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The effect of boundary conditions of casting on the size of porosity of heavy steel ingot

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ABSTRACT

Purpose: The paper presents new knowledge from numerical modelling of porosity in heavy steel ingot using ProCAST software. The main aim of numerical modelling realized under the conditions of the Department of Metallurgy and Foundry and Regional Materials Science and Technology Centre at the VSB-TU Ostrava is the optimization of the production of heavy steel ingots produced at the companyVítkovice Heavy Machinery a.s.

Design/methodology/approach: The selected method of numerical modelling enables 3D fully dimensional numerical simulation of steel casting and the subsequent solidification of steel with the possibility of prediction of ingot defects.

Findings: The numerical modelling of casting and solidification of the 90 ton heavy steel ingot under different boundary conditions of the casting led to these main conclusions: In all simulated variants, the final character of solidification was very similar. The lowest level of porosities were achieved in the variant when we used the longer filling time together with decrease of casting temperatures. However, the tested adjustment of casting technology appeared to have only small impact on the resulting porosity.

Practical implications: The change of geometry of the mould will have probably more effect on the character of the solidification than only the small changes of the casting parameters which are dependent on the steel grade.

Originality/value: On the basis of applied research in close collaboration with industry companies, the obtained data can contribute significantly to optimization the operating conditions, thereby increasing the efficiency of the steelmaking technology and final quality of cast steel.

Keywords: Casting; Heavy steel ingot; Modelling; Porosity

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1. Introduction

Despite the ever-increasing volume of continuous casting of steel, production of steel ingots for forgings and machine components is irreplaceable. Steel casting into the ingots enables production even of large components weighing up to several hundred tons. The main precondition of the competitiveness of any steel plant, not only in Europe, is production of a consistently high quality. However, despite significant advances in technology of production of steel ingots, we can observe the defects in the final forgings that may be caused by the non-uniform cast macrostructure of an ingot as well as the macrostructure, which is the result of plastic deformation during the subsequent process of the forming [1]. The solution to material weaknesses of forgings, or the final machine components, consists in a complex optimization of the steel casting process, as well as of the subsequent heat treatment and finally the actual process of forming. The knowledge of the existing casting parameters like casting speed, casting temperature of steel or the H/D ingot ratio is the main precondition for minimization of the well-known defects of steel ingots. One of the ways to monitor and optimize the production steps from the casting to the forming process is the use of methods of numerical modelling.

Great effort is devoted to the optimization of the casting technology of heavy forging ingots with use of numerical modelling. As it is evidenced by the results of the model and experimental studies performed e.g. by the authors [2-5], the size of the central defect is strongly dependent on the shape of ingot and the hot top. The best structure of ingot was obtained in the mould with the H/D ratio of 1.1. It was also confirmed that the extent of the central porosity and shrinkage cavities increases, if the rate of vertical solidification in the central part of the ingot exceeded the value of approx. 10 $mm \cdot min^{-1}$. In order to be able reduce the central porosity; it is necessary to have such solidification conditions, when the rate of vertical solidification does not exceed 10 $mm \cdot min^{-1}$ for an ingot weighing approx. 100 tons. In large ingots even lower rate of solidification is preferred. The maximum rate of solidification can be formulated as a function of the ingot diameter, H/D ratio of the ingot, ratio of the hot top diameter to the ingot diameter and its chamfer.

The results of simulation [3] have also shown that the increase rate of filling of the hot top led to reduction of the amount of solid phase formed in the hot top during the casting period, and thus also to a smaller extent of cavities in the ingot body. On the other hand, however, lowering of the height of filling of the hot top and polygonal shape of insulation led to the reduction of the time of solidification, and consequently to formation of larger greater shrinkage cavity, since it was cooled more rapidly than in case of the circular cross-section due to the larger contact area. Lowering of the height of filling of the hot top led also to the lower ferrostatic pressure, manifested by an increased volume of porosity. On the other hand, in contrast to the conditions for minimization of porosity, it is recommended to lower the height of filling of the hot top in order to minimize the segregation. The works, dealing with numerical verification of unconventional casting techniques, such as injection of crystallization nuclei [6] or methods of controlled crystallization methods [7-9], are also no exception. Attention has been also paid not only to optimization of the boundary conditions of casting, but also to the verification of the causes of possible secondary contamination of steel during casting due to erosion of the pouring ceramics [10,11], to secondary re-oxidation or entrainment of casting powder by dynamics of the inlet casting flow at the early stages of casting [12,13].

The presented paper is devoted to verification of volume defects, such as porosity, in a 90-ton heavy steel ingot under different boundary conditions of the casting 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 the VSB-TU Ostrava is the optimization of the production of heavy steel ingots produced at the VÍTKOVICE HEAVY MACHINERY a.s. (further also VHM). The VHM is traditional producer of large machinery components. The heavy steel ingots are used for production of crankshafts, propellers, rotor shafts for wind power plants, forged parts for the container of pressurizers, steam generators and collectors for both conventional and nuclear power engineering. For these products it is necessary to cast ingots weighing up to 200 tons.

2. Description of the simulated variants

The 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. The EAF capacity is 70 tons so the larger ingots are cumulated from two or three heats. In the case of casting of steel ingots, as it was confirmed above, the most important and most easily influenced technological boundary conditions include the casting temperature and the speed of the casting. In contrast, the material of the mould/shape of the mould or the grade of the cast steel cannot be arbitrarily changed. For this reason, the attention was focused on the verification of the extent of ingot volume defects depending on the casting temperature of steel and casting speed. Altogether 8 variants were simulated. An overview of the boundary conditions of individual variants is given in Table 1.

Table 1.
The overview of boundary conditions of simulated variants

Variant	Casting temperature [°C]	Total filling time [min]
T1560	1560	55
T1570	1570	55
T1580	1580	55
TFT47	1570	47
TFT55	1570	55
TFT60	1570	60
TFT65	1570	65
TFT65-TD30	1570→1540 during 65 min	65

The first three variants marked as T1560, T1570 and T1580 had the same time of filling and they differed by the temperature of casting. On the other hand the variants TFT47, TFT55, TFT60 and TFT65 differed by their total time of filling, while the considered casting temperature was the same. Based on partial results the last simulated variant was TFT65-TD30, in which we considered the total time of filling of 65 minutes and at the same a decrease of the casting temperature by 30°C, i.e. from 1570 to 1540°C during 65 minutes (which means that temperature of the steel in the ladle decreased approx. by 0.46°C·min^{-1}).

3. Definition of numerical model

Numerical modelling has already taken in metallurgy an irreplaceable position. Initial isolated simulations of character of flow in primary reactors, as well as simulations of solidification not only of steel, which were performed in the early eighties and nineties of the 20th century, became nowadays an essential part of the verification of setting of the process already long time before its implementation into industrial practice. Numerous simulation software programs are now available on the market and it is not always easy for the user to find out, which of the offered programs is the best exactly for verification and optimization of his process.

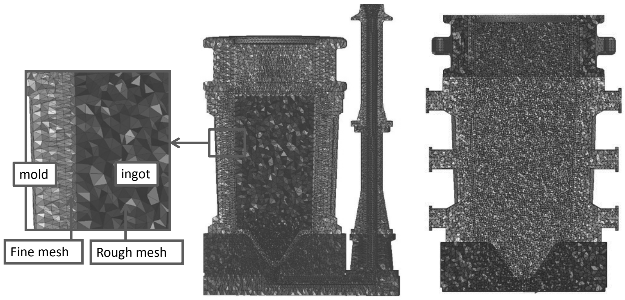
Thanks to the long-term scientific-research activities of collaborators of the Laboratory for modelling of the processes in liquid and solid phases in the area of the numerical and physical modelling studies, coupled with a much needed verification at industrial operation [e.g. 13,14], it was obtain within the project RMSTC a comprehensive commercial and educational license for the top quality program ProCAST for numerical modelling of the processes running during casting and solidification not only of steel. Configuration of the newly acquired software makes it possible to perform comprehensive analyses of filling, solidification and stresses not only of steel ingots, but also of continuously cast blanks, with prediction of defects and of residual stresses. The comprehensive solution is ensured thanks to the modules for calculation of filling and solidification, the module for prediction of macrosegregation, or the module for calculation of residual stresses.

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

3.1. Geometry modelling and computational mesh generation

The geometry of the casting system of 90-ton ingot was created in the CAD software.

The ProCAST software is based on the finite elements method. In the case of mesh generation, the first question is, whether the simulation of filling and solidification of the ingot will be made in one step, or whether the simulation is divided to separate computation of the filling and of the solidification. The calculation of the filling and solidification of steel ingots by the method of finite elements can be made separately - it is good not to include the mentioned steps in one simulation. Because, when large ingots are modelled, the mesh size becomes very large with respect to the thermal gradients, especially in the early stages of cooling. In order to obtain appropriate answers (i.e. more accurate temperatures), it is advised to generate few layers (of few mm in thickness) inside the ingot, as well as inside the mould, as it is shown in Fig. 1 [15]. On the other hand, the mesh for solidification could be simplified and generated more finely. For example, it is not necessary to have the whole gating system during the computation of the solidification. The reason for use of different meshes is the time of computation (the filling phase), as well as precision of results (the solidification phase), and particularly the size of volume defects. Therefore, mesh for simulation of filling was different than the mesh for solidification in our case. Mesh with the average size of elements of 30 mm/ 50 mm was used for the filling phase. A finer mesh was used for computation of solidification in the whole volume of the ingot body with the size of elements of 35 mm.



Mesh for filling simulation *Mesh for solidification calculation*

Fig. 1. The two different types of meshes used during numerical modelling of casting and solidification of 90-ton steel ingot [14]

3.2. Material properties

In pre-processing phase, the material properties of individual components of the casting system had to be defined. Because in real casting conditions the ingot was cast from two heats of the steel grade S355mod., the chemical composition of the weighted average of both heats [16] was used. The mould material was cast-iron. The thermodynamic properties of the steel and also of the mould material were generated by the CompuTherm thermodynamic database which is a part of the ProCAST pre-processor. To be sure, that the theoretically defined thermodynamic properties were correct, the mould material was also experimentally studied by the DSC thermal analysis, as it was published in [17].

3.3. Interface

Interface corresponded to interface heat transfer coefficients (HTC) between two different domains, where the “coincident” or “non-coincident” interface has been defined.

At an interface between two different materials, such as the ingot and the mould, there is usually a temperature drop. In this case, the nodes at the interface should be doubled (for a coincident interface), in order to distinct temperature on each side of the interface. As during mesh generation, there is one node at the interface, it is necessary at this stage to duplicate all the interface nodes (as shown in green in Fig. 2 below. This duplication operation is performed when “COIN” is selected. The interface, which is shown in yellow in the Fig. 2 has in fact a zero thickness [18].

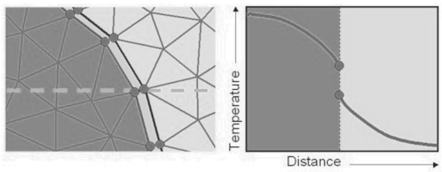


Fig. 2. Illustration of the coincident interface between two different domains [18]

In our case, the coincident condition was used between the interface of the ingot parts and mould parts, as it is shown in Fig. 3.

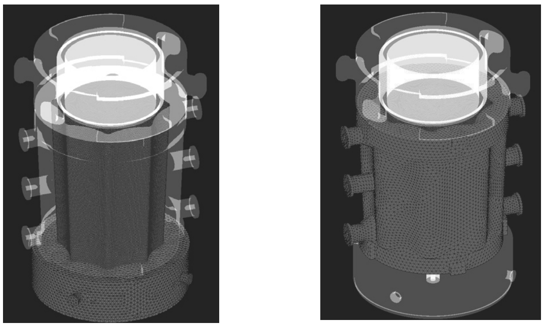


Fig. 3. Illustration of interface between the ingot body and the components of the casting system (mould)

Usually, the HTC is described in the literature as a constant. In our case, the HTC were set depending on the time or temperature. The validated coefficient was in the range 150-800 $W \cdot m^{-2}K^{-1}$.

3.4. Boundary conditions

The casting speed and casting temperature differed according to the simulated variant. The variant T1570 was set according to the experimental casting conditions of the ingot experimentally cast at the VHM. Other variants differed either by the casting temperature (T1560, T1580) or by the total filling time (TFT47, TFT55, TFT60, TFT65) or by both (TFT65-TD30), where T means Temperature, TFT is Total Filling Time and TD means the Thermal Difference (or Decreasing of Temperature during filling).

In pre-processing phase it was also necessary to define the heat boundary conditions. The heat boundary conditions allow defining of the heat transfer between the outside faces of a given domain and the outside world (air). The heat losses were defined using the emissivity, ambient temperature and heat transfer coefficient. The ambient temperature was set as time dependent. It was necessary to define the heat boundary conditions on the surface of the mould, on the surface of the hot top of the casting system and finally on the bottom of the plate, as it is shown in Fig. 4.

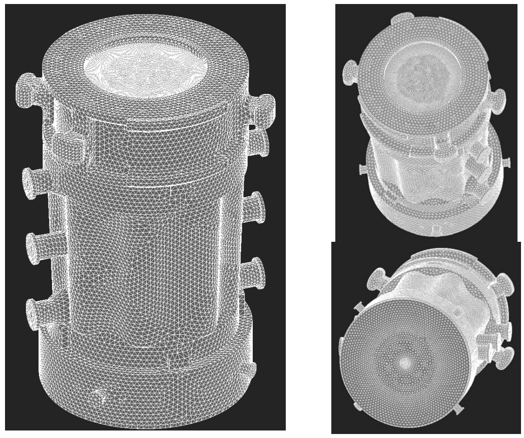


Fig. 4. The setting of the heat boundary conditions in PreCAST

3.5. RUN parameters

Before starting of processing (calculation), it was necessary to define the RUN parameters in the pre-processing phase. The RUN PARAMETERS define the conditions of calculation termination, the s.-c. STOP criteria. The stop criteria include the attainment of a certain temperature in the ingot or termination of the calculation at a particular time after filling. The number of steps of the calculation is also specified, as well as the size of time step and the frequency of storing of results of the temperature field and/or of heat flux [19].

The computational time of one variant was around 96 hours using two processor cores. It is, however, necessary to add to the time of the computation itself the time for preparation of the simulation and evaluation of the achieved results.

4. Discussion of the achieved results

The post-processing and the correct interpretation of results form an integral and very important phase of numerical modelling. Both graphical and numerical results can be obtained by numerical simulation. Use of animation, which is projection of individual profiles as a continuous process of change from the baseline to the final value over time is an effective means of illustration of the temperature, pressure, flow character profiles, fraction solid etc. The advantage is that after completion of the analyses, the temperature, velocity, or heat flow curves, etc., can be “extracted” from any computing node [1].

Due to the fact that the simulation of filling and solidification was done separately in two steps (the filling results were used for calculation of solidification in the second step), the results can be divided into the results obtained from the calculation of filling and the results obtained by the calculation of solidification.

4.1. The effect of casting temperature

Fig. 5 shows the final temperatures on the surface of the ingot immediately after filling. It is evident that the higher temperatures were achieved in the variant T1580.

Fig. 6 shows the example of the temperature fields in the half cross section of the ingot bodies 10 hour after filling, including the hot top. It is obvious that near the bottom of the mould the decrease in the temperature between the range of the solidus and liquidus temperatures already started occurring. The more rapid decline in the steel melt temperature near the bottom of the mould is probably caused by the heat dissipation, or the heat capacity of the mould pad.

It was supposed that the smallest extent of the porosity would be achieved in the variant T1560. But when we compared the evolution of temperatures in the body of ingots in time - see Fig. 6, the differences were slight. And in the end, the character of temperature evolution/fraction solid was very similar (see Fig. 7). Fig. 7 compares the temperature fields on the ingot surface immediately after stripping. The temperatures are identical. Fig. 8 shows with use of the shrinkage porosity the final porosity and size of the shrinkage in the hot top. 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 not concern the porosity alone. That's why porosity may appear at simulations larger than it will be in reality. Slight improvement of the extent of porosity can be observed in the variant T1560 namely in the top third of the ingot body. Nevertheless, if we compare the extent of porosity in the volume of the ingot body, it is obvious, that the difference of the casting temperature of +/- 10°C has no principal influence on reduction of the magnitude of porosity due to the total volume of metal. The maximal magnitude of porosity (share of volume of the calculation cell not filled with metal) varied up to do 2%. This porosity may be fully eliminated by the following forging. The porosity obtained by numerical simulation in the variant T1570 was also for completeness compared with the porosity discovered in the experimentally cast ingot (see Fig. 9). Thanks to different calculation meshes with different size of cells the magnitude of porosity obtained by numerical simulation agreed with the results obtained experimentally.

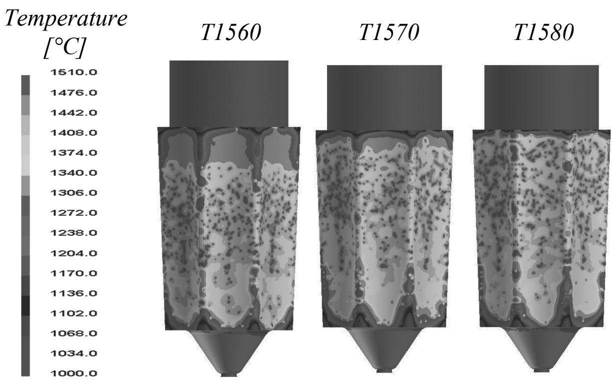


Fig. 5. Temperatures on the surface immediately after filling

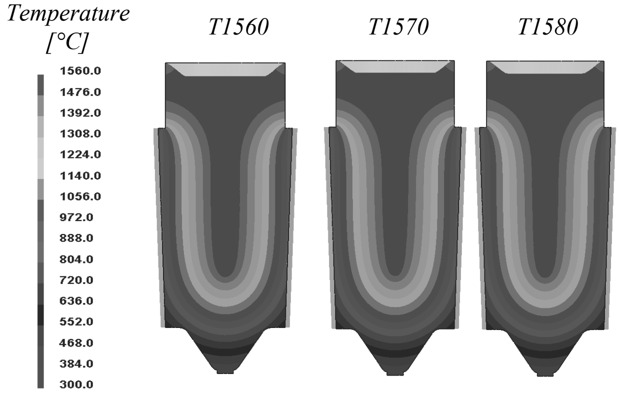


Fig. 6. The temperatures in the half cross section of the ingot bodies 10 hours after filling

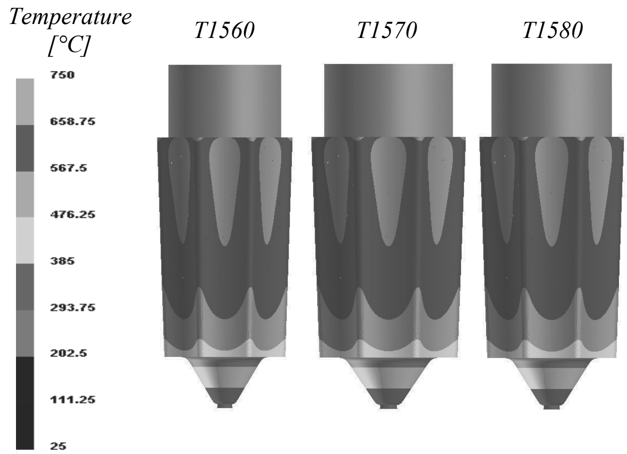


Fig. 7. The temperatures on the surface of the ingot bodies after stripping

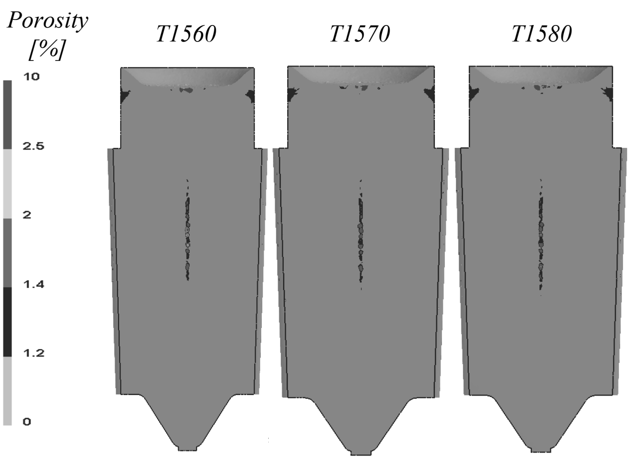


Fig. 8. The final porosity in the half cross section of the ingot bodies

4.2. The effect of total filling time

Fig. 10 shows the character of filling in the variants with different rate of filling, or total time of filling, with use of the “Fraction Solid”. Fig. 11 shows the temperature fields in the ingot body at the moment of full-filling. It is evident from Fig. 11 that only minimal differences occurred between distributions of temperatures over the ingot body. It would be possible to monitor the differences in detail by modification of the scale. Nevertheless, for conditions of this paper an illustration of distribution of temperatures in the course of solidification, namely 10 hours after completion of filling, is sufficient - see Fig. 12. It is possible to conclude from Fig. 12, that temperature fields after 10 hours equalized and they do not differ significantly, which led to the minimal differences of the final achieved porosity in the ingot body (Fig. 13). Fig. 13 shows slight positive improvement of the variants TFT65, where thanks to the slower character of filling the supply of hot metal was ensured for a longer time, particularly during the last stage of filling of the hot top. Slower filling and longer time of supply of hot metal led to the porosity with the max size of 1.5%. Smaller porosity on the shrinkage was achieved also in the area of the hot top.

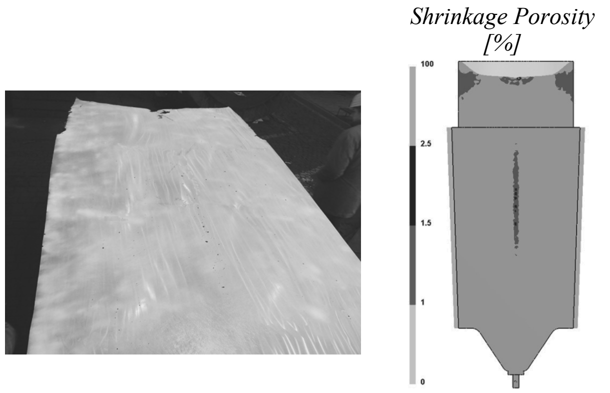


Fig. 9. Comparison of the porosity obtained in the experimentally cast ingot with the results of numerical simulation

Due to partial established facts our attention was further concentrated on verification of the magnitude of porosity in dependence on the extended time of filling with simultaneous drop of the casting temperature.

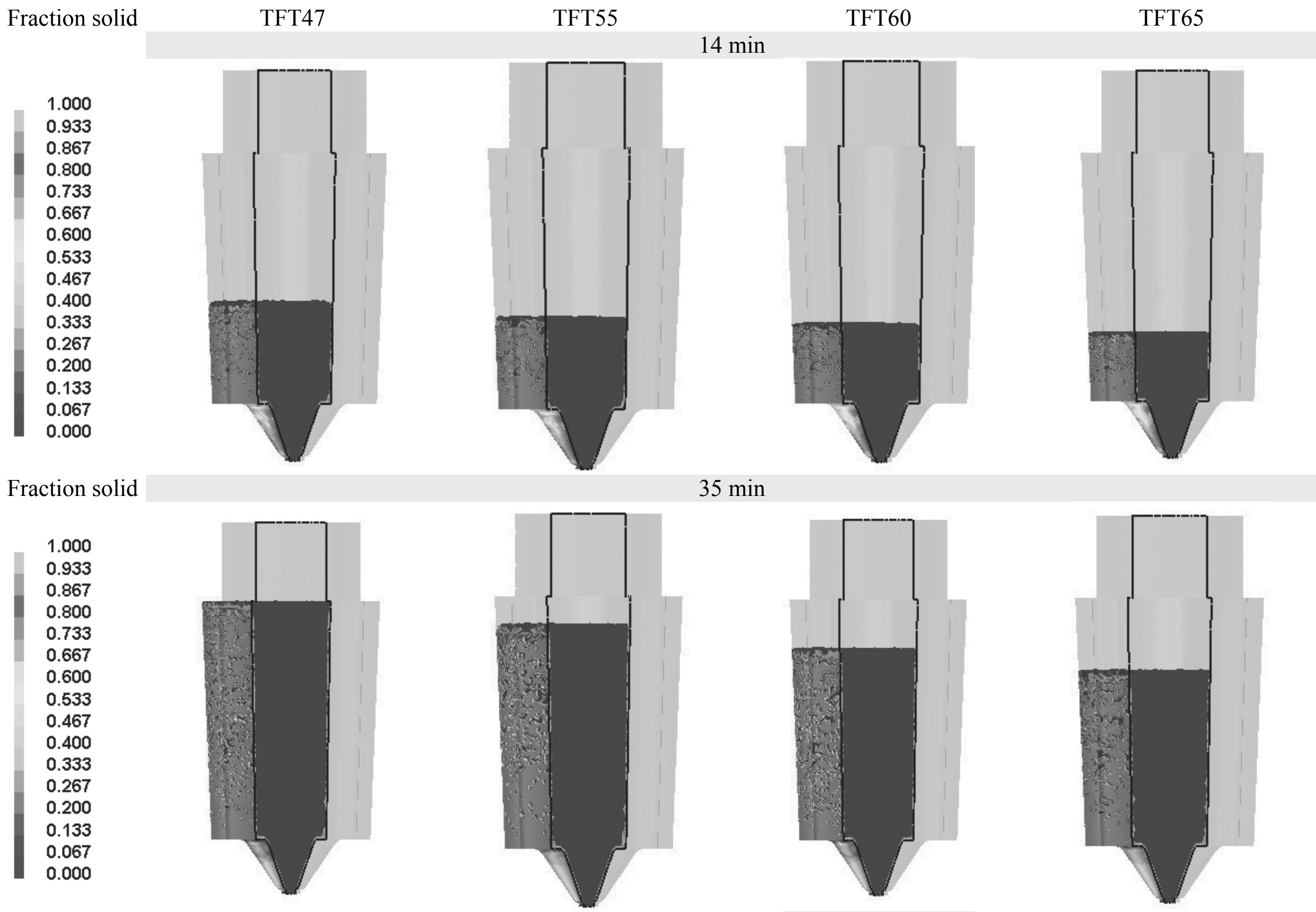


Fig. 10. Example of the manner of ingot filling at different rates of filling (or of total time of filling) in the minutes 14 and 35, and character of solidified fraction on the ingot surface

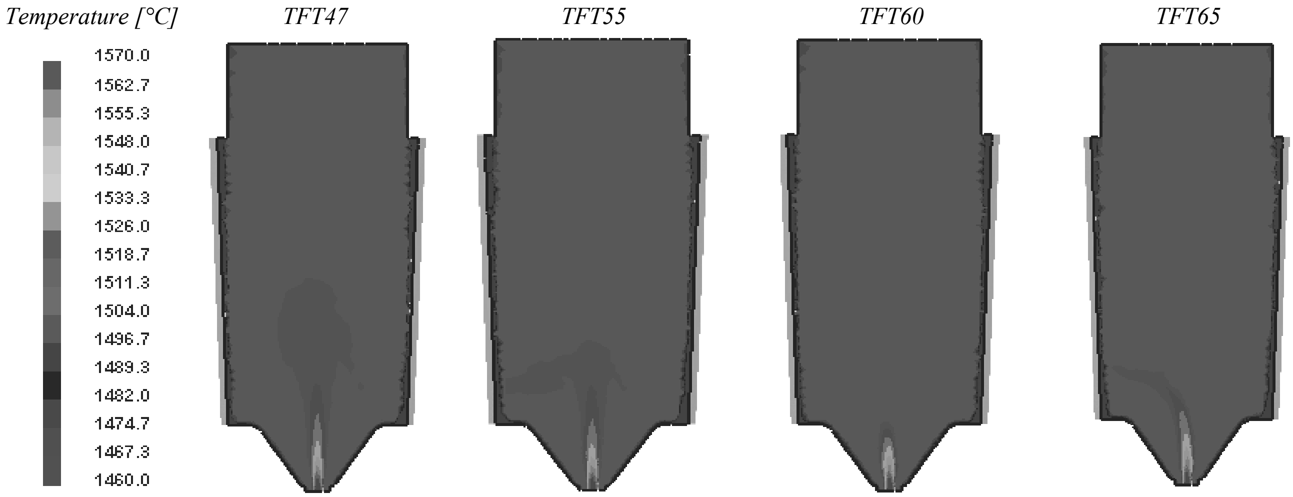


Fig. 11. Temperature field at the moment of full filling

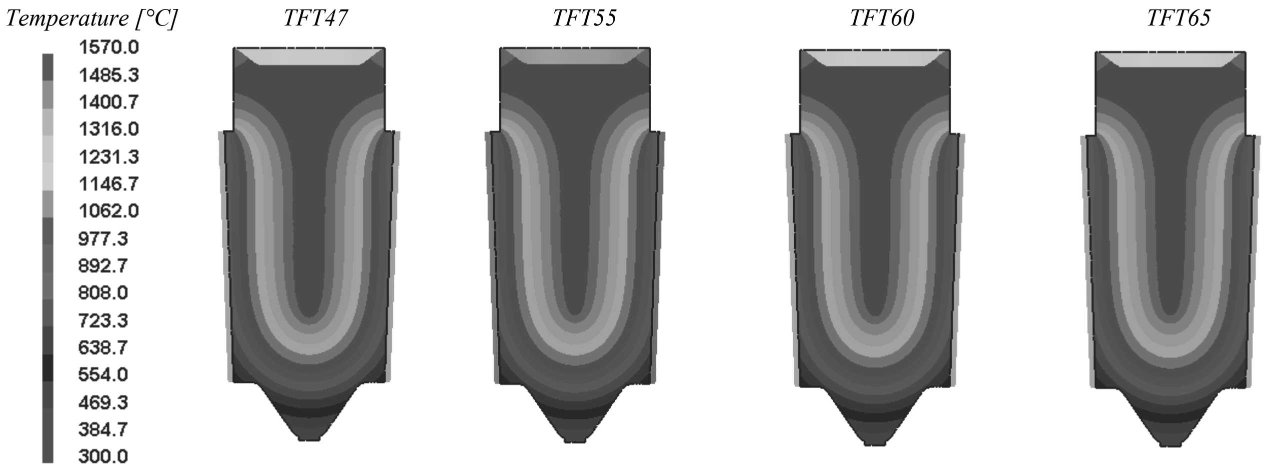


Fig. 12. Temperature filed of the ingot during solidification - 10 hours after completion of casting

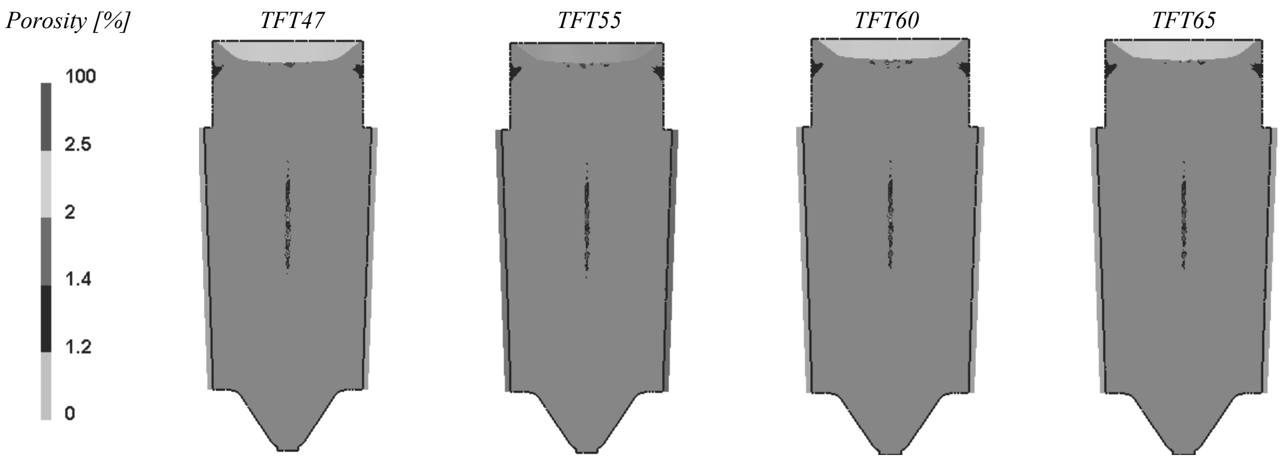


Fig. 13. Comparison of porosity obtained in individual variants at different total time of filling

4.3. The effect of longer total filling time together with decrease of the casting temperature during casting

When we supposed the longer filling time (65 min.), it should also be considered with the decrease of the casting temperature of approx. 30°C during 65 minutes (the casting temperatures decreased from 1570 to 1540°C in the ladle, which means that the temperature of steel in the ladle decreased approx. by $0.46°C\cdot min^{-1}$). In real conditions, however, the decrease of the temperature in the ladle will be probably smaller.

Nevertheless, as it was already mentioned above, due to the fact that decrease of the casting temperature together with longer time of filling led to slight decrease of the magnitude of porosity, it was natural to verify the solidification behaviour at the simultaneous change of both parameters. Fig. 14 shows a comparison of porosity with use of the function “CUT OFF” of the variants T1570 and TFT65-DT30. The reason for use of the variant T1570 was, that the boundary conditions of this variant were identical with those of the ingot cast experimentally (and it was thus possible to compare the results of numerical simulation with the real state). As it is evident from Fig. 14, the combination of modification of the boundary conditions led to a minimization of porosity in the top third of the ingot body. The porosity was predicted namely in the central part of the ingot body and it did not exceed the magnitude of 2%.

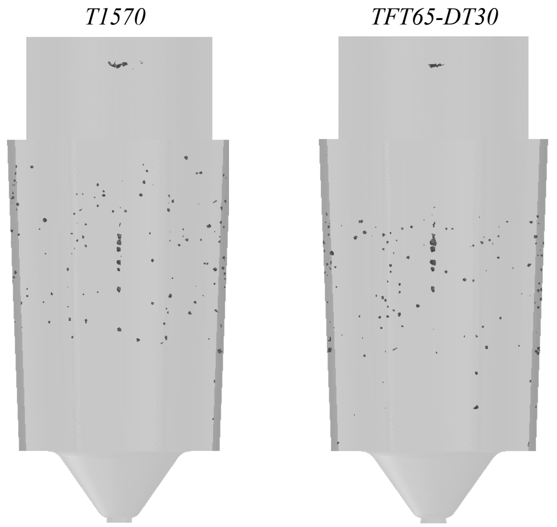


Fig. 14. Comparison of porosity with use of the function “CUT OFF”

5. Conclusions

The paper was devoted to the verification of porosity in heavy steel ingot depending on the boundary conditions of the casting using numerical modelling. Eight variants were simulated, where the casting temperature and casting speed (or the filling time) were changed. The simulations of the filling and solidification phase were done individually in two steps. Therefore, the mesh for filling could differ from the computational mesh for solidification. The thermodynamic properties of materials (steel, mould) were generated by the integrated thermodynamic database CompuTherm. The heat transfer coefficients were set in dependence on time or temperature. The one simulated variant had the same boundary conditions of the casting as the simultaneously experimentally cast ingot. This variant was used for comparison of the final extent of the porosity in the ingot body between the numerical and experimental results. It was evident from the numerical results, that:

- In all variants, the final character of the solidification was very similar.
- The slight extension of the time to solidus could be observed when we extended the filling time by 15 minutes (from 50 to 65 minutes).
- The lowest level of porosities were achieved in the variant when we used the longer filling time (65 min) together with decrease of casting temperatures approx. by 30°C because of the cooling of the melt in the ladle during 65 minutes of the casting.

However, the tested adjustment of casting technology appeared to have only small impact on the resulting porosity. So, the current casting technology is set properly.

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