THE USE OF NUMERICAL SIMULATIONS TO OBTAIN THE BASIC KNOWLEDGE ABOUT CASTING PROCESS OF HEAVY CIRCULAR INGOT

Vladislav KURKA, Marek VINDYŠ, Petr JONŠTA, Jaroslav PINDOR

MATERIÁLOVÝ A METALURGICKÝ VÝZKUM s.r.o., Ostrava, Czech Republic, EU
*vladislav.kurka@mmvyzkum.cz*

Abstract

During the casting of heavier ingots, internal porosity occurs during solidification due to shrinkage of the cast metal. Porosity, or non-metal-filled areas, is up to several centimeters inside large ingots. The present work deals with the study of physical-metallurgical parameters of casting a large circular ingot, leading to the elimination of porosity. Which was done using the numerical software Magma 5.4. In order to find the most suitable casting conditions, the planned experiment method called DoE was also partially used. Particular attention was paid to casting speed with investigation and finding the most suitable casting temperature. For the basic variant cast in the Magma software, an initial investigation of the temperature field and voltage state during the ingot cooling in the numerical software Forge NxT 2.1 was performed.

**Keywords:** Numerical, simulation, casting, solidification, Magma, Forge

1. INTRODUCTION

When casting heavier ingots weighing in the tens of tons, inner porosity occurs due to material shrinkage. Porosity or places inside large ingots not filled with metal are usually of a size of up to several centimetres [1], see **Figure 1** and **Figure 2**. Porosity can be removed or eliminated in several ways, namely by adjusting the mould shape, head extension shape or its structure, and also naturally by the speed and temperature of casting.

The main aim was to find the most suitable casting temperature and casting speed for 12 t ingot casting. And for the basic variant cast in the Magma software, an initial investigation of the temperature field and voltage state during the ingot cooling in the numerical software Forge NxT 2.1 performs.
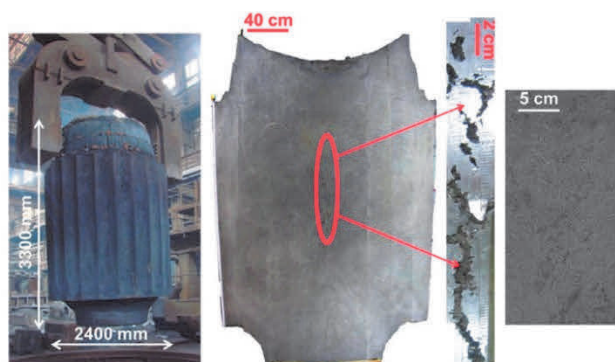

Figure 1 Porosity inside a heavy forging ingot, quality 30Cr2Ni4MoV [1]
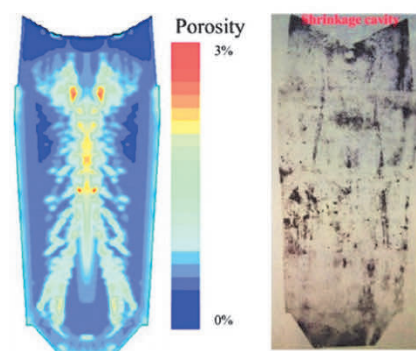
Figure 2 Porosity inside a large forging ingot, with 3.3 % C [2]

Three types of porosity can occur in a cast. The first type is called microporosity or pores occurring in the central part of the ingot where it is very difficult to feed metal. The second type are cavities and the third one is macroporosity, which grows with decreasing pressure caused by shrinkage and grows in the interdendritic space [3], see **Figure 3** which are mentioned by the author [4] and [5]. The authors tried to [6] successfully

solve porosity through controlled heat conduction, which is, of course, a completely different type of solution to the issue.
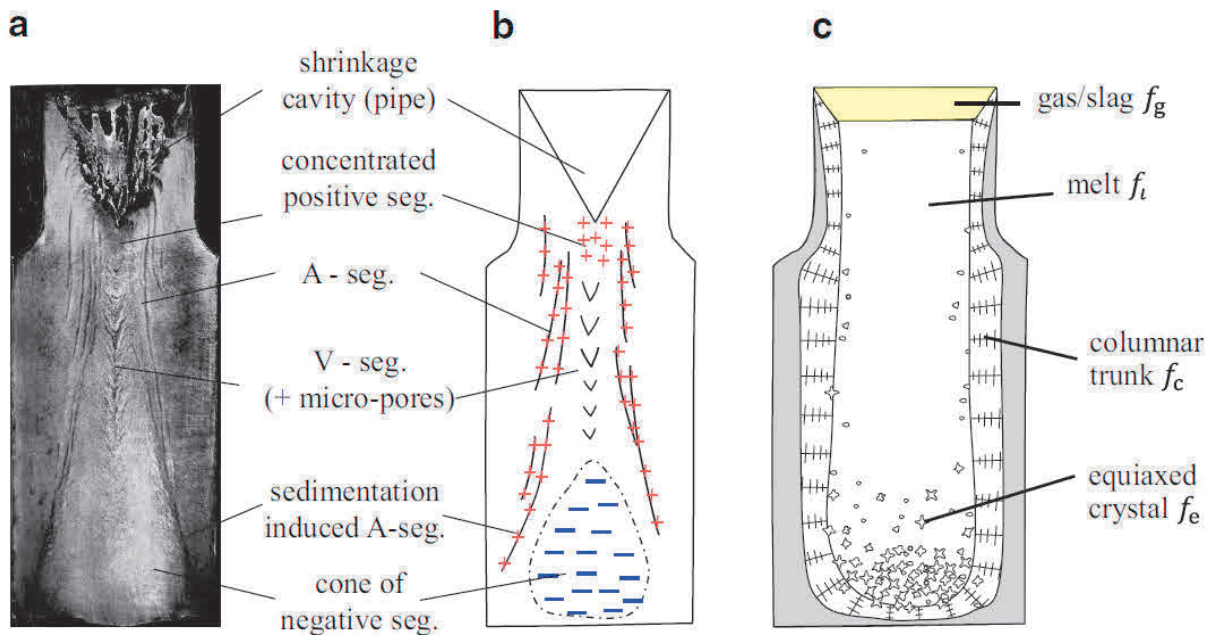
Figure 3 Scheme of solidification process and accompanying phenomena macro segregation and shrinkage, steel ingot weighing 10.5 tons with nominal composition 0.30% wt. C. a) Bauman's sulphur impression, b) schematic description of different types of macro segregation and shrinkage defects, c) a solidification process diagram and appropriate phases

2.   CASTING RESEARCH

Within the solution to the given issue, an analysis was carried out of a circular ingot casting of the A type with a weight of 12 t in Magma numerical software. The numerical solution was carried out on a casting set of 4 ingots weighing 12 t each. Own simulations were carried out on ¼ of this casting set, thus on one ingot, see **Figure 4**. The outlined ingot was subsequently transferred to individual elements, see **Figure 5**. To make it clearer, the following evaluations include pictures containing all the variants of numerical simulations.

 At the beginning, casting speed was analysed in dependence on the required temperature. Then, the most suitable speed of casting was chosen for which the most suitable casting temperature was found. First, a casting temperature of 1520 °C was defined and a casting time selected. The numerical simulation defined in this way is the so-called basic and was marked **"N.3"**. After performing numerical simulation **"N.3"**, the examinations were carried out deviating from this variant by the casting speed of the ingot body and head extension compared to the variant:

- T75H100.6 - the body cast 25 % more slowly and the head extension cast at the same speed.
- T125H100.7 - the body cast 25 % more quickly and the head extension cast at the same speed.
- T100H75.8 - the body cast at the same speed and the head extension cast 25 % more slowly,
- T100H125.9 - the body cast at the same speed and the head extension cast 25 % more quickly.
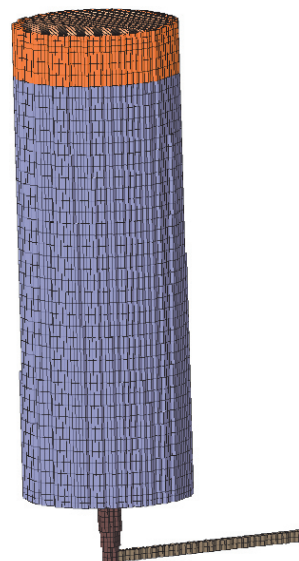
It resulted from the numerical simulations that the N3 variant has the lowest microporosity, the T75H100.6 version is the second, see **Figure 6**. Looking at **Figure 7** we can see that both variants also have the highest temperature during the first filling of the space in the mould. We can conclude from the simulations in **Figure 6** and **Figure 7** that the change in the casting speed of the ingot body has a great influence on the improvement of microporosity at the same casting temperature. For this reason, a second examination of the

best variant N.3 was carried out focusing on the impact of a change in microporosity when the casting speed changes and which differed from the N.3 variant as follows:

- T90H100.11 - the body cast 10 % more slowly and the head extension cast at the same speed.
- T110H100.12 - the body cast 10 % more quickly and the head extension cast at the same speed.
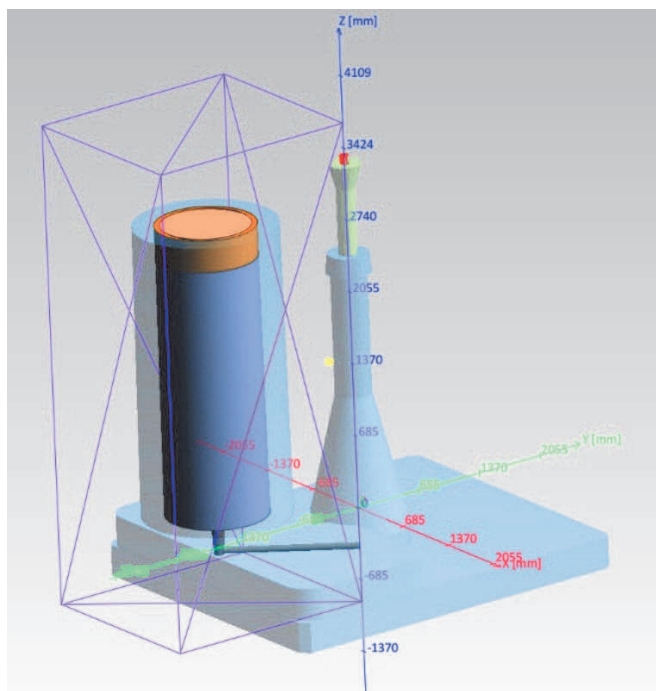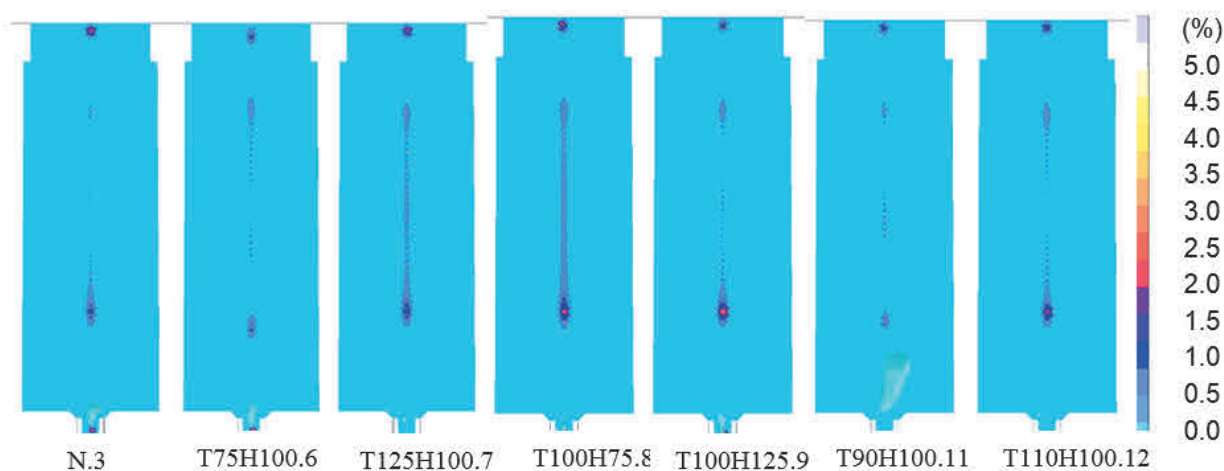

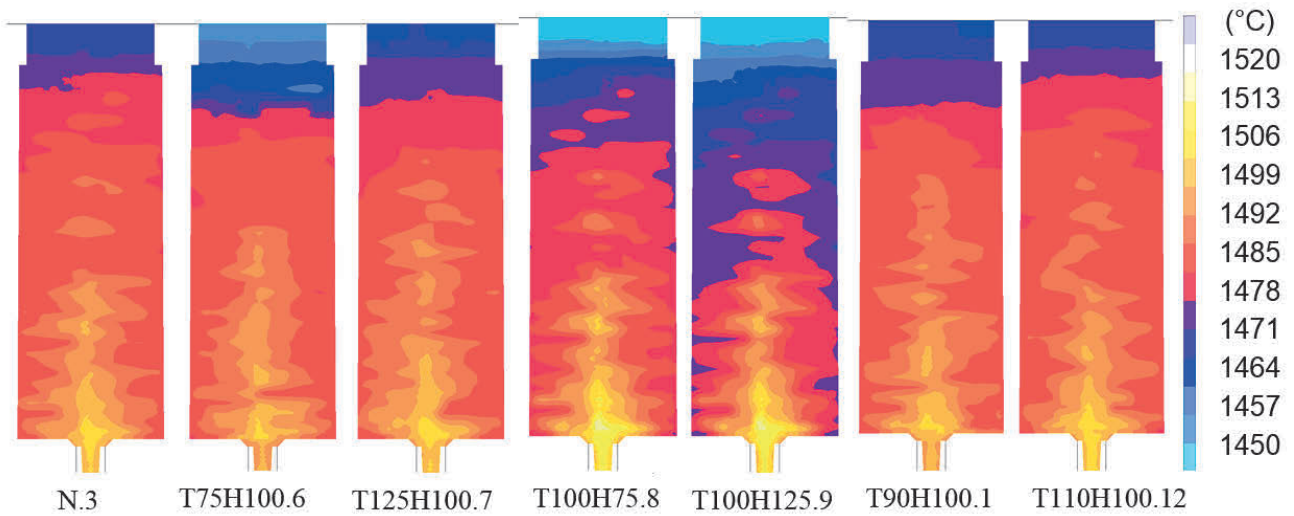**Figure 4** The geometric shape of the ingot, which was subsequently subjected to numerical simulation

Figure 5 An ingot converted to elements that were subsequently numerically simulated

The numerical simulations given above were subjected to examination and compared with the results of the N.3 numerical simulation. Based on the evaluation of microporosity, the numerical simulation marked T90H100.11 has the best result. For the casting conditions given in the T90H100.11 numerical simulation, the most suitable temperature of casting was looked in the range between 1515-1525 °C at the same casting speed.
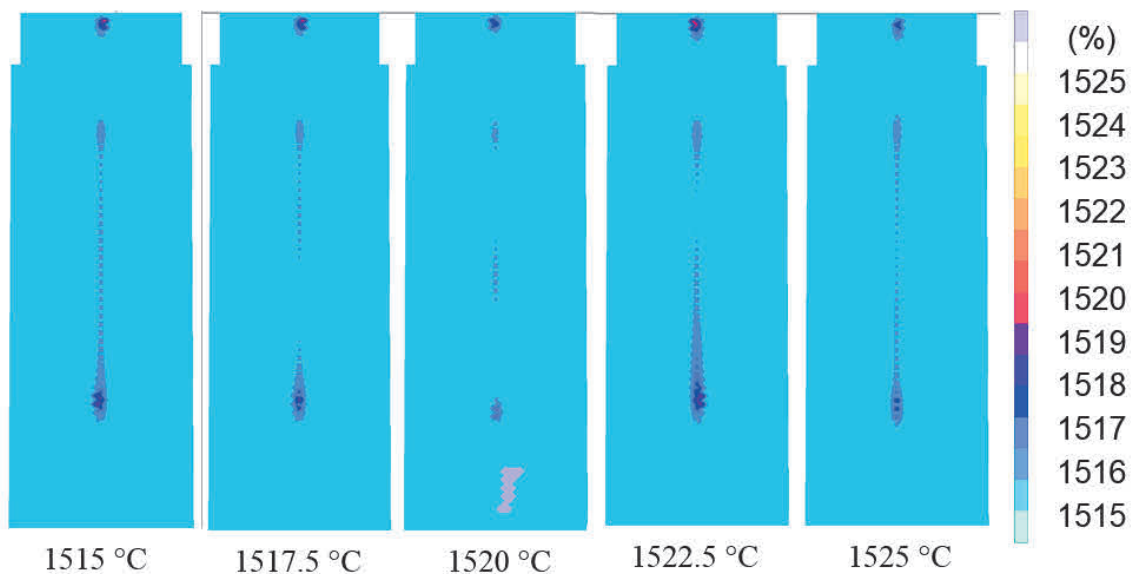

Figure 6 Microporosity in ingot after solidification, range 0-5 %

|						(°C)
						1520
						1513
						1506
						1499
						1492
						1485
						1478
						1471
						1464
						1457
N.3	T75H100.6	T125H100.7	T100H75.8	T100H125.9	T90H100.1 T110H100.12	1450

Figure 7 Melt temperature, at first entry to the site, ranging between 1450-1520 °C

The results of the numerical simulations performed were evaluated in this work mainly for microporosity in the T90H100.11 version with casting temperatures ranging between 1515-1525 °C, which are shown in **Figure 8**. When looking at microporosity in **Figure 8** it is obvious that the most suitable temperature is 1520 °C because it shows the lowest portion of microporosity inside the ingot body. This finding is also confirmed by the evaluation of numerical simulations using Magma software where it is obvious in 0 that the decrease in microporosity is greatest at a temperature of 1520 °C. Numerical simulations were also evaluated according to the course of solidification, see **Figure 10**, which shows that at a casting temperature of 1520 °C the melt solidifies the closest to the head extension. This indicates the maximum possibility of feeding the liquid metal from the head extension and also shows that microporosity in the ingot will not occur to a such a great extent as in the case of other ingots.

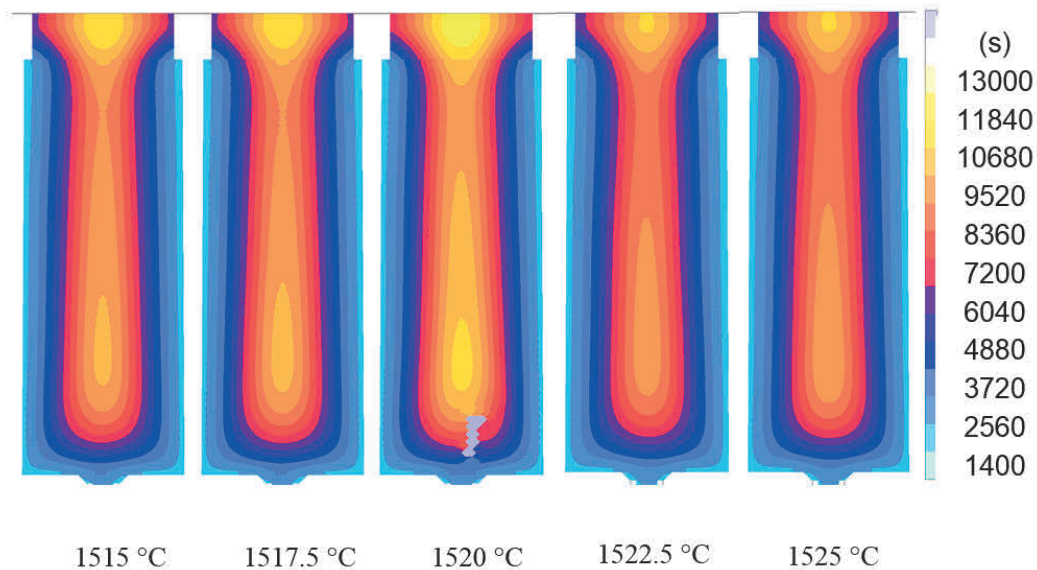|					(%)
					1525
					1524
					1523
					1522
					1521
					1520
					1519
					1518
					1517
					1516
1515 °C	1517.5 °C	1520 °C	1522.5 °C	1525 °C	1515

Figure 8 Microporosity in T90H100.11 numerical simulation ingots, with casting temperatures 1515-1525 °C, range 0-5 %
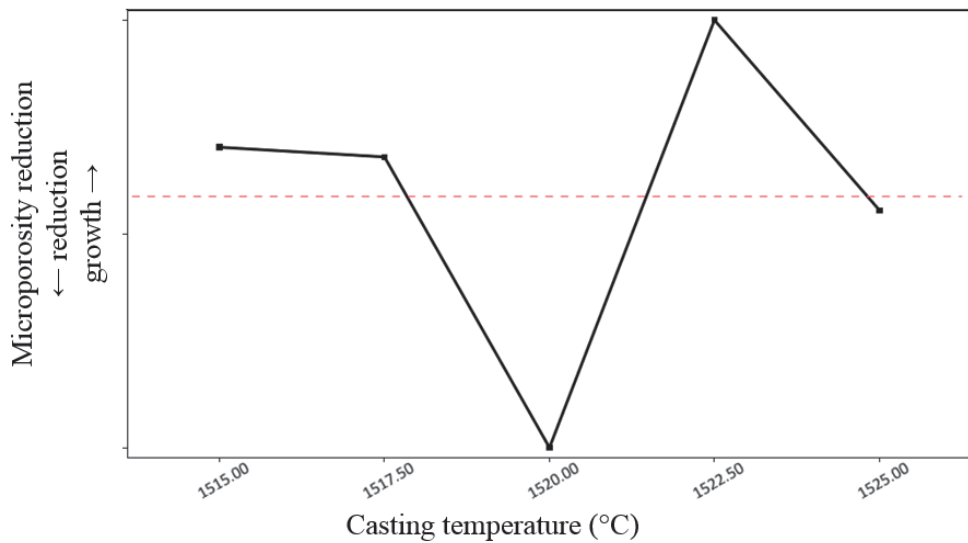
Figure 9 Effect of casting temperature on porosity reduction for T90H100.11, with casting temperatures 1515-1525 °C


Figure 10 Solidification time in individual parts of the ingot, T90H100.11, with casting temperatures 1515-1525 °C, range 1400-13000 s

3.   SOLIDIFICATION RESEARCH

Together with the numerical simulation of casting and solidification in Magma 5.4 software, an initial examination of the temperature field and stress state in the course of ingot cooling was carried out in Forge NxT 2.1 numerical software. The examination of the temperature field and stress state was carried out for the N.3 version. The set consisting of the ingot, head extension and casting pad designated for simulation was imported from Magma software right after the solidification of the entire ingot, thus after cooling of the entire ingot to the temperature of a solid. Non-transferred parts and parts from Magma were defined by the marginal conditions describing the thermal flux from the ingot to the surrounding elements (moulds) and the environment, and also by the marginal conditions including gravity, friction and expansion.

Figure 11 shows the initial temperature field of the ingot and casting pad, N.3 version ranging from 171-1407 °C. At the beginning of cooling the head extension has a homogeneous temperature field of 1100 °C due to the disruption of geometry caused by solidification in Magma software - the creation of a shrinkage cavity during solidification.

Distribution of the temperature field in the ingot after 5 hours within a temperature range of 20-821 °C is presented in **Figure 12**. On the left side of the figure, the ingot is cooled in the air; on the right side, the ingot is cooled in the mould. It applies to both types of ingot cooling that the hottest part of the ingot during solidification is in its central part. At the same moment, 5 hours after solidification, **Figure 13** shows the distribution of effective stress (von Mises), which characterizes stress intensity. On the left side of the figure, the ingot is cooled in the air; on the right side, the ingot is cooled in the mould. It is obvious from the figure that the largest stress is in the ingot cooled in the air, namely in its surface layer at the footing and just under the head extension. This corresponds to the lowest stress in the ingot which is located in the ingot axis at the footing and just under the head extension.
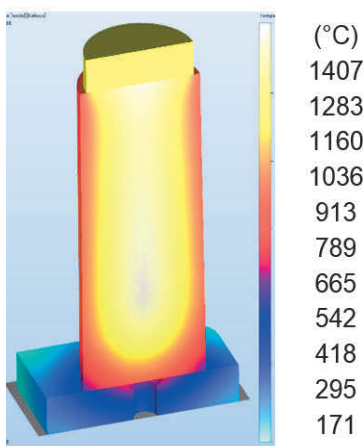
Figure 11 Initial temperature field of ingot, version N.3, range 171-1407 °C
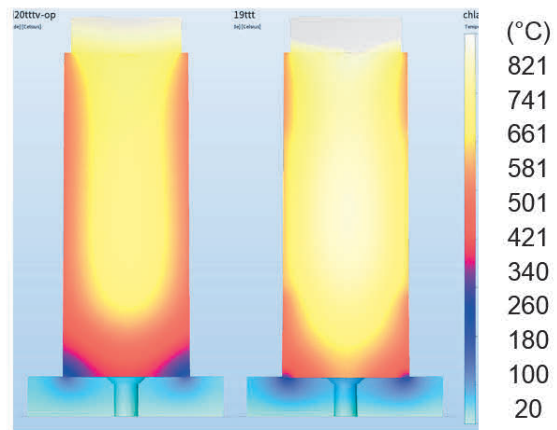
Figure 12 Temperature field of ingot after 5 hours of cooling (left in the air, right in the mould), version N.3, range 20-821 °C
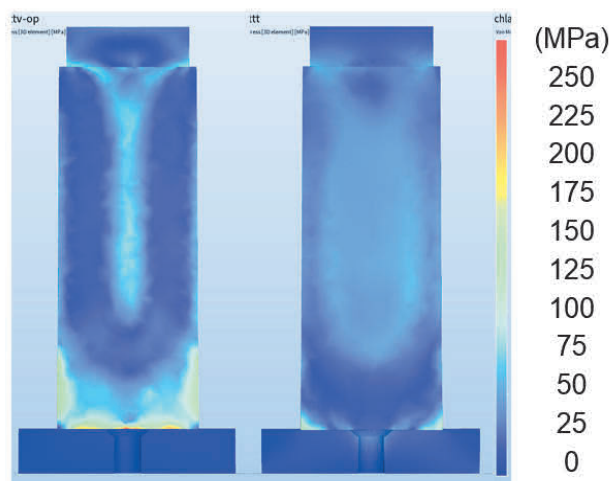
Figure 13 Distribution of effective stress in ingot, range 0-250 MPa

Effective stress distribution (von Mises) in ingot after 5 hours of cooling (left on the air, right in the mould), version N.3, logarithmic range 0-265 MPa

4. CONCLUSION

The submitted work presents basic knowledge from the area of large circular ingot casting obtained using Magma 5.4 numerical software. For the basic variant cast in Magma software, an initial examination was carried out of the temperature field and stress state during ingot cooling in numerical software Forge NxT 2.1.

It results from the performed numerical simulations of casting and solidification of the 12 t circular ingot that as concerns reducing microporosity at the selected temperature of 1520 °C, the most suitable numerical simulation chosen was that marked N.3, this being the originally suggested one. It has been proved that a change in speed of the ingot body casting has a greater positive influence on microporosity than a change in speed of head extension casting. To find out whether it really is the best variant, an examination of N.3 was carried out where the casting speed was decreased and increased in the ingot body by 10 %. It resulted from this that at the same speed of the head extension casting, it is more advantageous to cast the ingot 10 % more slowly (version marked T90H100.11) than the initially proposed N.3. For this T90H100.11 version, the most suitable casting temperature was 1520 °C.

It results from the performed primary examination of the numerical simulation of the temperature field and stress state in the ingot being cooled down in Forge software that when cooling the ingot in the air, large stress occurs in the surface layers of the ingot, namely up to 250 MPa in the parts which solidified first.

ACKNOWLEDGEMENTS

REFERENCES

[1] WANG, J., FU, P., LIU, H., LI, D., LI, Y. Shrinkage porosity criteria and optimized design of a 100-ton 30Cr2Ni4MoV forging ingot. *Materials and Design*. 2012, vol. 35, pp. 446-456.

[2] HONGHAO, G., FENGLI, R., JUN, L., XIUJUN, H., MINGXU, X., JIANGUO, L. Four-Phase Dendritic Model for the Prediction of Macrosegregation, Shrinkage Cavity, and Porosity in a 55-Ton Ingot. *Metallurgical and materials transactions a*. 2017, vol. 48A, pp. 1139-1150.

[3] WU, M., LUDWIG, A., KHARICHA, A. A four phase model for the macrosegregation and shrinkage cavity during solidification of steel ingot. *Applied Mathematical Modelling*. 2017, vol. 41, p. 102-120.

[4] CHVOJKA, J. *Vady ingotů*, 1st ed. Praha: SNTL, 1968. 256 p.

[5] ŠMRHA, L. *Tuhnutí a krystalizace ocelových ingotů*, 1st ed. Praha: SNTL, 1983. 308 p.

[6] PINDOR, J., KURKA, V., KOSŇOVSKÁ, J., ŠTEFANIŠINOVÁ, Š., SOCHA, L., PYSZKO, R. Effect of Cooling of the Ingot on its Macro-structural and Chemical Heterogeneity. *Hutnicke listy*. 2017, vol. 70, no. 3, pp. 47-57. ISSN 0018-8069.