THE DEVELOPMENT OF HOLLOW INGOT CASTING TECHNOLOGY AT VÍTKOVICE HEAVY MACHINERY A.S.

Pavel MACHOVČÁK, Aleš OPLER, Zdeněk CARBOL, Martin KORBÁŠ, Marek KOVÁČ, Vladimír KRUTIŠ

a) VÍTKOVICE HEAVY MACHINERY a.s., Ruská 2887/101, Vítkovice, 703 00 Ostrava, Czech Republic, pavel.machovcak@vitkovice.cz

b) MECAS ESI s.r.o., Technická 15, 616 69 Brno, Czech Republic, marek.kovac@mecasesi.cz

Abstract

Development of hollow ingot casting technology began in VÍTKOVICE HEAVY MACHINERY a.s. based on the growing demands for production of large hollow forgings, i.e. in particular shells, or hollow rings and pulleys. The use of hollow ingot as a semi-finished product for the production of forgings mentioned above brings not only economic efficiency but also achieves better quality parameters in the final forgings. Forging properties are more homogeneous in all directions and the scale of the macro-segregation is significantly lower than in case using conventional ingots. Forgings can then be used for the most demanding requirements, including applications for nuclear power because of their greater safety and durability. Numerical simulations of casting and solidification were used during the development of hollow ingot casting technology. The final variant of casting system, which has been verified in practice, was chosen just based on these simulations. This paper describes experience with the introduction of hollow ingot casting technology and evaluation of the first tests of hollow ingots.

Key words: hollow ingot, ingot casting, macro-segregation, numerical simulation, test experiment

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 consistently high quality. Among all forged parts, the rings or the shells for press vessel is traditionally made by removing the center part of the conventional ingots. It is well known that this work is not efficient process to make the rings or shells. Therefore, it is expected to save the processing cost and energy, improve the product yield to make the forged rings and shells when the hollow ingot with a hollow center is used. However, the main reason for the development of this new type of ingot was significant reduction of “A” segregation in the ingot and consequently in final forging. This is especially important for forgings for the most demanding requirements. These include forgings for nuclear power and petrochemical industry, i.e. shells for steam generators, pressurizers and reactor vessels. The use of hollow ingots as a semi-finished product for cylindrical forgings brings the following additional benefits. In summary: hollow ingots takes less time to raise to forging temperature, by virtue of their smaller effective cross section; they require fewer forging operations, because the upsetting and punching steps become redundant. This is shown schematically in Fig. 1. It is stated that it is possible to achieve following savings by using of hollow ingot instead classic, conventional forging ingot for forging large shells:

-Forging yield: up to 35 % reduction of weight
-Manufacturing time: up to 3 times less forging sequences when considering large shells issued form heavy ingots requiring efficient blooming to consolidate properties
Environmental and energy costs: significant cut in CO₂ gas emission (up to 50 %) due to the shortening of the forging program and the reduction in weight

![Diagram of forging process](image)

**Fig. 1:** The conventional cylindrical forging route compared to that of the hollow ingot [1]

The development of hollow ingot casting technology was launched for the first time probably at Sheffield Forgemasters International Ltd. in the United Kingdom already in the 50th 20th century. Subsequently, the development of hollow ingot and its production started in AREVA Creusot Forge in France, in Kawasaki Steel Corporation in Japan and in POSCO in Republic of Korea. [1,2,3] VÍTKOVICE HEAVY MACHINERY a.s. (further also VHM) began development of hollow ingot casting technology based on the increasing demand for the production of hollow forgings, not only the above mentioned forging for nuclear power but also for other hollow forgings for different customers.

2. **NUMERICAL SIMULATIONS – TOOL FOR IMPROVEMENT OF PRODUCTION OF INGOTS**

The optimum design of the hollow ingot mold, number of inlets, and material and shape of core is necessary to produce hollow ingot in the required quality. Work on numerical simulations started after the literary analysis of available information on the production of hollow ingots. Ingot weighing 57 tons was chosen for the first trial. Numerical simulations were performed by MECAS ESI s.r.o. Their casting software ProCAST was used for these numerical simulations.

The core of hollow ingot casting system should be continuously and uniformly cooled because this core is always in contact with the molten steel directly all around its periphery. Heat transfer must be uniform both from the outside, it is from the mold, as well as from inside, it is from the core. Only under these conditions will be metallurgical center of the hollow ingot in the middle of the wall thickness the ingot. A number of potential core materials with different shapes and a number of potential cooling media were tested in these simulations. Sand, hematite and low carbon manganese steel were tested as a material for core of hollow ingot. Two main types of core were designed. The first type was solid core that has a hole in the center and the cooling medium is able to flow through the hole in the center of the core. The second type is two steel pipes with the gap. This gap between two pipes is an expansion gap and is necessary during shrinkage of inner diameter of ingot during its solidification. Different bevel of the core was also considered. Air, nitrogen...
and water were considered as a cooling medium at different intensities in these numerical simulations. The course of casting and solidification of hollow ingot were investigated during numerical simulations, porosity prediction and macro-segregation decomposition was also determined. Simulation of contact pressure on the core was performed due to find out whether the core will be able to remove after solidification of hollow ingot. Numerical simulations have also shown that the core must be very well treated before casting because it must be able to resist high temperature. The core temperature reaches almost 1 000 °C during solidification of hollow ingot, although it is actively cooled. The course of solidification of 57 tons hollow ingot at 10 000 seconds is shown in Fig. 2. This figure shows that course of solidification is uniform and metallurgical center is in the middle of the hollow ingot wall.

Fig. 2: Fraction solid during solidification of hollow ingot weighing 57 ton at 10 000 seconds

The number of inlets is one of the important factors to uniformly fill the molten steel in the mold. In the case of conventional ingot, the molten steel is filled through an inlet located in the middle of bottom part of mold. However, the location of inlet or inlets should be changed from the middle to any other position because of the core located at the center of the mold. To find the optimum number of inlets, numerical simulations by using various numbers of inlets from 2 to 4 were performed. Based on the results of these simulations, the molten metal is stably filled for 2 inlets design, while in case of 3 and 4 inlets design, filling of mold with liquid steel was not stable. This different behavior is due to the filling rate depending on the number of inlets.

Numerical simulation with emphasis on the distribution of selected important elements macro-segregation after solidification was also carried out. Boundary conditions of this simulation were set according to real casting conditions of experimentally cast ingot in VHM. Real chemical composition of used heat, casting temperature and casting speed, mold temperature and real temperature around the casting system were used for this numerical simulation. On Fig. 3 are shown the distribution of carbon (left picture) and manganese (right picture) on cross section of 57-ton hollow ingot. It’s always a half of hollow ingot, i.e. left side represents the core of the hollow ingot, right side is mold wall. These results were compared with real distribution of selected chemical elements.

Works on the design of larger hollow ingots (more than 100 tons) were initiated after verification of the production of 57-ton hollow ingot and its evaluation. These ingots are already prepared for specific order for
nuclear power. Delivery of several shells from steel grade 10Gn2MFA weighing 70 – 113 tons is required. For this reason, casting systems for hollow ingots weighing 118 – 140 tons were proposed. From previous experience with forging of 57-ton hollow ingot raised the demand for the same wall thickness along the height of the hollow ingot. Therefore, the core shape was modified. The new core bevel is approximately the same as the bevel of mold. Also in this case, different core shapes and different ways of cooling the core were tested during numerical simulations, so that prevent to its melting and to enable remove the core after solidification of the hollow ingot.

![Fig. 3 Macro-segregation of carbon (left) and manganese (right) over the cross section of hollow ingot – steel grade S355J2G3 (ladle analysis: C 0.21 %; Mn 1.29 %)](image)

3. HOLLOW INGOT CASTING EXPERIMENT

Based on the results of numerical simulation the best variant was chosen for experimental casting of 57-ton hollow ingot. Generally is recommended height-diameter ratio H/D close to 1.0 and also in the case of our experiment we kept this recommendation. This type of molds is enough wide that it is possible insert the core inside. Steel grade S355J2G3 was chosen for first experimental castings of hollow ingot due to reduce the cost of these experiments. Standard steel production technology at EAF, LF and VD was used for these trial heats. Very important is casting speed. This parameter is set up especially with regard to forced heat transfer through core. In general, the hollow ingot casting speed is lower than in case of conventional ingots. There is a risk of formation of crack on the inside diameter of the ingot at higher casting speed. Two 57-ton experimental hollow ingots were cast at steel plant VHM a.s. In Fig. 4 is shown hollow ingot after striping at steel plant. First experimental ingot was forged into forging with three different diameters, see Fig. 5. It was done in order to investigate the influence of the forging ratio on the properties of forged shell. Three forging ratios were used: 2, 3 and 4. Ultrasonic examination was done on this forging according to SEP 1921, level E/e. Only one indication was found. It was on the place of original surface crack on the internal diameter. Results of the ultrasonic examination confirmed the literature data that it is possible to reduce the forging ratio to only two when hollow ingot is used. After careful evaluation of the first experimental ingot was cast second hollow ingot of the same type. Casting speed and casting temperature were decreased during casting of the second experimental hollow ingot to reduce the risk of cracking. These two major changes of technological parameters led to successful production of hollow ingot without any defects. This ingot was
forged into shell with outer diameter of 1570 mm and internal diameter of 930 mm. Wall thickness was the same along entire high in this case and was 320 mm. Total length of this forging was 4000 mm.

**Fig. 4** A 57-ton hollow ingot after stripping at steel plant VÝTKOVICE HEAVY MACHINERY a.s.

**Fig. 5** Drawing of the forging from the first trial hollow ingot
4. RESULTS AND DISCUSSIONS

The material S355J2G3 was used for both experimental hollow ingot. Targeted production chemical composition and cast analysis of both trial heats is shown in Table 1. Evaluation was carried out on samples from forgings. Fig. 5 shows locations of sampling from first experiment. Evaluation of macrostructure, chemical composition on cross section, determination of the content of non-metallic inclusions were performed as well as determination of mechanical properties such as tensile test, Charpy impact test at different temperatures, Brinell test in three mutually perpendicular directions. This would give us information about isotropy of the properties of material.

Table 1: Ladle analysis of experimental heats

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>min.</td>
<td>0.19</td>
<td>1.20</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.020</td>
</tr>
<tr>
<td>max.</td>
<td>0.22</td>
<td>1.35</td>
<td>0.30</td>
<td>0.012</td>
<td>0.005</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.08</td>
<td>0.040</td>
</tr>
<tr>
<td>Heat 1</td>
<td>0.21</td>
<td>1.24</td>
<td>0.25</td>
<td>0.005</td>
<td>0.004</td>
<td>0.13</td>
<td>0.23</td>
<td>0.17</td>
<td>0.07</td>
<td>0.032</td>
</tr>
<tr>
<td>Heat 2</td>
<td>0.21</td>
<td>1.29</td>
<td>0.27</td>
<td>0.008</td>
<td>0.002</td>
<td>0.13</td>
<td>0.13</td>
<td>0.08</td>
<td>0.04</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Macrostructure of all samples was similar, uniform without significant structural anomalies. Also inclusion content was very low. Chemical analyses were carried out over the cross section of samples, so we get information about the distribution of the segregation through wall thickness after forging. Content of carbon, manganese, phosphorus and sulfur was analyzed. Performed analysis shows that the samples from the bottom of the hollow ingot did not show segregation. Elevated concentrations of individual elements were detected only in the top part of ingot. However, the extent of the segregation was much less than it can be expected in case of conventional ingot of this weight. Plot of transverse carbon and phosphorus segregation are shown on Fig. 6a, 6b. These areas of segregation were predicted using numerical simulation. Chemical analysis of these elements shows that metallurgical center of hollow ingot is not directly in the middle of ingot wall but it is shifted closer to the core. This is caused by lower heat transfer through the core.

![Plot of transverse carbon segregation pattern](image1)

![Plot of transverse phosphorus segregation pattern](image2)

**Fig.6** Plot of transverse carbon and phosphorus segregation pattern

Further, tensile test in three mutually perpendicular directions at a temperature 20 °C and impact-strength test at 20 °C, 0 °C, -20 °C, -40 °C and -60 °C were performed. These tests showed isotropic properties of evaluated material.
CONCLUSION

The hollow ingot production route is capable of producing material with excellent segregation characteristics. Design of casting system for new ingot type was performed based on the results of numerical simulations. The technology of hollow ingot casting was successfully verified in practice. Hollow ingot weighing 57 tons was cast at steel plant VÍTKOVICE HEAVY MACHIENRY a.s. Predicted area of segregation were confirmed during subsequent analyzes. Significantly lower extent of segregation and better homogeneity of the properties was demonstrated during the investigation. Furthermore, 120 tons hollow ingot casting system was designed based on the experience with development and production of the first type of hollow ingot.

ACKNOWLEDGMENTS

We would like to express thanks to the Ministry of Industry and Trade of the Czech Republic for the financial support within the frame of the project TIP No. FR-TI3/243

REFERENCES

