INTENSIVELY COOLED INGOT DURING CASTING AND SOLIDIFICATION AND ITS INTERNAL HOMOGENEITY PREDICTING BY USING NUMERICAL SIMULATION IN MAGMA 5 SOFTWARE

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Abstract

This paper presents intensively cooled ingot during casting and solidification and comparison of obtained results with numerical simulation in Magma 5 software. The technology of intensive cooled ingot has been developed and physically verified in MATERIAL AND METALLURGICAL RESEARCH Ltd. The results of the numerical casting simulation of the cast ingot were obtained in the Magma 5 software, which includes a new module, including the heat transfer through the flowing medium. The 1.3520Mo steel melt was cast in both cases into a V2A ingot mould set, the forging ingot weighing 1,690 kg. Intense heat removal was provided by a cooler placed on a casting plate, which became an integral part of the ingot after melt casting.

Keywords: Cooling, steel, water, simulation, structure

1. INTRODUCTION

In the MATERIAL AND METALLURGICAL RESEARCH COMPANY s.r.o. (hereinafter referred to as MMR) have been developing technologies for increasing the quality of cast materials for many years. Research and Development was focused on manufacturing technologies, alloying additives and casting parameters, followed by melt refining technology, especially under reduced pressure, see [1], and also using slag modes to increase yield, see [2] and last but not least by alloying the gaseous nitrogen into the melt. All of these works were focused on molten steel in the melting aggregate. Subsequently, the work at MMR was focused on controlling the casting process, because the casting process is generally controlled by casting temperature, casting time, and ingot mould assembly. MMR added another element, namely ingot cooling during casting and solidification. For ingot cooling, we used the knowledge and experience of the authors [3], [4], [5], [6], [7], [8], [9], [10], [11].

The technology of intensive cooling of steel casted into the ingot mould has been designed, tested and evaluated in the MMR, this technology is protected by patent no. CZ306775B6. The aim of this work was to reduce the temperature of the casting steel to eliminate the occurrence of internal porosity and segregation. Two ingots of quality 1.3520Mo were cast in this work, both ingots have the same chemical composition and the same casting temperature and casting time conditions were observed for both cast ingots. Both ingots were compared from the point of view of macrostructural and chemical homogeneity in the longitudinal axial section and three cross sections at the height of the ingot. Comparison of the heat output through the mould wall and the amount of heat dissipated from by cooling was determined. The influence of heat to change internal defects and chemical composition was compared with numerical simulation of casting and solidification in Magma 5 software. Numerical simulation in Magma 5 software was done in cooperation with Magma, using a newly module for removing heat from a cast ingot.

2. COOLING EXPERIMENTS

The technology of ingot cooling was verified on the steel quality of 1.3520 modified by molybdenum and referred to later as 1.3520Mo. The required chemical composition of the 1.3520Mo steel and the chemical composition of cast melts from the induction furnace (hereinafter IM) into the casting furnace (hereinafter CL) for both experimental melts are given in the **Table 1**.

Table 1 Required and target chemical composition of the steel grade 1.3520Mo

Steel 1.3520Mo		Chemical composition (wt%)										Tlik. (°C)
		C	Si	Mn	Cr	Mo	Cu	Ni	P	S	Al	
Requirement	min.	0.90	0.35	0.90	1.30	1.20	-	-	-	-	-	1471
	max.	1.10	0.65	1.20	1.65	1.30	0.250	0.30	0.027	0.030	0.010	1450
Melt in the CL uncooled melt		1.00	0.44	0.99	1.53	1.24	0.035	0.08	0.018	0.009	0.018	1457
Melt in the CL cooled melt		1.01	0.52	1.03	1.55	1.26	0.03	0.12	0.025	0.008	0.021	1458

First, the uncooled ingot was cast and then the intensively cooled ingot was casting under the same metallurgical conditions. The steel melt for both ingots was manufactured in IM and in both cases weighing 1750 kg. After melting the basic charge and alloying ingredients, the chemical composition control and modification of the elements content was performed by alloying to the required range. After heating melting temperature 1600 °C, the melt was cast from IM to CL. The melt was cooled to 1551 °C during pouring into the CL. The relatively high casting temperature, 94 °C above the liquidus temperature, was chosen on the basis of long-term practical experience for these types of steels, because in the low-capacity ladle the liquid steel cooled faster. Subsequently to 1 min. the melt was poured under a protective atmosphere of argon to the ingot forging mould assembly V2A type. The casting time of the ingot was 5.5 minutes and pouring time of the whole ingot was 7.2 min. In the case of a cooled ingot, the cast melt was intensively cooled from the beginning of casting. The weight of cast ingots was 1,690 kg. Both ingots solidified in the mould and after approx. 60 min. were stripped and placed in annealing furnace for 4 hours at a temperature of 770 °C followed by slow cooling in the furnace.

3. EVALUATION OF ACHIEVED RESULTS

Ingots were cut at the height into 4 samples marked I, II, III and IV, and these sections were examined. The samples were evaluated to a macro-structure perspective. Further samples were taken from the cross sections marked A, B and C. In these samples the chemical composition was determined from the centre of the ingot to its edge and macrostructure was also evaluated.

When comparing the macro-structure of the uncooled and cooled ingot, see **Figure 1**, the influence of intensive heat removal is evident, especially on the shape of the columnar crystals and the porosity, which starts at 100 mm higher in the case of the cooled ingot in the axial cut as compared to the uncooled ingot. This corresponds to the course of the melt temperature change from the liquidus temperature to the solids temperature, see **Figure 2**, numerical simulation in Magma 5 software. The cooled ingot at the bottom has a substantially displaced porosity towards the upper part, see **Figure 3**, which we value very positively. The observed dimensions of the zones on the height of the two ingots are shown in **Figures 4** and **5**. The main features of the macrostructure (the porosity and the occurrence of the columnar crystals) of the two ingots are compared in **Figure 6**.

The macrostructures show that the influence of intense cooling has significantly manifested in the bottom part of the ingot where the zone of coarse, differently oriented crystals has grown. In addition, it has been found that intensive heat removal during casting and solidification has a major effect on reducing the segregation of the C, Cr and Mo elements. The calculation of the heat balance showed that approximately 20 % of the heat was removed from the cooled ingot than from the uncooled ingot. The highest heat removing was at the bottom of the cooled ingot.

The evaluation of the ingot macrostructure showed that in both cases the porosity was closed - the melt under the head extension has solidified before the ingot body. It follows that the head extension does not sufficiently fill the filling function of the molten metal to the ingot. Based on this finding, the shape and size of the head extension has been optimized.

Figure 1 Macrostructure in the axis of uncooled and cooled ingot

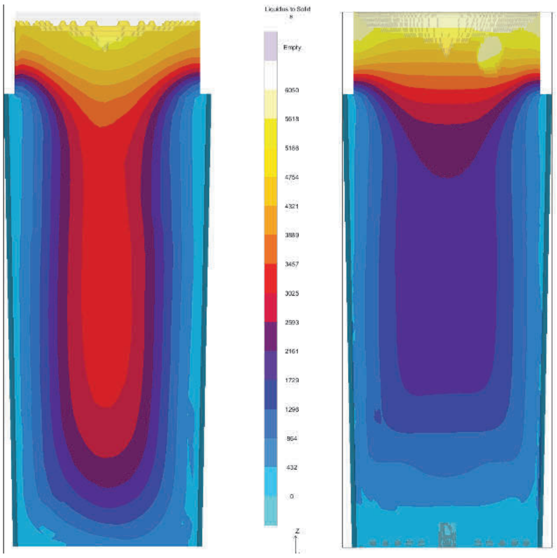

Figure 2 Solidification of molten steel Quality 1.3520Mo from liquidus to solidus temperature, for uncooled and cooled ingot in software Magma 5

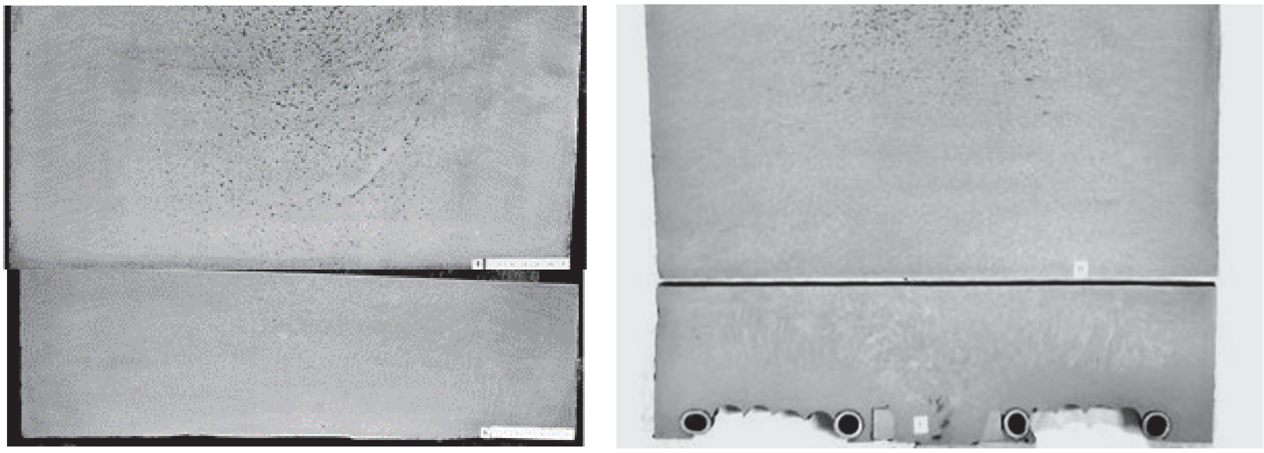

Figure 3 Macrostructure in the axis of uncooled and cooled ingot, detail of the bottom part of ingots

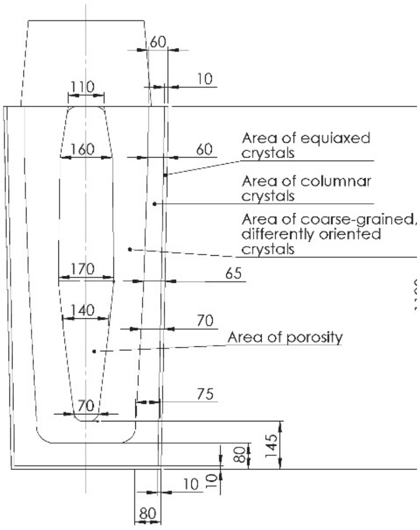

Figure 4 Schematic analysis of macrostructure in the axis of uncooled

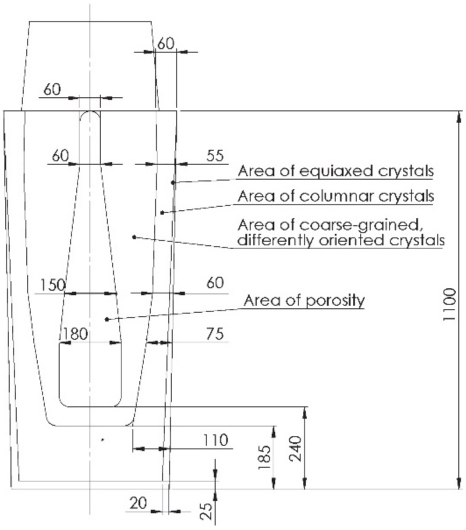

Figure 5 Schematic analysis of macrostructure in the axis of cooled ingot

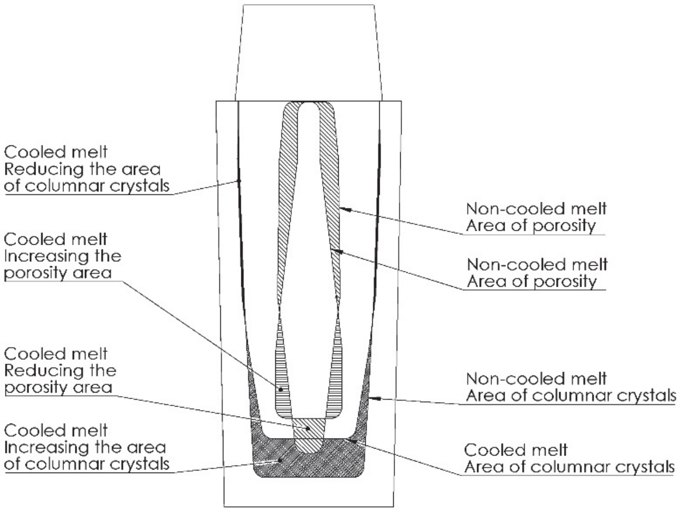

Figure 6 Schematic analysis of macrostructure in the axis of uncooled and cooled ingot

4. EVALUATION OF CHEMICAL COMPOSITION

Comparison of the uncooled and cooled ingot shows that at the bottom part the C, Cr and Mo elements have a very low negative segregation due to the intense heat transfer from the melt when the ingot is solidified. A smaller difference of segregation is observed in the middle of the ingot height. Conversely, in the section below the head extension, the segregation of C and, above all, of Cr and Mo is lower for the cooled ingot than for the uncooled, see **Table 2**. The course of the carbon concentration in the ingot's bottom part both in the experiments performed and in the numerical simulation in Magma 5 is identical, see **Figure 7**.

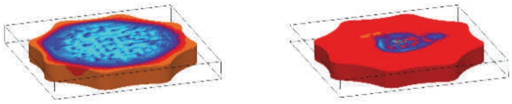

Figure 7 Course of the content of carbon in cross-section of the uncooled and cooled ingot, in the bottom part of ingots, in software Magma 5, range 0.850 to 1.100 % C

Table 2 Chemical composition of the samples in cros-section A, B and C of the ingots - the first measurement

Sampling site	Indication	Element content (wt%)						Coefficient of segregation (1)					
		C		Cr		Mo		C/Co		Cr/Cr		Mo/Mo	
		un-cool.	cool.	un-cool.	cool.	un-cool.	cool.	un-cool.	cool.	un-cool.	cool.	un-cool.	cool.
Bottom part	A1	0.95	1.01	1.52	1.54	1.25	1.30	0.95	1.00	0.99	0.99	1.01	1.03
	A2	0.98	1.01	1.52	1.54	1.27	1.29	0.98	1.00	0.99	0.99	1.02	1.02
	A3	0.99	1.01	1.53	1.54	1.28	1.29	0.99	1.00	1.00	0.99	1.03	1.02
	A4	1.03	1.02	1.54	1.55	1.28	1.30	1.03	1.01	1.01	1.00	1.03	1.03
	A5	1.03	1.03	1.55	1.56	1.30	1.31	1.03	1.02	1.01	1.01	1.05	1.04
Ingot	B1	0.97	0.97	1.50	1.50	1.23	1.22	0.97	0.96	0.98	0.97	0.99	0.97
	B2	1.00	0.99	1.51	1.52	1.24	1.26	1.00	0.98	0.99	0.98	1.00	1.00
	B3	1.02	1.01	1.54	1.55	1.28	1.29	1.02	1.00	1.01	1.00	1.03	1.02
	B4	1.03	1.04	1.55	1.55	1.29	1.30	1.03	1.03	1.01	1.00	1.04	1.03
	B5	1.03	1.02	1.55	1.56	1.29	1.31	1.03	1.01	1.01	1.01	1.04	1.04
Under the head extension	C1	1.01	1.01	1.51	1.54	1.22	1.30	1.01	1.00	0.99	0.99	0.98	1.03
	C2	1.01	1.03	1.52	1.55	1.26	1.32	1.01	1.02	0.99	1.00	1.02	1.05
	C3	1.02	1.04	1.55	1.56	1.30	1.33	1.02	1.03	1.01	1.01	1.05	1.06
	C4	1.01	1.04	1.55	1.56	1.28	1.31	1.01	1.03	1.01	1.01	1.03	1.04
	C5	0.99	1.01	1.55	1.56	1.29	1.31	0.99	1.00	1.01	1.01	1.04	1.04
Melt in in the CL		1.00	1.01	1.53	1.55	1.24	1.26	-	-	-	-	-	-

5. EVALUATION OF THE THERMAL BALANCE

For uncooled and cooled ingots, the thermal balance of the ingot mould set was determined. The heat from the surface of the ingot mould, the heat accumulated in the mould wall and the head extension, the heat produced by the cooling medium, and the enthalpy of the ingot was finally determined.

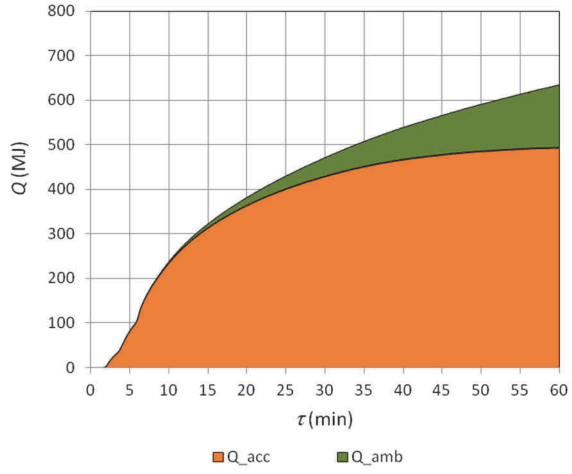

Figure 8 Items of thermal score of non-cooled ingot

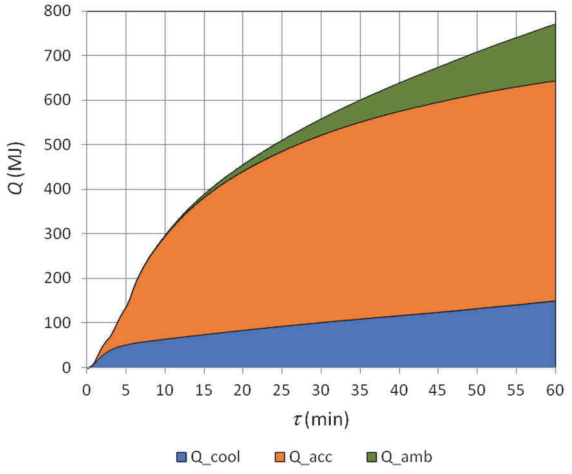

Figure 9 Items of thermal score of cooled ingot

In the graphs **Figure 8** and **9**, the individual colors represent the heat accumulated in the wall of the ingot mould set Qacc (J), heat abduced to the surroundings Qamb (J) and heat abduced by the cooling medium Qcool (J) as a function of time. The total height of all areas represents approximately the loss of the enthalpy from the ingot in the neglect of the heat of other heat items Qoth. Comparison of the heat balances of uncooled and cooled ingot results in about 20 % more heat to be removed from the cooled ingot than the uncooled ingot for the same time period, i.e. 772 MJ of the cooled ingot versus 635 MJ of the uncooled ingot.

6. CONCLUSION

The macrostructural characteristics, the chemical heterogeneity analysis of the 1.3520Mo steel ingot and the numerical simulation in the Magma 5 software show that the influence of the intense cooling of the cast ingot manifested itself greatly in the bottom part of the ingot, where the zone of the columnar crystals increased. The evaluation of the macrostructure also shows that the cooled ingot compared to the uncooled ingot has a significant porosity shift to the upper part of the ingot. However, for both ingots, the porosity of the ingot body was closed, which is related to the insufficient insulation of the head attachment.

The head extension is solved separately. Comparison of the chemical composition in ingot cuts by height and cross-section shows that the intense heat removal during casting and solidification has a major effect on reducing the segregation of the C, Cr and Mo elements.

Thermal balances showed that approximately 20 % of the heat was removed from the cooled ingot more than from the uncooled ingot. The highest increase in heat output was found at the bottom part of the ingot.

ACKNOWLEDGEMENTS

This paper was created in the Project No. LO1203 "Regional Materials Science and Technology Centre - Feasibility Program" funded by Ministry of Education, Youth and Sports of the Czech Republic. The work was carried out within the scope of the project "Support of Science and Research in the Moravian-Silesian Region 2015"".

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