# CASTING AND SOLIDIFICATION SIMULATION OF 65 T STEEL INGOT IN THERCAST SOFTWARE

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**Abstract**

The presented paper deals with a numerical simulation of casting and solidification of a 65-ton ingot made of 25CrMo4 low-alloy chrome-molybdenum steel. The aim was to focus on the assessment of steel melt flow, the risk of formation of microporosity and segregation according to Niyama or Suzuki criteria respectively, solidification. The numerical simulation was done for parametric analysis of solidification process in casting based on boundary conditions. Correctly set values of casting parameters like casting speed, casting temperature of steel, H/D ingot ratio are the essential precondition to minimize the defects of steel ingots.

**Keywords:** Numerical simulation, THERCAST software, steel ingot, casting, solidification

## 1. INTRODUCTION

Heavy ingots are metallurgical semi-finished products intended mainly for the production of high quality forgings used in mechanical engineering, e.g. for the production of crankshafts for ship engines or special parts for the power industry - conventional and nuclear (turbines, heat exchangers, steam generators). The production of heavy forging ingots is accompanied by the occurrence of segregation of individual elements in the steel structure, porosity and other defects which, during further technological processing, may lead to anisotropy of the mechanical properties of forgings and unsatisfactory results of non-destructive testing. The 25CrMo4 grade is used for the production of axles for high-speed trains, mainly because of its high strength, good toughness, ductility and high resistance to impact loading. The ever-increasing customer demands for the quality of the final products, especially in terms of structural and mechanical properties, are forcing manufacturers to optimise production technology. This may involve adjusting the temperature regimes used to conduct the melting process, changing the shape and size of the coke, the casting speed, the method of cooling the ingot, etc. The production of heavy ingots is financially very expensive, and very often technological changes are first examined by mathematical modelling and numerical simulations using finite-element calculations [1-5].

The finite element method (FEM) is a numerical method solving differential equations in two or three space variables. To solve a problem, the FEM subdivides a large system into smaller simpler parts that are called finite elements.  The finite element method formulation of a boundary value problem finally results in a system of algebraic equations. The method approximates the unknown function over the domain. The boundaries of the area solved is then replaced by polynomials. The basic elements describing the surface are triangular or quadrangular spots. In spatial representation, these are prisms, tetrahedrons or pyramids.

Modern finite elements simulation programs can simulate the prediction of the melt during casting, the interaction of metal and mold, deformation of the casting – stress, estimation of the future structure and microstructure. Each individual model computes heat transport, speed and method molds, metal flow in the mold, solidification kinetics, structure formation, porosity models, stress calculation and other [6].

In the company MATERIÁLOVÝ A METALURGICKÝ VÝZKUM s.r.o., the THERCAST® software is used for the optimization of metallurgical processes.

THERCAST® is a computer software tool that works on the basis of the finite element method (FEM). It is intended for foundry processes, continuous casting and ingot casting. THERCAST® allows us to accurately analyse various production processes from the beginning of casting to the end of the solidification phase. It may be used to study the thermal field of the metal object and some surrounding components during the process. It is able to determine flow rates, pressure, stress or deformation in metal. Based on this, it can calculate the final shape and properties of the casting. A characteristic feature of THERCAST® is its ability to predict the real behaviour of the material in the mould and during the gas evolution during the process. It predicts results verified by real processes thanks to an accurate thermo-mechanical model. The software also contains a powerful solver of systems of vector equations for the efficient use of computing power using parallel calculations [7].

The aim of the presented work is to examine the physical properties of the low-alloy steel during the ingot casting process, and mathematically verify the proposed ingot casting technology and confirm the boundary conditions, especially pouring temperature and speed, height/width ratio of the ingot, where is important that the liquid core is not closed in the critical central area of ingot.

## 2. NUMERICAL SIMULATION

Generally, the numerical solution of each task is divided into three stages: a) pre-processing: includes the geometry modelling and the computational grid generation process and definition of calculation. b) processing: involves the computation in the solver. c) Post-processing: focuses on evaluation of the results. [8].

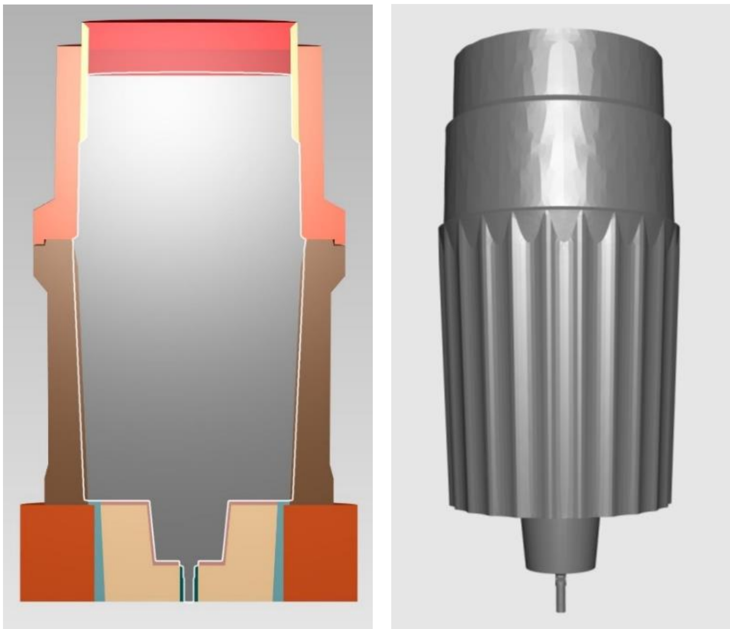

**Figure 1** 3D ingot geometry

In the presented paper, the simulation of low-alloy chrome-molybdenum steel grade 25CrMo4 with a solidus at 1,445 ˚C and liquidus at 1,486 ˚C for bottom poured ingot (**Figure 1**) was carried out on THERCAST software. Chemical composition of 25CrMo4 steel is shown in **Table 1**. At the company MATERIÁLOVÝ A METALURGICKÝ VÝZKUM s.r.o. the THERCAST NxT 2.1 software from French Company TRANSVALOR is currently used for numerical simulations of casting and solidification of melt steel. The properties of the refractory materials and heat transfer coefficients, including material models, were therefore intentionally from THERCAST library and they are shown in the **Table 2.**

**Table 1** Chemical composition of 25CrMo4 steel

| **Elements** | C | Si | Mn | P | S | Cr | Mo |
|---|---|---|---|---|---|---|---|
| **Wt%** | 0.25 | 0.1 | 0.75 | 0.01 | 0.01 | 1.1 | 0.2 |

**Table 2** The thermo-physical value of simulation

| Thermo-physical properties | Operating condition |
|---|---|
| Thermal conductivity | 34 $W \cdot m^{-1} \cdot K^{-1}$ |
| Specific heat, c | 830 $J \cdot Kg^{-1} \cdot K^{-1}$ |
| Density, ρ | 6,931 $Kg \cdot m^3$ |
| Liquidus temperature | 1,486 ˚C |
| Solidus temperature | 1,445 ˚C |
| Latent heat | 265,000 $J \cdot Kg^{-1}$ |
| Viscosity | 0.0065 $kg \cdot ms^{-1}$ |
| Pouring temperature | 1,550 ˚C |

The filling rate was defined at 0.00034868 $m^3 \cdot s^{-1}$ and the heat transfer after filling was set according to the table above. The casting temperature was 1,550 ˚C and the ambient temperature 20 ˚C. This task is redefined as a thermal task.

## 3. DISCUSSION OF RESULTS

The simulation results can be divided into 2 possible groups, the simulation results obtained by casting into the mould and the post-filling results obtained by solidification computation. **Figure 2** shows the filling of the ingot from the bottom at 70, 95% and the filling of the ingot at 99% with the vectors represented with a relative scaling down to 20%. The values (from the surface) are positive inside the metal and negative towards the air. (m). In laminar flow, only streamline flow is seen throughout the filling, where the tracks of the individual liquid particles are in parallel layers to each other. The total casting time of the ingots was simulated to be 65 minutes.

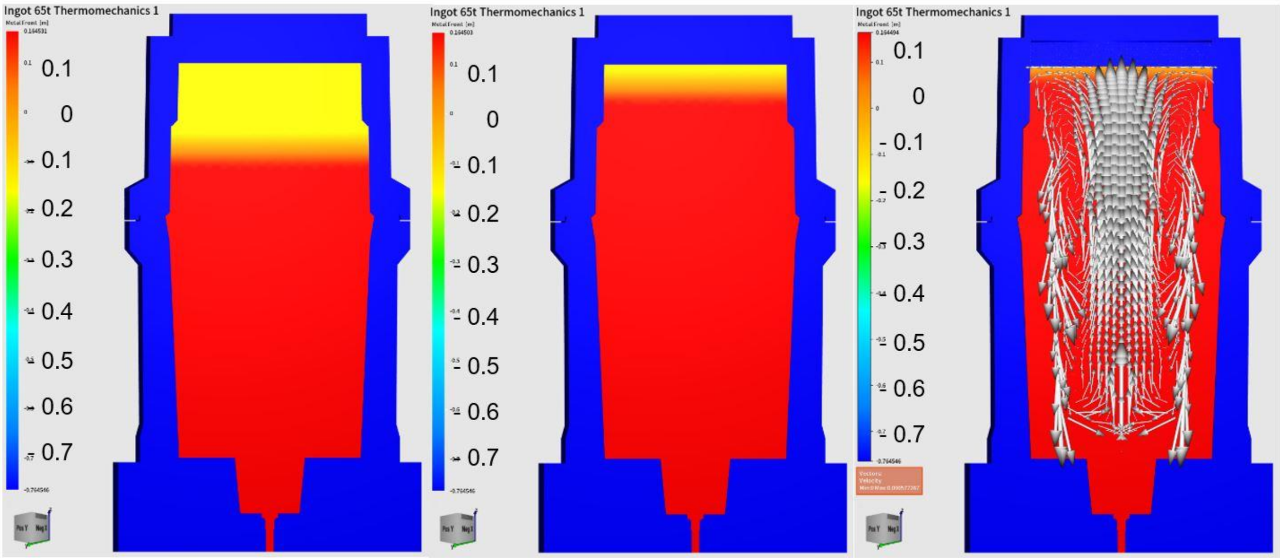


**Figure 2** Mould filling a) 70% b) 90% c) flow using velocity vectors

**Figure 3** shows an example of the temperature field and liquid phase fraction just after the ingot is completely filled. The results show a representation of the temperature of the mold, base, etc. (˚C). The temperature of the ingot was simulated ranging from the casting temperature until 400 ˚C. The percentage of liquid and solid phase, on a scale of 1 indicates liquid and 0 indicates solid phase. According to the thermal calculation, complete solidification is reached in 61,650 s, i.e., in about 17 hours.

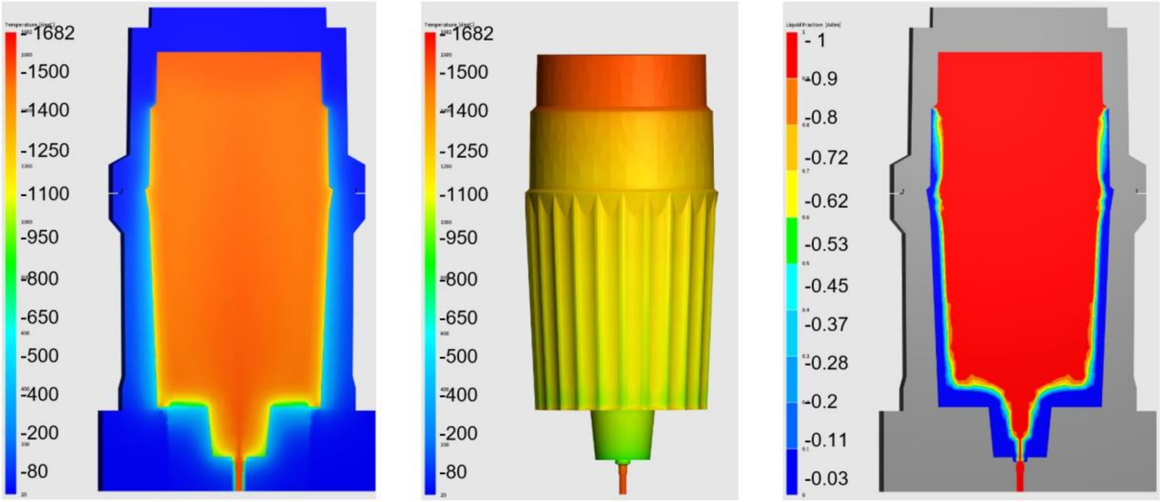


**Figure 3** Temperature field after full ingot filling a) in cross section b) around the ingot c) liquid phase fraction

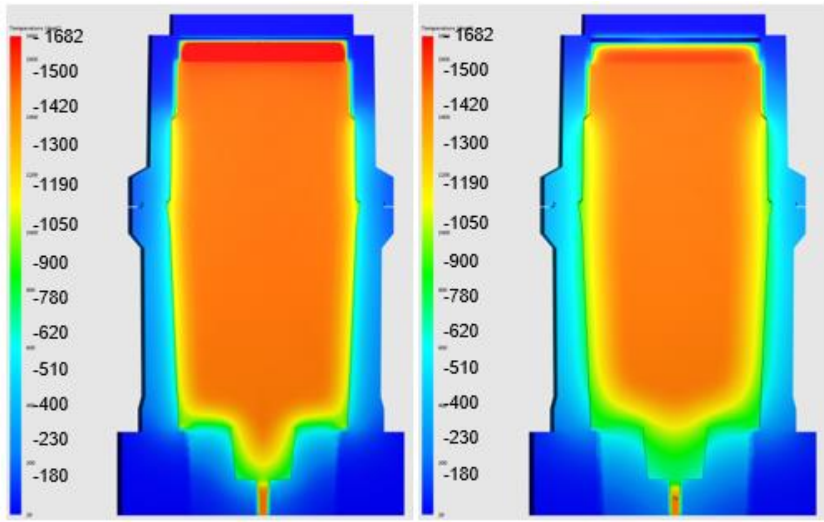


**Figure 4** Temperature fields of steel during solidification a) 25% of solidification b) 50% of solidification

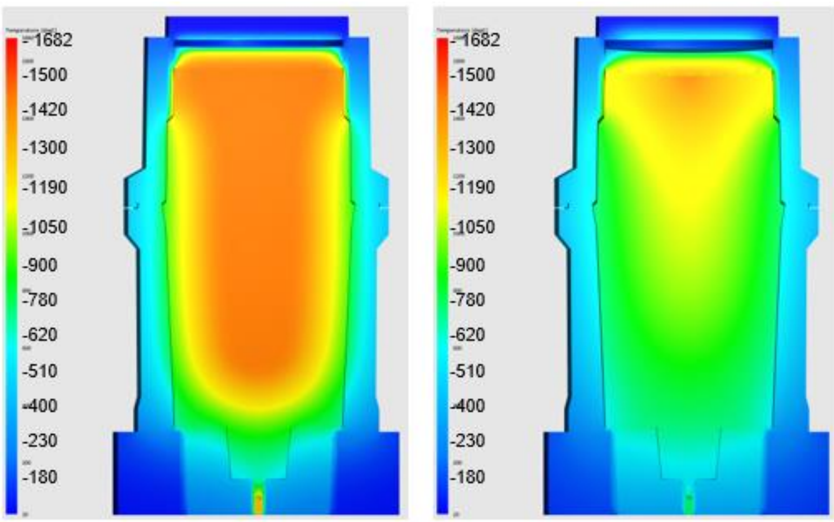


**Figure 5** Temperature fields of steel during solidification a) 75% of solidification b) 100% of solidification

**Figure 4** and **5** show the temperature of steel (and mold) during solidification at 25, 50, 75, 100% of solid phase. The temperature fields indicate that a thermal knot is generated in the central part of the ingot, which increases with time towards the head of the ingot. The simulation showed that the height to width ratio of the ingot body was appropriately chosen to allow for gradual cooling without enclosing the liquid core in the critical central region.

**Figure 6** shows the shrinkage of the cast ingot after cooling. Shrinkage is one of the important parameters that shows the volume loss in the dimensions of the ingot. Shrinkage occurs due to the reduction of temperatures, but also due to the increase of pressure or special processes leading to volume reduction. When the liquid steel comes into contact with the wall of the die, crystallization of the surface skin of the ingot begins. The shrinkage of the surface of the solidifying ingot is compensated by plastic deformation of the steel in the first stages of solidification. In the case of the 65t ingot, the shrinkage is particularly significant in the head of the ingot.

The Nyiama criterion (**Figure 7**) indicates the porosity inside the metal after solidification and determines the critical values, for the 65 t ingot simulation these values are very small, less than 0.22. This indicates a very low possibility of defects in the ingot body.

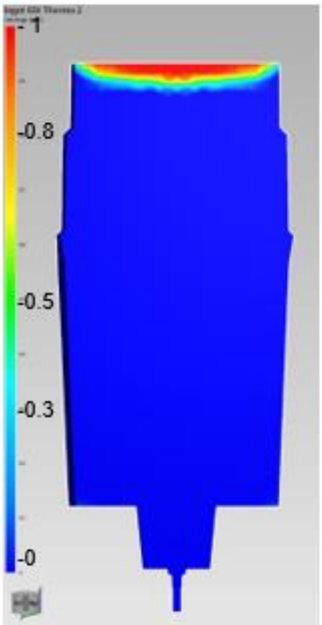


**Figure 6** Shrinkage

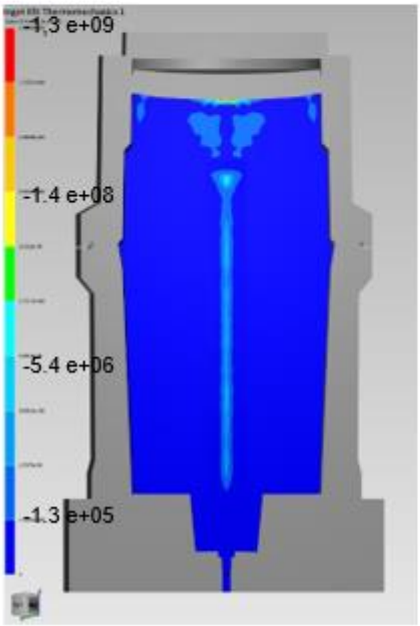


**Figure 7** Porosity

## 4. CONCLUSION

The present paper deals with the casting and solidification of 65t ingot of low-alloy Cr-Mo steel 25CrMo4 using numerical simulations. The work was carried out using the French software THERCAST. The results of the casting and solidification simulation are presented. Attention was focused on the temperature in the ingot during casting and cooling, on the ratio of the liquid phase as a function of temperature and time, on the segregation after solidification of the ingot. Simulations showed that complete solidification occurs in about 17 hours, the geometry of the ingot was designed appropriately to cool gradually without enclosing the liquid core in the centre of the ingot, an important parameter also for the Niama criteria, which the simulations calculated to be less than 0.22, i.e., minimal occurrence of defects in the ingot body. The results obtained showed that the software used, based on the finite element method, can simulate relatively accurately the temperature, pressure and velocity fields in the casting system, shrinkage, porosity, voids, as well as stress, strain, density and others. A big advantage of this software is the easy change of boundary conditions and adaptation to new conditions, making it suitable for process optimization.

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