### THE UTILIZATION OF NUMERICAL MODELING TO OPTIMIZE THE PRODUCTION OF HEAVY FORGING INGOTS IN VÍTKOVICE HEAVY MACHINERY a.s.

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#### Key words

Heavy forging ingots, numerical modelling, thermography, hollow ingot, macrosegregation, VÍTKOVICE HEAVY MACHINERY

#### Abstract

The paper will present new knowledge and experiences with verification and optimization of production technology of heavy forging ingots using the results of numerical modelling and of operational experiments at steel plant in VÍTKOVICE HEAVY MACHINERY a.s. Based on the results evaluation from complete series of numerical simulations of casting and solidification of ingots weighing from 25 to 200 based their tons and on operational verification, it enabled to reduce a production cost while internal quality of steel ingots is also at very high level. The numerical modelling was carried out in the ProCAST software. The ingot geometries were created in CAD system SolidWorks. Before the computational grid generation of finite elements in Visual-Mesh module, the geometries were subjected to analysis of the topology. The calculation results of filling and solidification of ingot allowed to decide about the best options that were subsequently applied during ingot production and assessment of productivity.

The attention is also paid to comparing the results from numerical simulations with operating experiments of production of 90-tons steel ingot. The operational process was

monitored by the thermal camera in order to get complete information about the values of heat flows which were used as the basic input parameters of numerical simulation. The real 90-ton ingot was cut and analysed. Chemical homogeneity as well as micro and macrostructure were evaluated in ingot sections.

The last significant chapter of this paper presents the information about the production of hollow ingots. Hollow ingot is used as a semi-finished product for the production of hollow forgings, especially shells and rings. In this type of ingot, the segregations are at minimum level and also very good isotropic properties are achieved due to differences in the occurrence of solidification. The reduction of the production costs is the next considerable benefit.

#### 1. Introduction

Despite the ever-increasing volume of steel continuous casting, production of steel ingots for forgings and machine components is irreplaceable. Steel casting into the ingots allows even for the production of oversized components weighing up to several hundred tons. The main precondition of the competitiveness of any steel plant 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 due to the non-uniform cast microstructure of an ingot as well as the macrostructure, which is the result of plastic deformation during the subsequent process of The solution the formina. to material weaknesses of forgings, or the final machine components, consists from а complex optimization of the steel casting process as well as of subsequent heat treatment up to the actual process of forming.

VÍTKOVICE HEAVY MACHINERY a.s. (further also VHM) is traditional producer of large machinery components. The typical products of this company are crankshafts, propeller and connecting shafts, rotor shafts for wind power plants, forged parts for the container of pressurizers, steam generators, heat collectors both exchangers and for conventional and nuclear power engineering. For these products it is necessary to cast ingots weighting up to 200 tons. Steel plant of VHM is equipped with EAF, LF, VD and VOD facilities. Ingots from 1.7 up to 200 tons are bottom casted. Typically 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 form two or three heats. For solving problems of ingot casting and solidification VHM cooperate together with Technical University of Ostrava and with MECAS ESI s.r.o. using software ProCAST. Experiment was performed in which 90-ton ingot cast and cut. Chemical was heterogeneity was investigated on this cut ingot. Results from this experiment are used for ingot casting optimization. The main aim of this work is to reduce occurrence of macrosegregation in steel ingot.

#### 2. Operational verification

An experimental 90-ton ingot was cast at steel plant VHM due to determine the extent of chemical heterogeneity. Structural carbon manganese steel (S355J2G3 according to EN 10 250) was chosen for this trial. As mentioned in introduction, this type of ingot is casted from two heats. Each of these two heats had different content of copper and nickel in order to determine mixing of these two heats in solidified ingot. Content of other elements was target at the same level. Chemical analysis of both heats and the weighted average of the both heats reflecting different weight of these heats is shown in Table 1. The course of ingot casting and solidification was monitored using thermography Ingot was cut after solidification and heat treatment. Heat treatment was performed in order to prevent cracking during the cutting. Penetration test and sulphur print was done on the longitudinal cut of this ingot. To determine chemical heterogeneity was used several analytical methods. Analysis of following elements was required: carbon, manganese, sulphur, phosphor, copper and nickel. Chemical analyses were performed in 5 vertical axes and in 15 horizontal lines on a half of the ingot. A total of 1 279 points were analysed. Contents of manganese, silicon, copper and nickel were measured using a mobile optical emission spectrometer. Carbon and sulphur were measured using LECO CS 600. Phosphorus content was determined by titration.

heat No.	С	Mn	Si	Р	S	Cr	Cu	Ni
1	0,194	1,30	0,26	0,008	0,0008	0,11	0,13	0,51
2	0,200	1,27	0,27	0,009	0,0010	0,14	0,46	0,12
w. average	0,196	1,28	0,26	0,009	0,0009	0,12	0,26	0,36

**Table 1**: Chemical composition of both heats

 for experimental ingot

According to expectations, content of elements, mainly such as carbon, manganese, sulphur and phosphorus increased towards the axis of the ingot and towards from bottom to top part of ingot. Chemical composition of carbon and sulphur in ingot axis are shown in **Figure 1** and **2**.

Content of copper and nickel on the half of the ingot is shown in **Figure 3** and **4**. It is evident form these figures that there is an area where there are not both heats mixed. There is solidified layer of steel only from first heat containing only nickel at the bottom part of ingot. These obtained results were used mainly for comparison with results from numerical simulations.



**Fig.1** Carbon content in the experimental ingot axis



**Fig. 2** Sulphur content in the experimental ingot axis

#### 3. Numerical modelling

The knowledge of existing casting parameters like casting speed, casting temperature of steel or the H/D ingot ratio is the main precondition to minimize the well-known defects of steel ingots. Especially in demanding metallurgical conditions, it is appropriate to apply the method of numerical modelling using some of the available simulation software.

The aim of numerical modelling realized under the conditions of the Department of Metallurgy and Foundry and Regional Materials Science Ingot Casting – Simulation 2



Fig.3 Copper content in the experimental ingot



Fig.4 Nickel content in the experimental ingot

and Technology Centre at VSB-TU Ostrava is the verification and optimization of the production technology of heavy steel ingots produced in VÍTKOVICE HEAVY MACHINERY a.s., especially focused on minimization of macro-segregation.

The numerical modelling of filling and solidification of the steel ingot was performed using ProCAST software. The software allows 3D, fully dimensional numerical simulation of filling and solidification of steel including prediction of ingot volume defects, such as porosity and shrinkage. The software allows to modelling the macro-segregation as well. Due to the Flow and Stress modules, it is possible to take into account the effect of natural convection and the formation of air gaps between the ingot body and the inner wall of the mould during the calculation, and to predict the emergence of internal stress, which can ultimately lead to cracks and rupture [1,2].

In general, the numerical solution of each task is divided into three stages:

1. Pre-processing: includes the geometry modelling and the computational mesh generation process, and definition of calculation.

2. Processing: involves the computation in the solver.

3. Post-processing: focuses on evaluation of the results.

The conditions of numerical model setting were based on real conditions of the experimentally cast 90-ton steel ingot produced in VÍTKOVICE HEAVY MACHINERY a.s.

#### 3.1 Geometry and computational mesh

The computational mesh geometry and generation of the casting system of the 90-ton steel ingot was made in cooperation with MECAS ESI s.r.o. The ingot geometries were created in CAD system SolidWorks. The comparison of the real and CAD geometry of the casting system is shown in **Fig.5** [2,3].

Before the computational grid generation of finite elements in Visual-Mesh module, the geometries were subjected to analysis of the topology. Topology is a field of mathematics concerned with examining the properties of geometric shapes, which are maintained in reciprocally unique double-sided continuous images. The individual components of the geometry of the cast system are loaded into the pre-processor of grid generation gradually. Before the loading of the next geometry element, it is necessary for the previous components to stay aligned and connected with only one surface. The contact of two parts through one surface is necessary for a correct calculation of heat transfer.

In **Fig. 6** is final computation mesh of the casting system. The volume ingot mesh consists of 348,794 nodes. Total volume of tetra elements is 1,766,041. The mould has

rough mesh. For the more appropriate description of geometry, the details, insulation, and ceramic parts have a better mesh.



**Fig.5** Comparison of the realand CAD geometry of the casting system in case of a 90-toningot [2]



**Fig.6** View of the final computational mesh of the casting system [2]

#### 3.2 Entering the calculation conditions

The final mesh of geometry was saved in \*. mesh format and subsequently loaded in the ProCAST module for calculation entry, also called the PreCAST. It was necessary to define [4]:

- material properties of the individual parts of the casting system,
- heat transfer coefficients on the interface of elements of geometry,
- boundary conditions, such as casting temperature, casting speed, conditions

of heat losses through the surface of the ingot,

- operating conditions (such as gravity),
- initial conditions of calculation,
- calculation parameters –the s.-c. RUN PARAMETERS.

The boundary conditions may not be represented only by constant quantities, but they can reach the values defined by the function, table, etc. The most important boundary conditions for the calculation of filling and solidification of steel ingots with the predictions of size of volume defects include the temperature of cast melt, casting speed and the definition of the heat transfer method through the mould wall. To describe the appropriate temperature distribution on the mould, most authors [5, 6] use for individual interface (e.g., mould wall-ingot body, mould mat-ingot, etc.) the different coefficients of heat transfer. Depending on the materials that are in contact, they range from 100 to 1000 W.m<sup>-2</sup>.K<sup>-</sup> <sup>1</sup>. The calculations must include the influence of heat loss through walls of mould and through the hot top, and also the thermal effect of exothermic and insulating powders. The calculation of the size of the central shrinkage, or the central porosity is also influenced by the calculation of the formation of the air gap between the mould wall and ingot body during the solidification and cooling due to the shrinkage. This software, due to its special module, automatically calculates with the modification of the heat transfer coefficient on the ingot / mould interface as soon as the air gap begins to form, which is given by equations [7]:

$$h = \frac{1}{\frac{1}{h_0} + R_{gap}}; R_{gap} = \frac{1}{\frac{k}{gap} + h_{rad}}$$
(1)

where *k* is the air conductivity, *gap* is the width of air gap and the  $h_{rad}$  is the radiation equivalent coefficient of heat transfer.

Among other things, RUN PARAMETERS define the conditions of calculation termination, the s.-c. STOP criteria. Among 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 [3,4].

#### 3.3 Thermography measurements

As was already above mentioned, the course of changes in the temperature field on the surface of the casting system during experimental casting of a 90-ton ingot was also monitored using thermal imaging cameras. Thermography measurements were performed using the camera AVIO TVS 700. According to the tables for emission coefficients, the value of emissivity was set at 0.85. At the time of measurement. an average ambient temperature was 26 ° C under conditions corresponding to the operation of a steel plant. The measurement was not affected by the increased dusting or drafts, and it was done with a tripod at constant distance of 6.5 Self-evaluation images was meters. of SW GORATEC performed in the Thermography Studio v4.5 [2].

## 3.4 Discussion of numerical simulations results

The computational time of one variant is around 96 hours using two processor cores. However, to the time of your own computation it is necessary to add a preparation of the simulation and evaluation of achieved results. The calculation with macro-segregation is much more longer – the computation time of 3D mesh was around 170 hours.

The simulation results can be divided into the results obtained from the calculation of filling and results obtained by the calculation of solidification.

**Fig. 7** shows the character of the mould filling with the steel and the final filling time in seconds. A real time of the filling during the experimental casting of 90-tons ingot was 56 minutes. Sometimes, the user may not be interested by the filling of the last percents (e.g. the end of the filling of a head). Therefore, during the simulations, the effect of the one timestep of the filling of the head of the casting system with remaining 10% of the steel on the final surface temperature of the mould was

tested. This timestep is defined using the run parameters ENDFILL. This means, if the ENDFILL=0.90, once 90% will be reached, the remaining 10% of the steel will be filled in one timestep.



**Fig.7** : a) Character of the filling corresponding to the real casting conditions of 90-tons ingot b) character of the filling using run parameters ENDFILL=0.90.

During tuning of the setting of numerical simulation of filling and solidification of a 90-ton ingot, more than 10 configurations were calculated up to now. A sample of difference of temperature profile on the surface of the ingot obtained for the first variant and for last variant 20 minutes after the initiation of filling and in the end of filling, where thermography measurement results have been used, is captured in **Fig. 8** [2]

Authors of the paper used the possibilities of Visual Viewer of ProCAST and adjusted the scale of numerical simulation results to the scale of thermography. Selecting and editing of the colours were dependent on the colour sense of the user. The advantage of Visual Viewer postprocessor is the display of temperature in precise contours - changing of the minimum and maximum values can provide accurate information about the temperature in the chosen location of the geometry. Fig.8 shows in the first column the temperature evolution on the mould surface for the original setting, where the values of heat transfer coefficients ranged from 100 to 1,000 w.m<sup>-2</sup> K<sup>-1</sup> as is typical in these simulations. However, it is obvious that the temperature values on the mould surface are below the values measured thermography during the measurements

(second column). Therefore, it was necessary to adjust the coefficients according to the measured values depending on time. The third column already captures the evolution of the temperature on the mould surface after adjustment of the coefficients of heat transfer. The results of thermography measurements and numerical simulation are already converging [2].



**Fig. 8** Comparison of the temperature on the ingot mould surface a) 20 min after the initiation of filling b) after filling

The last simulated variant of the filling with the corrected values of heat transfer coefficients was used for simulation of macro-segregation during the solidification of the ingot. In Fig. 9 is compared the macro-segregation of carbon content calculated by numerical simulation with the real measured values of wt.% carbon in the cross section of the real experimental cast 90 tons ingot. The character of the profile of wt.% C was achieved as a point measurement according to the condition of experimental measurement using LECO. We can see that the trend is very good. The next attention will be focused on explanation of the places with negative segregation of carbon in the middle of the ingot body and the differences between the achieved from carbon content real measurement and carbon content calculated using ProCAST.

# 4. The utilization of numerical modelling to optimize the production technology

Numerical simulations of ingot casting and solidification are used for different purpose. Two main directions of their use are the optimization of existing production technology and the development of new types of products. Optimization of the production technology is especially improving product quality and reduces production costs.



**Fig.9:** a) View on the macro-segregation of carbon content on the cross section of the ingot b) comparison of profile of the carbon content in the centre axis from numerical modelling and from the plant measurement using LECO

## 4.1 The development of hollow ingot casting technology at VHM a.s.

Casting of hollow ingot has been known for a long time from various producers of heavy forgings. The European manufactures can mentioned for example Sheffield Forgemasters International Ltd. and AREVA Creusot Forge. The great advantage of using hollow ingots as a semi-finished product for the production of forgings such as shells and rings is mainly lower level of the segregations. Other advantages are shortening forging time and production yield increase. Given the growing demand for hollow forgings starting development of technology for hollow ingot also in VITKOVICE HEAVY casting MACHINERY a.s. First, numerical simulations of casting and solidification of hollow ingot were carried out. Particularly suitable core material and method of its cooling was investigated. New casting system for 57-ton hollow ingot was designed based on the results of these numerical simulations. Hollow ingot casting was verified in practice, 57-ton hollow ingot, which was cast at steel plant VHM is shown in Fig. 10. This ingot was

forged on the shell. Forging was cut into samples and investigation was carried out.



**Fig. 10:** A 57-ton hollow ingot after stripping at steel plant VITKOVICE HEAVY MACHINERY a.s.

#### 4.2 Hot top optimization

In the context of the modernization the forge plant at VHM, namely the construction of the manipulator at 120 MN press, and with regard to availability of better insulating boards of hot top ingots can be considered to reduce the size of the hot top of selected heavy forging ingots. Numerical simulations of the influence of reduced amount of the hot top on the quality of ingot were performed on a number of ingots from 25 to 200 tons of various steel grades. It was evaluated the influence of the following parameters: final shape of shrinkage; increase in the volume of predicted porosity; distribution of predicted segregation, especially carbon, manganese and sulfur. Results of numerical simulations were compared with values obtained during experiment described in chapter 2. Based on this investigation, it was possible to reduce the height of hot top and it was achieved savings of liquid metal from 3 to 5 % depending on the type of ingot.

#### 5. Conclusion

It was performed an experiment in which level of chemical heterogeneity was investigated. A 90-ton ingot was cast from two heats. The course of casting and solidification of this ingot was monitored using thermography. The mixing of both heats in the ingot was investigated. Also segregation of carbon, manganese, sulfur and phosphorous was detected. In parallel with this experiment numerical simulations of casting and solidification were performed. The conditions of numerical model were setting based on real conditions. Results of numerical simulations are used to optimization of ingot casting technology and to the introduction of new products.

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