Quality Prediction of Cast Ingots

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Today, more than 90% of all steel semi-finished products are continuously cast. Ingot casting production is increasingly concentrated on special alloys and products, which can only be produced by this process and where all of the typical quality issues associated with ingot casting are accepted. Steel ingots are subsequently subject to further processing steps, the most important of which is forging.

There is no doubt that proper quality control and cost savings throughout the whole production process are key factors for a competitive production. The quality of the as-cast ingot is the starting point for all subsequent heat treatment and deformation processing. The state-of-art tool to investigate and predict product quality is simulation. With casting process simulation, it is possible to teem, solidify and cool a virtual ingot to predict e.g. shrinkage, centre-line porosity, segregation, inclusions, residual stresses and cracks that originate during casting. The simulated properties of the as-cast ingot can be transferred to a subsequent forging simulation in order to predict their influence on the quality of the final product.

This paper shows how the quality of a cast ingot can be predicted using simulation. Emphasis is laid on those casting defects that will affect the quality of the forged end-product. The simulation of ingot casting starts with tapping a steel melt of a given chemistry from a ladle. The teeming, solidification and cooling of the ingot are simulated with the casting process simulation software MAGMA5. The results of this simulation are then mapped as input to a forging simulation.

The results of the integrated process simulation illustrate the future capabilities for the virtual prediction of the quality of ingot cast and forged products.

The dominating casting process in today's steel industry in terms of tonnage is continuous casting. More than 90% of all steel semi-finished products are continuously cast. The remaining areas of application for cast ingots are to-be-forged blocks, heavy slabs and heavy blocks for seamless tubes. Although there is a decreasing need for cast ingots, they will remain a necessity for products which can only be produced through this process [1].

Steel ingots are subsequently subject to further processing steps, the most important of which is forging. There is no doubt that proper quality control and cost savings throughout the whole production process are key factors for a competitive production. The quality of the as-cast ingot is the starting point for all of the subsequent heat treatment and deformation steps. There is a need for a through-process methodology to predict possible defects and to optimize the whole process chain such that the best possible quality and lowest reject rate is obtained.

Most major quality problems in ingots originate from the casting process. Defects like shrinkage, porosity, segregation, non-metallic inclusions and cracks are initiated during teeming of the liquid steel and / or during solidification in the mould. There are various parameters of the casting process that can be modified in order to limit defects and, if not completely prevent their existence, reduce their number and appearance so that the product fulfils the quality specification.

It is of basic importance to monitor potential defects as early as possible in the production process. Subsequent processing like heat treatment and hot deformation can then be performed in an optimized way to achieve the best possible quality at lowest production costs.

Beside the quality, there is a clear need to keep the yield of the production processes as high as possible. Issues to be mentioned are e.g. the size of the hot top, lifetime of cast iron moulds, energy savings by reduction of internal scrap rates or efficient usage of proper insulation material. These aspects are taken into account directly when casting simulation is used. The production process yield can be optimized even further if as much information as possible about the cast product is transferred to the analysis and optimization of the deformation process.

Casting process simulation

Casting process simulation has been applied in foundries for almost 30 years. During this time, the simulation of casting processes has experienced significant development [2]. Particularly the simulation of steel casting is a field with a long tradition for the application of simulation. Today, casting process simulation is established as a part of daily working routines to predict casting quality in many production plants. In most cases, simulation is applied to optimize the production process. Proposed lay-outs for mould, feeders, cooling chills, the gating system and various process parameters are input into the simulation program. Afterwards, virtual casting processes are carried out in order to determine potential risks for defects and to predict material properties. The casting process can be visualized and analysed in a much more intensive and cost-saving way than would be possible with “real” experiments. Temperatures, metal velocities, flowing particles as well as the solidification process, potential defects and also material properties can be analyzed. With the simulation software MAGMA[5], the ingot quality can be predicted with a view on all the aspects that are discussed in this paper. To provide an example, fig.1 shows the temperatures at one particular point of time during teeming of a 90 t ingot.

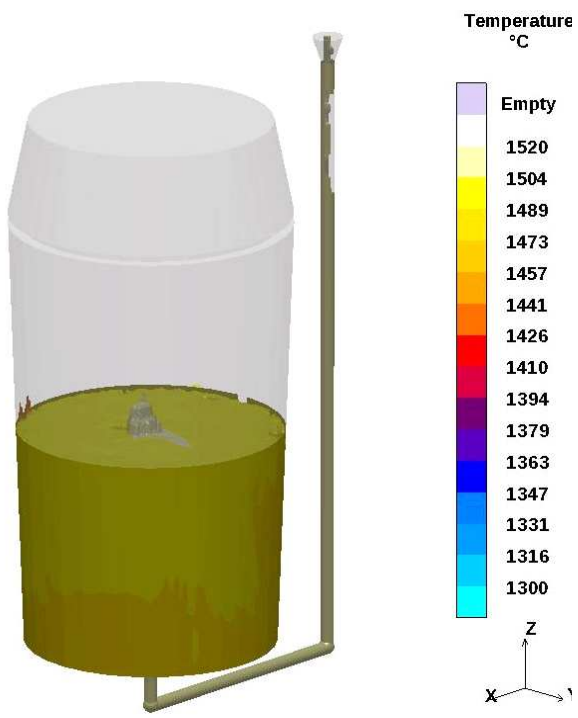

Fig. 1: With casting process simulation, the whole process can be examined in detail. This picture shows the temperature distribution inside the mould at 38% of teaming.

Defects in ingot casting

Shrinkage and porosity

The specific solidification pattern of ingots leads to a characteristic shrinkage appearance, see fig. 2. There is always a shrinkage cavity in the hot top, but it has to be assured that this primary shrinkage does not extend into the block. In case of an unfavourable solidification pattern, shrinkage can also appear inside the block, far below the hot top. Dissolved gases can also influence porosity development in a steel ingot.

In many cases, problems with centre-line porosity are reported. This porosity is small in comparison to the hot top shrinkage cavity and is found along a line in the centre of the block.

Porosity in ingot casting is influenced by various factors like insulating powder, hot top insulation, hot top geometry, ingot height and diameter (H/D), ingot conicity and so on. Depending on the size and position of porosity, it is possible to close them in subsequent hot deformation process, e.g. forging, [3].

Casting process simulation can be applied to optimize the casting process to prevent porosity from being formed. If its presence is inevitable, it is of importance to transfer information about the size and position of the porosity to the deformation simulation. There, it is possible to determine the forging process parameters that are required to close the porosity or to maximize the yield of the final product.

Macrosegregation

Segregation is an in inhomogeneity of the concentrations of alloying elements and impurities in the steel. Macrosegregation is differentiated from microsegregation dependent on the particular scale at which the concentration differences are observed. Most alloying elements are more soluble in the liquid phase than in the solid phase. Thus, as the metal solidifies, alloying elements in the mushy zone (solidifying liquid-solid mixture) are rejected from the growing solid dendrites into the neighbouring interdendritic liquid. This liquid becomes increasingly enriched with alloying elements as solidification proceeds. On the scale of the dendrites (tens to hundreds of microns), segregation results in a non-uniform solute distribution in and between the dendrite arms. This is termed *microsegregation.*

The movement of liquid melt or the liquid-solid mixture during solidification lead to a spread of these micro-scale concentration differences over larger areas up to the scale of the whole ingot or parts of it.

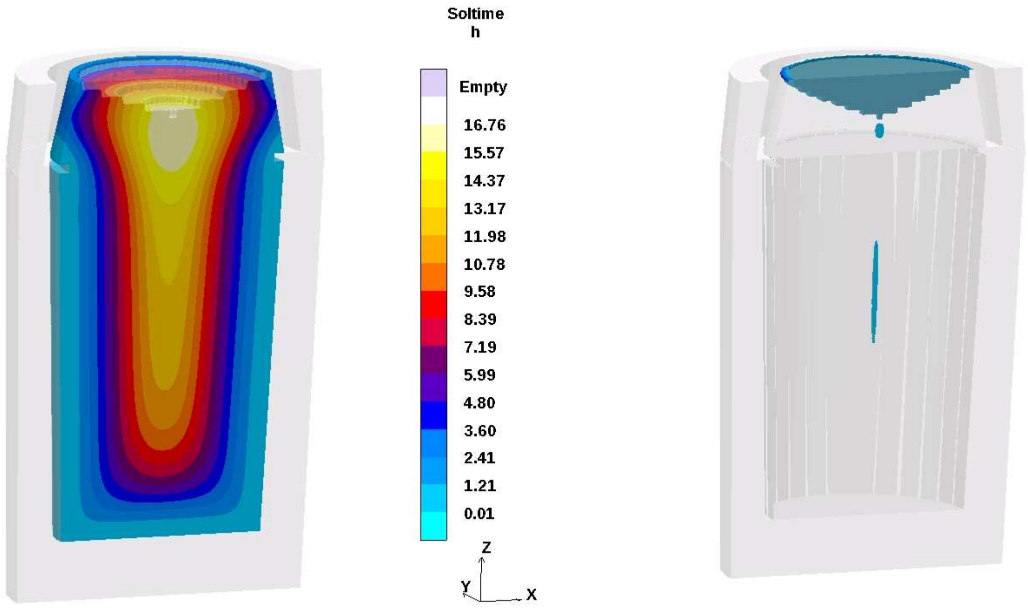

Fig. 2: Simulation allows monitoring of the solidification process in detail – the left picture shows the local solidification times for the ingot in a sliced view. The right picture shows the shrinkage cavity and the porosity that result for the given ingot under the assumed conditions

The resulting inhomogeneities in concentration are called *macrosegregation*.

The dominant mechanism for moving the liquid melt is thermo-solutal convection flow, see fig. 3. This flow is driven by local differences in temperature and chemistry that affect the local density of the melt. In addition, the growing mushy zone provides a resistance against the melt flow which increases with increasing solid-fraction.

Macrosegregation can result in a cast ingot with regions having a composition quite different from the nominal value, either being higher (positive segregation) or being lower (negative segregation). A state-of-the art model to simulate thermo-solutal convection and macrosegregation is described in [4]. This model has been extensively applied to the simulation of the solidification of heavy steel castings [5]. It has also proven to give good results in application to heavy ingots [6].

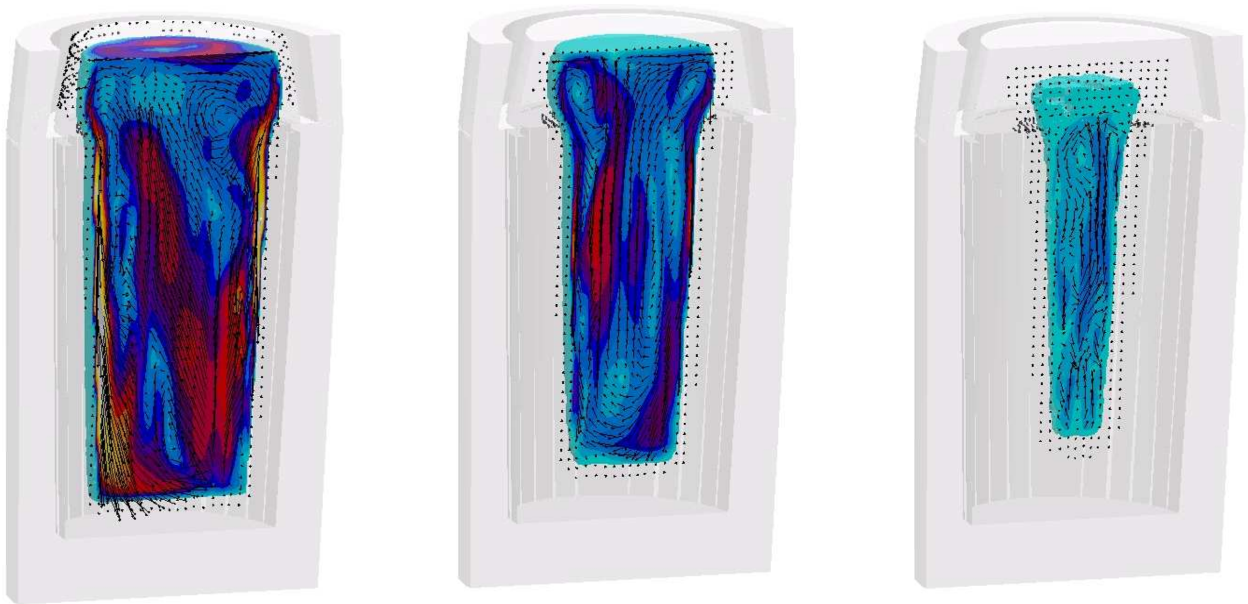

Fig. 3: With advancing solidification, thermo-solutal convection occurs in a progressively smaller area und thus is dampened by the solidifying structure. The left picture shows the convective flow velocities for the 40% solidified ingot, the middle picture shows the velocities for 65% and the right picture for 85% of solidification. Vectors illustrate the local flow directions.

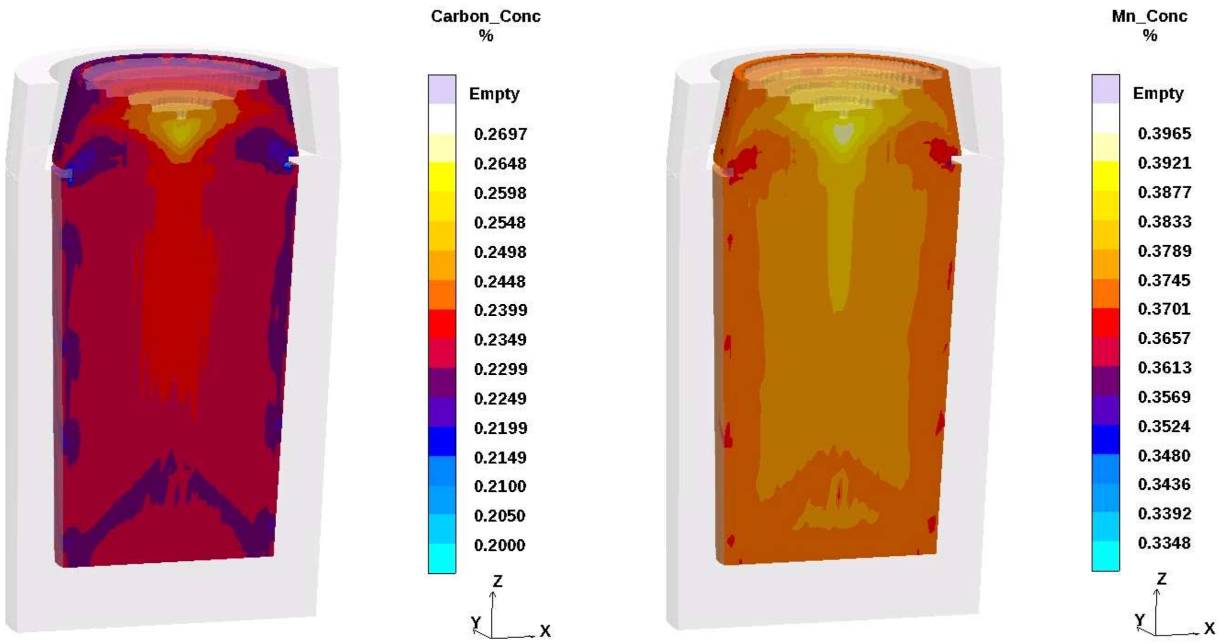

Fig. 4.: Ingot macrosegregation has a decisive importance for the cast quality. The left picture shows the concentration profile for carbon, the right picture shows the local manganese concentrations. Each element is taken care of in the simulation by taking into account its specific thermochemical behaviour at the solid-liquid phase boundary and solid diffusivity in the solidified material.

Segregations lead to locally lower material properties. The locally chemistry variations can lead to a different thermochemical behaviour, e.g. when it comes to forming precipitates or local hot spots that induce shrinkage.

Inclusions

Cleanliness is a topic of basic importance in steel production. Non-metallic (oxidic or sulphuric) inclusions lead to a local degradation in mechanical properties. For example, they decrease the ductility and fracture toughness of the steel.

Large inclusions are a reason for fatigue problems. When brittle oxide inclusions, embedded in the steel matrix, are exposed to deformation during rolling or forging, they can lead to cracks. Inclusions close to the ingot surface can cause various kinds of surface defects [4].

Inclusions can have various sources. They can be deoxidation products (carried over from the ladle), slag particles, refractory particles, particles from hot top insulation or casting powder, reoxidation products generated during casting or precipitates from solidification and cooling. The inclusion size ranges from 10 µm up to around 1 mm. It is known that the majority of those inclusions that are most critical for the steel properties are caused by reoxidation during casting. Experimental observations have shown that the fraction of reoxidation inclusions is between 60% and 83% of the total [7, 8].

The most common oxygen source for reoxidation is the exposure of the free melt surface to air during teeming. An important factor is a proper shrouding of the steel when being poured from the ladle. Nevertheless, it is of decisive importance to take care of the flow of liquid steel in the runner system and inside the mould. In many cases, the flow is highly turbulent and the steel melt enters the mould through the nozzle with a high velocity. Particularly at the beginning of the teaming process, this can lead to heavy splashing.

With casting process simulation, the flow during teeming for a combination of parameters like runners and nozzle geometries, teeming rates and temperatures, etc. can be investigated. Potential actions for process optimization can be investigated virtually. Particles can be monitored during the filling process and during their movement caused by convective flow during solidification. The formation, growth and agglomeration of reoxidation particles can be followed, fig. 5. Thus, a proper prediction of steel cleanliness for the cast product is possible.

A properly designed casting process should reduce the number of inclusions, particularly of large ones, inside the solidified cast ingot. The majority of inclusions should float up into the top slag. The information about which kind of inevitable inclusions are to be expected at which position of the block should be transferred to the deformation simulation.

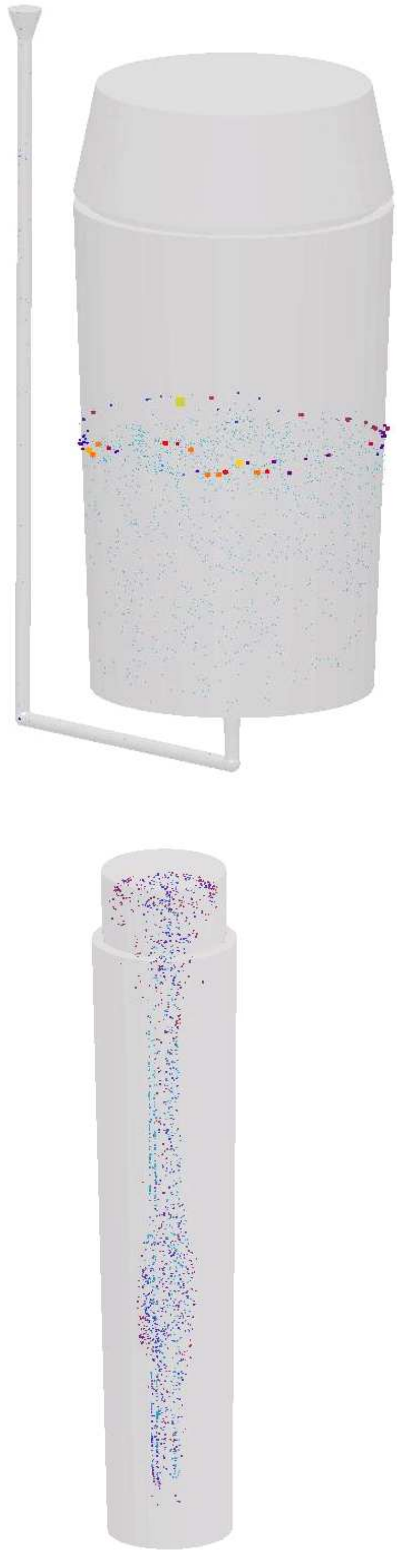

Fig. 5: Reoxidation particles are formed during teeming by contact of the steel melt to air. After their formation they move with the melt flow. Additional air contact allows them to grow and in addition agglomeration mechanisms take place. It is desired that the particles of a critical size float to the top surface of the melt. The upper picture shows reoxidation particles during teeming. The inclusions of various diameters are visualized. The particles are transported with the flow of the bulk liquid. During solidification and cooling, flow conditions are dominated by thermo-solutal convection. Unfavourable solidification leads to the inclusions being trapped inside areas of late solidification (hot spots). In the small (2 ton) ingot in the bottom picture, inclusions remain in the center of the ingot at the end of solidification. A lot of them are trapped inside an area quite close to the ingot bottom.

Cracks

During cooling, residual stresses build up in the different layers of the solidifying ingot. The stress development strongly depends on the heat transport properties of the steel and the cooling rate. If the already solidified outer shell cools down and thus shrinks rapidly in comparison to the inner area, cracks can occur. In order to prevent these cracks, there is a need to properly control the cooling rate and/or for a hot transfer to the deformation (forging or rolling) process.

The stresses that are built up in the ingot and also in the mould can be simulated. By comparison of these stresses with the known material properties, it is possible to predict cracks that are initiated during casting. Based on further information from solidification, the simulation can also identify regions in danger of hot tearing. It is very advantageous for the optimization of the forged product to transfer information about cracks potentially formed during casting to the forging simulation.

Summary

It has been demonstrated how simulation can help to optimize the ingot casting process to achieve best quality and high yield. The most relevant defects that appear in cast ingots have been discussed. The final product is always subject to further processing, first of all by hot deformation. It is of basic interest for the production to have a through-process view on product quality and process yield. The authors propose to transfer the results of casting process simulation to the hot deformation (forging) simulation. This will help to assure the best possible quality of the final product – at the lowest production costs.

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