the content of the phosphorus corresponds to the border section of the slab ingot body. Small difference between the results can be caused by the following limitations of numerical modelling: no solid movement, no grain sedimentation, fully equiaxed dendrites, no columnar dendrites.

The final porosity in the original slab ingot was detected in higher volume range in comparison with the polygonal conventional ingot, as it is evident from **Figure 4**. On the other hand, the porosity in slab ingot of the new design brought the expected efficiency and it led to a lower volume of this volume defect. The differences/contradictions relate with the directional solidification from the bottom to the hot top of the ingot bodies and with the ability of the hot tops to fulfil the liquid metal in the last stages of the solidification into the ingot body.

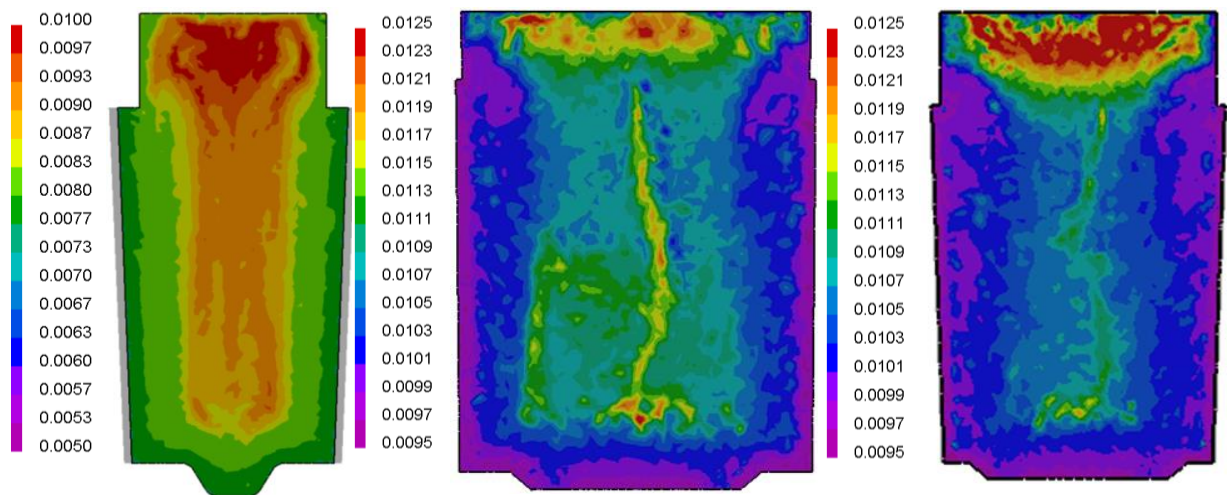


Figure 3. Comparison of the distribution maps of macrosegregation of phosphorus (in wt. %) between the conventional polygonal ingot (left), original slab ingot (middle) and slab ingot of the new design (right) The defined content of phosphorus in the simulation was for the conventional ingot 0.004 wt.%, for the slab ingots it was 0.01 wt. %.

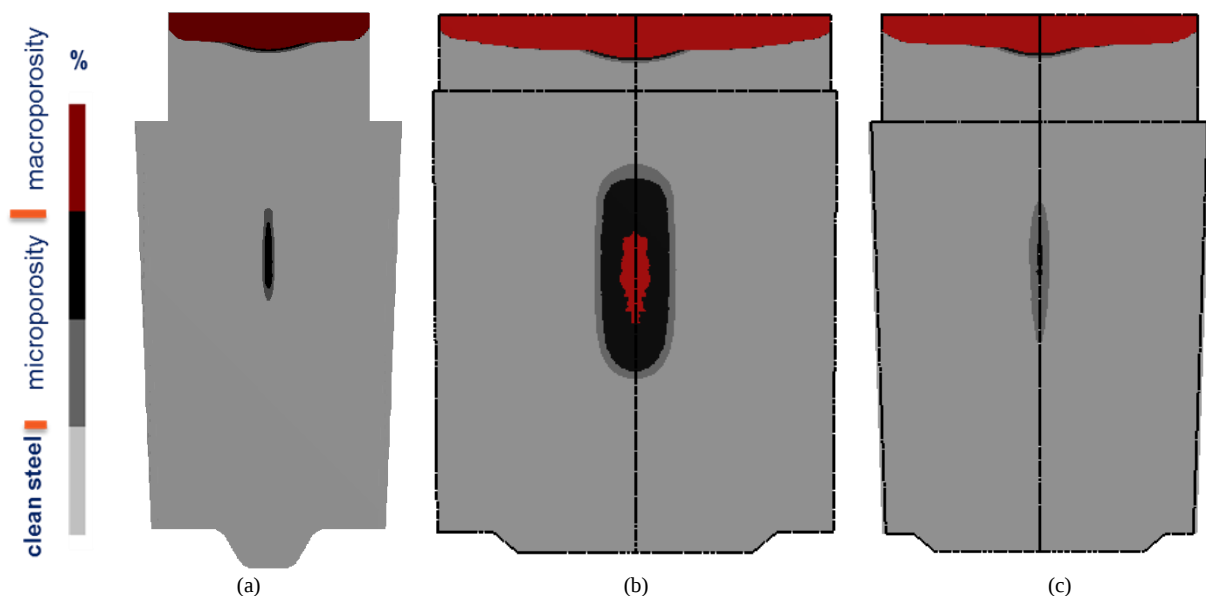


Figure 4. Comparison of the final porosity in (a) conventional polygonal ingot (b) original slab ingot (c) new design of slab ingot.

4 Conclusions

The paper was devoted to verification of production of the slab ingot from tool steel using the plant experiment and 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 the production of the special forgings by the slab ingot. The attention was also concentrated on reduction of the final porosity and macrosegregation in dependence on the new design of the mould for slab ingot. From the research, it was found that:

- the range of macrosegregation in slab ingots was lower than in the case of conventional polygonal heavy forging ingot of the same weight that were produced from the same steel grade;
- on the other hand, in the central axis of the ingot body of the original slab ingot, a large volume of microporosity was predicted in comparison with the conventional polygonal ingot. Nevertheless, the huge minimization of the porosity was achieved by the new design of the shape of the slab ingot. This microporosity can be eliminated by the following forging.

Acknowledgement

This paper was created with the financial support of the TA CR under the project No. TA04010035, in the Project No. LO1203 "Regional Materials Science and Technology Centre - Feasibility Programme" funded by Ministry of Education, Youth and Sports of the Czech Republic, and in the support of the projects of "Student Grant Competition" numbers SP2016/89 and SP2016/103.

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