Process development of Ingot casting using simulation approach

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Abstract

The current article provides an overview of a possible new approach to cover problems of mold failure during an ingot casting production. Due to the high thermal loads subjected on the mold during the casting process, cracks can appear after some production cycles. A modeling approach to understand the crack formation by casting simulation is presented. The simulation takes into account the internal stresses during the mold production and shows how these stresses further develop during a number of ingot casting production cycles. The simulated stresses are analyzed in detail and compare well with the location of the observed cracks. An outlook shows how the investigations will proceed to identify technical measures to reduce mold failure.

Keywords

ingot casting, casting simulation, stress simulation, residual stress, crack formation, mold failure, ProCAST

Introduction

Many of the advanced ingot casting manufacturers, have already applied casting simulation for ingot production in the recent years. The main focus of such modeling approaches is typically focused on the quality of the ingot casting including porosity & inclusions, and also micro structure & residual stresses.

Simultaneously another important aspect of an ingot casting production is the mold itself, used to make the ingots. The ingot casters are highly interested in this mold behavior during the ingot production. The mold is subjected to a high thermal loading during the casting process, inducing stresses, resulting in significant wear, which could in turn lead for specific ingot geometries, an early mold failure. The work presented here covers initial attempts to address ingot casting quality from the viewpoint of the mold by means of casting simulation.

Different technical aspects in the ingot manufacturing process

The manufacturing sequence of an ingot production can be technically divided into two main stages. In the first stage, the mold made of cast iron, is produced by a sand casting process. In the second stage, this mold is used for ingot casting in a gravity die casting process.

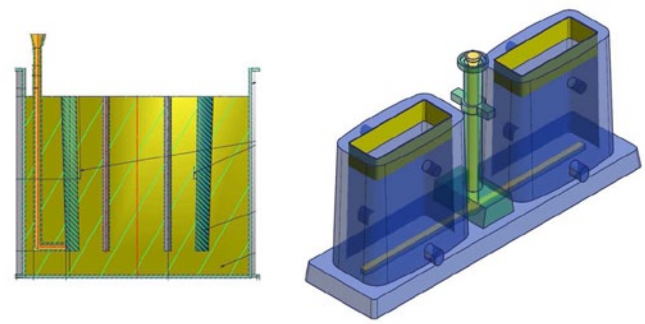

***Figure 1**: Manufacturing setup for the ingot mold casting in a sand mold (left sectional view) & manufacturing setup of a twin-cavity ingot casting process (right).*

Cast iron with lamellar graphite, in which the graphite occurs in the form of thin irregularly shaped lamellae, is used for the ingot mold for several reasons. At first, the process has a good castability even in rough industrial environments. No great efforts need to be put in the process handling. Further advantages of lamellar structure for the given application are in particular high compressive strength, vibration damping and resistance to corrosion.

Finally the most important mold-property, playing a role in the next step for the steel-ingot casting quality is the thermal conductivity of the iron mold. The thermal conductivity of cast iron depends mostly on two factors: Firstly, the amount and form of excreted graphite, since graphite has a decisive influence on heat transfer: compact forms of graphite (nodular, vermicular), reduces the thermal conductivity, while lamellar graphite has the highest thermal conductivity. Secondly, the alloy composition of cast iron, where silicon has the greatest influence: higher percentage of silicon, lower the thermal conductivity. In order to achieve good results for the steel-ingots, it is extremely important to understand the behavior of the mold, representing the ingot geometry, as well as the influence of the thermal conductivity of the mold on the cooling behavior and hence also the microstructure of the steel-ingot. Unmindful modifications of the mold geometry or steel casting process can lead to immense economic harm. Therefore any alteration should be examined carefully (simulation and – if possible – laboratory testing) before the actual application on the shop floor.

The occurrence of cracks in the mold should be avoided for two reasons:

- **The quality of the steel-ingot suffers from the cracks.** Minor scratches on the ingot-surfaces, caused by the cracks in the mold, can lead to serious damage of the ingot. Extensive repair would be the only solution, though; there is a high risk of a whole ingot failure.

- **To have an extended mold-lifetime.** The initial crack development in the mold, will lead to a subsequent mold failure after a few production cycles. The cracks need to be repaired during the initial stages, to avoid any further propagation. Cracks are usually filled with a special sealant. Repair / replacement of the mold however, represent a major cost factor.

For the production of ingot casting, both the molds, which are open on both ends, are placed on a (also cast iron) bottom plate. The bottom plate is equipped with a filling system to have a bottom-up less turbulent ingot filling. This avoids to a great extent, oxide inclusions, which are mostly formed due to possible over-lapping of molten metal free surfaces, during top pouring. The simulation and optimization approaches for the ingot production are not a focus of this article.

Figure 2 shows typical crack pattern of the selected case which appear after a limited number of ingot production cycles. The sensitivity of a certain ingot production depends largely on the specific geometry of the ingot and the mold. The crack can be observed at the inner part of the mold. While the crack is horizontal at the long side of the ingot geometry *(image on right)*, its orientation is vertical at the shorter side of the mold geometry *(image on left)*.

Figure 2*: Typical crack pattern on mold after a limited number of ingot production cycles*

The numbers of production cycles before initial cracks appear are subject to large fluctuations and depend mostly on the mold geometry. However, significant trends can be observed. Initial cracks on the mold geometry considered in this article, appear usually in a range of 25-30 production cycles. In some molds, deep cracks (even throughout the whole wall thickness) occur in the first 1-5 production cycles, which are attributed to iron casting defects coming from the previous stage.

Based on the past experience on similar ingot molds, it is observed, smaller the ratio of the side lengths of the mold, lower is the crack occurrence & greater is its lifetime. The cause for this behavior is probably a more uniform stress distribution. This could be an additional topic of investigation for the future work.

The process modeling approach

The cracks in the mold are a result of the thermal loads subjected on the mold and the corresponding internal stresses. The occurring stresses have a very unfavorable effect on the fatigue strength.

Statistical studies have shown that the alloy composition of the mold, regardless of the geometry, seems not to be a decisive factor for crack formation, as long as the composition is producing a lamellar microstructure. The effects of the alloying elements in combination with other graphite forms (nodular, vermicular) will be part of examination for future work.

Residual stresses continue to remain, even after the original cause for its occurrence (external forces, no thermal equilibrium) has been removed (mold removal, cooling down to room temperature). While presence of residual stresses can have various reasons, in the present case mainly two apply:

- **Thermal residual stress (first type)**: When cooling down the mold (after casting of the mold itself, as well as after ingot casting into the mold), thermal residual stresses arise because outer edges and inner core cool down at different rates, creating a natural temperature gradient. Faster cooling and shrinkage of the near-edge positions may create tensile stresses, as well as local regions exceeding the yield strength. After temperature equilibrium has been reached between surface and core, residual compressive stresses occur in the boundary area.

- **Residual stress (second type)**: Phase transformations or formation of precipitates may lead to local structural tensions (inhomogeneous microstructure). Those occur primarily on phase boundaries. Also **dislocations (third type)** must also be taken under consideration.

While modeling is often performed to address the properties of the ingot, the presented approach concentrates on what happens in the mold. This covers the modeling of the mold production itself and then the thermal and stress loads on the mold, during the ingot production. Both aspects of ingot production are addressed in this article, as well as how they can be linked together in a chain of simulations.

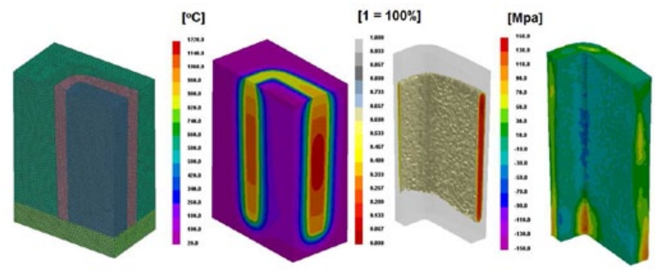

***Figure 3**: Finite Element mesh and selected simulation results of the mold production*

Figure 3 shows the FE (Finite Element) mesh of the mold production *(left side)* and selected results from the modeling of the mold production *(from left to right: temperature, fraction solid, internal stress)*. Due to the symmetrical setup of the mold geometry it was possible to simulate only one quarter of the process. Furthermore the filling of the cavity was neglected in the simulation and only thermal and stress aspects were taken into account. The area representing the mold (RB T20) was initialized with 1236 °C (casting temperature) while the surrounding sand (silica sand) had initially a temperature of 25 °C. The internal stresses after solidification and cooling down to room temperature are shown in ***Figure 3*** right side.

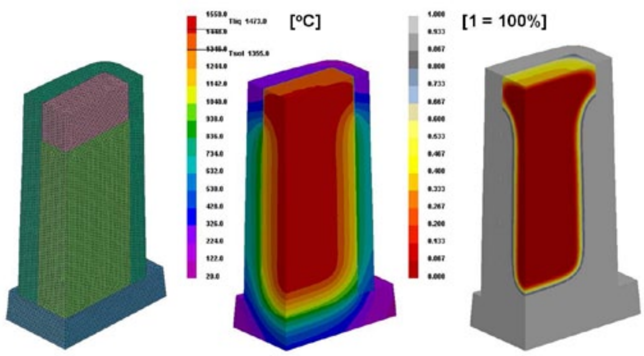

***Figure 4**: Finite Element mesh and selected simulation results of the ingot production*

Figure 4 the FE mesh of the ingot production *(left side)* and some results from the modeling; temperature *(center)* & fraction solid *(right)*. The geometry of the mold in this set-up is corresponding to the "cast" part from the previous simulation case. For the ingot, typical standard steel properties were taken (casting temperature 1550 °C). By analyzing temperature field and solidification behavior, the influence of the insulated material in the top region of the mold, helping longer feeding can be observed. While the cast alloy is cooling down faster at the bottom and in the middle part, the top remains hotter for a longer time.

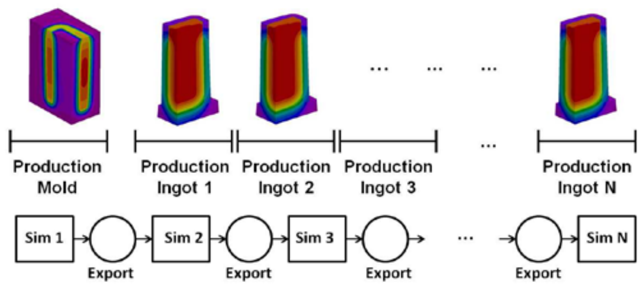

***Figure 5**: Simulation chain of mold production and multiple ingot production cycles*

Since the crack problems appeared not in the first ingot casting but after a limited number of ingot production cycles it was necessary to follow the development of internal stresses in a seamless manner. To do so, a simulation scheme shown in ***Figure 5*** was used. The first stage of the simulation is the mold production. One result of this simulation is the internal stress field after the mold reaches room temperature *(shown in **Figure 3** right side)*. This field is used in the first ingot production simulation as the initial stress distribution for the mold material. Because the FE mesh of mold production *(**Figure 3** left side)* and the mesh of the ingot production *(**Figure 4** left side)* are not identical (different number of nodes and nodal coordinates), this transfer is performed with a mapping algorithm available in ProCAST. Now the thermal and stress field of the first ingot production is simulated. Due to the thermal load from the solidification of the ingot, the stress field in the mold is modified. The stress field at the end of this cycle is used once again as the initial stress field for the second cycle and so on. As such, the distribution and the development of the stresses in several ingot production cycles can be described realistically.

Stress modeling results and analysis

In the following section, the stress results obtained by the previously described simulation scheme will analyzed.

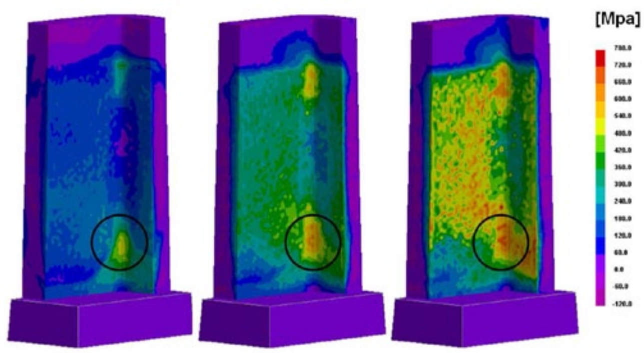

Figure 6*: Principle stress 1 in the mold after 1, 5, 10 ingot production cycles, respectively*

Figure 6 shows the principle stress 1 (component of the stress tensor with the highest value) after 1, 5, 10 ingot production cycles, respectively. Each stress state is representing the conditions at the end of the cycle which is also used to initialize the ingot production for the next cycle. It is clearly visible that the inner surface of the mold is under tension. This tension is increasing with increasing numbers of production cycles. The dominant tension area *(marked by a circle)* is near to the location where the crack *(**Figure 2**)* is crossing the inner corner of the mold in the real production process.

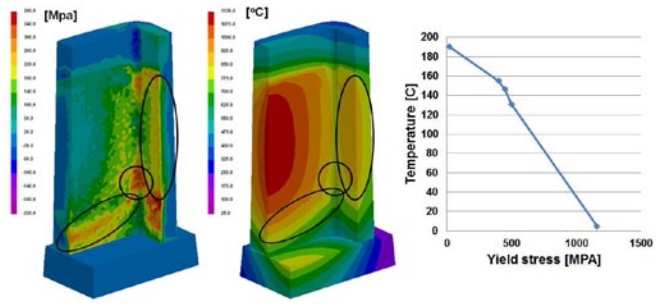

Figure 7*: Principle stress 1, temperature distribution at a selected time step together with the Yield stress of the mold material as a function of the temperature*

In order to understand the crack mechanism it is important to keep in mind that the stress fields need to be analyzed together with the temperature fields since the mechanical properties of the mold are temperature-dependent. The mold material might resist high stresses at low temperature while low stresses can already lead to a material failure when the temperature is high enough. For this reason the stress and temperature distribution at the 10th production cycle was analyzed in more detail. ***Figure 7*** shows a moment in the production time, when medium high tension values (250 MPa) appear while the temperature values in these regions are also at a higher level (around 900 ^{o}C). These marked regions *(**Figure 7**)* compare well with the crack locations observed in ***Figure 2***.

The presented casting modeling results were obtained using the ESI casting solution software - ProCAST.

Conclusion and outlook

The presented work laid out different aspects of ingot production from the viewpoint of the mold. In order to understand the reasons for crack formation caused by thermal wear, a modeling approach was applied. The stress development in the mold was investigated. Starting from the initial mold production by sand casting process, the modeling follows further internal stress distributions during several cycles of ingot production. The observed stresses compare well with the crack locations observed in production when the thermal and stress fields are analyzed keeping in mind the temperature dependent yield stress of the mold material.

These initial results will further be developed to identify technical measures to reduce mold failure. Since the mechanical properties and stress behavior of the mold are largely depending on the microstructure, it will be investigated in the future work, how the mold failure will behave using other graphite forms (including the dependence of alloy composition) and hence enable, better control of the ingot quality. Another route will be to investigate, if the thermal wear can be reduced by a better thermal management due to changes in the technical casting parameters and the mold geometry, including the ratios of the side lengths of the mold.

References

[1] Sholapurwalla, Adi; Scott, Sam (2006): Integration of Advanced Simulation Techniques with Process Development in the Modern Foundry. AFS Metalcasting Congress 2006, Paper 06-032.

[2] Samonds, Mark; Zhu, J.Z. (2003): Coupled Thermal-fluids-stress Analysis of Castings. MCWASP 2003

[3] Guo, Jianzheng; Samonds, Mark (2004): Property Prediction with Coupled Macro-micromodeling and Computational Thermodynamics. MCSP6-2004: Kaohsiung.

[4] Hasse, Stephan (2008): Giesserei Lexikon. Schiele&Schön: Leoben.

[5] Spur, Günter; Stöferle, Theodor (1987): Handbuch der Fertigungstechnik. Carl Hanser: München.

[6] Macherauch, Eckhard; Hauk, Viktor (1983): Eigenspannungen: Entstehung, Messung, Bewertung. Deutsche Gesellschaft für Metallkunde: Frankfurt am Main.