June 2013: Numerical processing gains in importance
Experience with pouring simulation in three French steel mills

Since the first introduction of software to simulate the pouring and solidification of steel, opinions on its usefulness have been divided. In the meantime, significant progress has been achieved with respect to the degree of maturity of the software as well as regarding the performance of the computer systems used for it. In order to get an idea of the current usefulness of simulation in the daily practice of a steel plant, the author gained first-hand experience by interviewing three application specialists from major French steel companies who were ready to share their related experiences.

“We produce a wide range of special steels in the form of long products,” says Joëlle Demurger, Research Group Manager Process Simulation at Ascométal Creas in Hagondange (France). Ascométal is a specialty steel manufacturer with a workforce of approximately 2,250 employees, three steel plants and a further three locations where dressing and straightening as well as production of semi-finished products is performed, together with an R&D centre. The customer range includes manufacturers with very high quality standards such as the automotive industry, manufacturers of springs and ball bearings as well as manufacturers in the field of petrochemical plants and mechanical engineering. Steel production is exclusively performed on the basis of scrap using electric arc furnaces. The range of grades mainly includes special alloy steels with many variants, some of which are patented. Most steel is poured by continuous casting with dimensions of 95-300 mm complemented by the production of cast ingots with weights ranging from 5.2 to 7.5 tons.

Objectives when using simulation
“We use the simulation programs Therccast and Solid to analyse problems impeding the casting process and to improve production and product quality,” adds J. Demurger. With the help of these programs, the researchers try to get a better understanding of phenomena such as the formation of macrosegregations and porosity or the sagging of crystallites in the melt and to improve their quality control criteria. Another aim is to model key aspects of the process such as interactions between the metal and the mould, the slag or the covering powder, or to depict the trajectories and the trapping of precipitates. With respect to quality assurance, the simulation is primarily used to get to grips with internal defects such as cracks, porosity and segregations as well as the condition of surfaces where cracks can originate.

Outline of the equipment used for continuous casting operations in the steel plant of Ascométal (Graphics : Ascométal)
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With respect to productivity in the steel mill the simulation with Thercast serves to test out higher pouring speeds, to reduce the effects of crystallite sagging and to reduce the scatter of the process results. Last but not least, the software serves to characterize materials by determining thermo-physical and rheological properties such as viscosity or the doughy state. Further fields of application are measurements on industrial plants and the monitoring of parameters such as temperatures.

Example: Improving the continuous casting process

“In our Hagondange works, we experienced problems with certain sensitive alloys developing internal cracks in the corners as well as with melt breakthroughs below the mould during continuous casting in the format 240 x 240 mm,” explains J. Demurger. The first remedy was to reduce the pouring speed, but this decreased productivity. So attempts were made to use the simulation software Thercast to get a better understanding of the underlying mechanisms and thus solve the problem. Both cracks and melt breakthroughs are the result of tensions within the mushy zone between the melt and the already solidified outer shell of the strand. To simulate this process, a thermo-mechanical model with exact boundary conditions was required in order to compute and verify the stresses in accordance with the model stipulated by Thercast. In a first pass, the continuous casting plant had to be fitted with sensors in order to monitor the parameters determining the process. These data were then used as input for a 3D model of the process. After this task was completed, it became possible to use the Yamanaka criterion to determine the zones prone to the risk of cracking. The result was a direct correlation between the bulging of the cast strand and the modelling. A sensitivity analysis of the process (equipment and operating conditions) delivered the proof that minimization of the defect risk immediately after the strand has left the outlet of the mould could be achieved either by extending the mould or by fitting the plant with an additional supporting roller set. It was then decided to opt for the second solution, which was not only cheaper, but also easier to implement. Furthermore, extending the mould would have made it more difficult to adjust its conicity – which also has to take account of the specifics of the alloy currently used.

Example: Reduction of the content of inclusions in ingot casting

“As many of our alloys are used for components with high demands regarding fatigue strength, a high level of purity is a primary criterion of quality,” says J. Demurger. The high cycle fatigue strength of the parts produced thereby essentially depends on a low inclusion content. As part of its strategy to reduce this, Ascometal therefore relies on a long-term R & D program, which aims to identify and reduce the causes of such inclusions in cast ingots. In the context of this multi-parameter approach, pouring simulation using Thercast plays an important role. The inclusions one can find in an ingot are partly of endogenous and partly of exogenous origin. Endogenous inclusions have a size distribution that significantly differs from that of exogenous inclusions. While the latter have a much more detrimental influence on the fatigue properties of the components, if one intends to achieve useful results, one will have to adopt a holistic approach taking the complex interactions between the two types of inclusions into account. One of the main sources of inclusions is chemical reactions of the melt with atmospheric oxygen. In order to investigate this
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mechanism, a thermodynamic model was used, which makes it possible to estimate the inclusion type as a function of the oxygen content. If the oxygen content in the melt is exceptionally high, manganese silicates will tend to be formed instead of aluminium oxides. This compound may then attack the refractory of the runner, resulting in its degradation and in a significant increase in contamination by exogenous inclusions. One of the measures taken as a result of this study was thus to opt for refractory components with high alumina content, which proved to be less vulnerable to attack by manganese silicates. Furthermore, it was decided to select a supplier whose products were found to be more resilient with respect to this type of attack.

The key factor for minimizing the content of both endogenous and exogenous inclusions continues to be the prevention of contacts between the liquid steel and the atmosphere during pouring. Pouring is therefore always performed under inert gas. Additionally, the surface of the melt is protected using a covering powder to further prevent any contact with the air. If however the influx of the melt through the bottom of the mould is too fast, the resulting turbulences will rip open the powder layer causing considerable oxidation. Worse still, the turbulence tends to tear away ceramic particles of the refractory materials and to suck liquid or solid contaminants from the surface down into the ingot, where they are often trapped. In order to optimize the related parameters, a computational fluid dynamic model has been created using Therca, which simulates the effects of different diameters of the duct through which the steel flows into the mould. This simulation clearly showed that a large diameter of the duct will considerably reduce turbulences as well as their adverse effects. This finding was subsequently confirmed by experiments. In combination with additional measures in the implementation of the amended pouring procedure and additional improvements, the steel mill was able to achieve considerable reductions of the inclusion content in its products.

Applying pouring simulation at Industeel France

“Industeel France, which is part of the Arcelor Mittal Group, provides alloys and high-quality products for industry sectors such as power generation, mould and tool-making or recycling,” says Isabelle Poitrault, Manager, Steel Process Section in the Research Center Le Creusot (France). The four industrial sites of the group - two in France and two in Belgium – each have specialized production programs and manufacture ingots, sheets or sand castings with very high masses in small quantities. Within the group, I. Poitrault heads a team that helps the various works in solving production problems and improving processes. Due to the very wide range of applications, the individual products vary greatly. In the segment of cast ingots alone, Industeel produces nearly 50 different formats by bottom pouring with weights between 2 t and 300 t and a large variety of geometries: flat, cylindrical, rectangular, or even circular. This product segment also encompasses the vacuum-casting of cylindrical ingots weighing between 90 t and 260 t.

Another market segment served by Industeel is large-sized sand-moulded castings such as casings for nuclear power plants. For the production of such parts one needs 90 to 400 tons of molten steel. Further products of Industeel are steel slabs with a thickness between 220 to 300 mm and a width of 2,000 mm produced by curved mould continuous casting. They are further processed by rolling according to customer specifications and then put to use in a broad range of applications such as heat exchangers and sheets for chemical reactors, or even as stainless steel
sheets for bridges such as the Millennium Bridge. As can be expected in view of the wide range of products and application fields, the alloy bandwidth is quite extended and encompasses carbon steels, low to high alloy Mn-, Cr-, Ni-, Mo- and V-steels through to super alloys and nickel base alloys.

Right first time is a must

“In view of the very high demands of our customers and the enormous quantities of material we put to use when creating products that are often unique pieces, every mistake would be costly,” says I. Poitrault. Her job thus consists of providing information to the productions teams that will help them succeed right away. In this context, the systematic recording of employee experience is a very important aspect since the time period between orders for two comparable products can sometimes exceed ten or more years. After such long intervals, people have often forgotten the experiences gained at that time — provided they are still employed at the company. Her responsibilities thus include the documentation of the know-how of all staff involved in the production.

The investigation of the casting process must include all aspects relating to the emptying of the pan and the filling of the ingot or sand mould up to the solidification and cooling of the metal. For the simulation of these processes Industeel uses the programs Solid and Thercast. The results achieved with both programs are regularly compared to reality, for example by casting an ingot und cutting it up afterwards for analysis, or by fitting it with sensors in order to record vital parameters of the phenomena to be investigated.

Objectives when using simulation software

Despite the fact that Solid is limited to 2D, it is quite useful in the field of metallurgy (estimates of segregation and microstructure), while Thercast with its 3D approach is very highly suitable for the description of flow behaviour and mechanical properties: “One of our objectives is therefore to integrate the functions of Solid into Thercast”, affirms I. Poitrault. Simulation is mainly used to add to the existing knowledge base regarding the following topics:

- Solving current quality problems using Thercast by modelling the filling of the ingot or sand mould, the flow processes in the melt, the solidification, the distribution of inclusions, the formation of the shrink hole and the stresses within the solidified component,
- Reducing costs by minimizing the loss of material in the head and bottom parts of ingots. With every new mould design, Thercast is used to model the head insulation in order to minimize its length and thus the loss of material during cropping. Similarly, the program is also used to reassess the rules currently in effect for the existing stock of moulds,
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- Solving of problems related to the formation of undesirable metallurgical phases that can form in massive pieces when solidification and cooling in certain areas of the piece pass through critical zones of the TTT diagram that favour their occurrence. In these cases, the simulation can provide limit values with respect to the maximum size of ingot or the minimum cooling rate to be maintained in order to avoid the problem.
- Solving of problems associated with cracks that first develop in the outer skin of the ingots and can spread further inside during the subsequent thermo-mechanical treatment or processing by rolling. Unfortunately, this problem is still far from being solved because the underlying mechanisms are not yet understood well enough.

Experience gained by Aubert & Duval

“We produce a range of special steels and superalloys for the needs of a very demanding clientele in the areas of aerospace, nuclear energy, tooling, defence and automotive industries,” says Jessica Escaffre, Melting Process Development Engineer at Aubert & Duval in Ancizes (France). With a workforce of around 4,000 employees in ten locations, the company has specialized in the development, smelting and hot forming of special steels, super alloys and non-ferrous metals such as aluminium or titanium, which are delivered in the form of components or long products. The ingots produced by pouring are either rolled, free forged or die forged. Part of the production is delivered in the form of semi-finished products.

The Ancizes works produce special steels. Melting is performed using electric arc furnaces. The steel is subsequently refined in a ladle furnace or in an AOD unit and alloyed to the desired composition. The production of ingots is performed by bottom pouring. Afterwards, these ingots are either passed on for downstream processing or remelted for further purification. Aubert & Duval also has a vacuum induction melting unit (VIM). The steel from this unit is directly poured into moulds, and the ingots thus produced exclusively serve as input material for the electro-slag remelting (ESR) or vacuum arc remelting (VAR) units.

Production of ingots

“The team I belong to mainly focuses on understanding and optimizing processes for alloy production and casting ingots, while another team deals with downstream processes such as rolling, open die forging or drop forging,” says J. Escaffre. In its activities, her team has to differentiate between the bottom pouring and remelting process types. With regard to bottom pouring, the main objective is to get a better understanding and thus better control of the mechanisms that lead to the formation of a variety of flaws that affect either the quality of the material or the productivity of the processes. The ingots produced have a broad weight range from 2 tons to 27 tons, with either round, square or octagonal cross-sections. The alloy spectrum includes 250 grades ranging from low alloy steels to super alloys.

To minimize the formation of shrink holes, bags with an insulating powder are lowered deep into the mould near to its bottom before pouring starts. When the rising steel reaches the bags, the powder is released and forms an insulating cushion on its surface. In the top area of the ingot, the insulating effect of the powder may be further enhanced – according to requirements - by “hot top” plates or by adding another powder with an exothermic
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effect. The purpose of these schemes is to delay solidification of the ingot head in order to reduce the formation of shrink holes.

Defect types
“We have to deal with the whole range of defect types that can arise during the casting of ingots,” explains J. Escaffre. The three main problem groups are oversized shrink holes, porosity and inclusions. The latter can be of either endogenous or exogenous origin. Exogenous inclusions come from different sources such as slag, the refractory material or the mould powders and insulation plates protecting the ingot top, but they can also stem from trivial sources such as the refractory lining of the furnace, the ladle or the runners. Another source of defects coming forward from time to time and often resulting in the total loss of an ingot are cracks or hot cracks. An additional class of problems that have to be tackled are segregations, which can lead to uneven distribution of the various alloying elements both transverse to the ingot cross section and over its length.

Simulation programs
“We have two different programs to analyse the formation of these defects and thus to define strategies to prevent or at least reduce them,” J. Escaffre adds. The first is Solid with its 2D model, which describes the thermal processes as well as the fluid dynamics and in addition takes into account the formation and transport of crystallites in the melt. The software is able to simulate nucleation and grain growth and describe the sedimentation cone at the foot of the ingot formed by sagging crystallites. Thercast, the other software used by Aubert & Duval, models in 3D and works on the basis of FEM analysis. It is used to monitor and improve processes for the production of cast ingots. The program was developed to simulate the pouring and solidification processes both for ingot and continuous casting. Its thermo-mechanical models make it possible to examine in detail the many complex interactions between solidification, cooling, shrinkage, melt and mould and many other parameters of the process. This makes it possible to perform sensitivity analyses for the existing processes. The software provides information on temperatures, stresses, porosity and segregation for each location of the casting and for any desired time. This allows a very detailed analysis of the condition of the material, which can also be used for the simulation of downstream treatment processes. The thermo-mechanical model also predicts the formation of air gaps resulting from the cooling of the ingot in the mould. These gaps insulate it against the mould wall and can cause defects on the surface as well as inside the ingot. The program also allows for the modelling of insulating or exothermic powders forming an insulating pad on the ingot top that protects it from cooling too rapidly, thus helping to minimize shrink holes.

Advantages and limits of simulation
“The advantage of the 3D modelling used by Thercast is that you can also perform calculations on ingots whose geometry would be difficult to depict in 2D,” says J. Escaffre. Depending on requirements, both simulation
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programs are sometimes used in parallel, especially when there is time pressure, since the 2D approach of Solid yields results much faster than the much more complex 3D modelling of Thercast.

“With respect to the current state of development of simulation programs, one can say that for ingot casting in moulds – in contrast to the situation in the field of continuous casting – it is not yet possible to achieve exact results”, comments J. Escaffre. The main reason for this is that certain physical input parameters are not known with sufficient accuracy. Both programs, however, are well suited for comparative analyses, for example when assessing the sensitivity of a process with respect to the variation of a parameter such as the rate of filling of the mould. And they are equally useful for assessing insulating elements of the ingot top with respect to the emergence and development of unwanted defects.

For such studies, one should pick out a particular type of defect and vary the parameters of the process in view of this flaw: we are therefore talking about sensitivity analyses. The results thus provide information on how single parameter variations affect the defect to be examined, as well as all of the effects described by the software. While it is necessary to regularly reconcile and verify the results using experiments, the simulation will in any case help to drastically reduce the necessary number of trials - or to avoid unpleasant surprises at the start of production.

Another advantage of the use of the programs is the opportunity to adjust thermo-physical data such as the latent heat of the alloys used by instrumentation of a mould with thermocouples to record the evolution of temperatures during pouring and cooling.

Current advances

“Together with several partners, we are currently participating in a joint research project aiming at developing and validating an improved version of Thercast,” says J. Escaffre. The project partners include CEMEF (Centre de Mise en Forme des Matériaux of the École des Mines de Paris). The project aims at modelling the formation and migration of crystallites within the ingot during solidification and the resulting impact on segregation models and integrating them in the software. Another addition to the software intends to include the modelling of another material subjected to a solid-liquid phase transition – e.g. with regard to the powder for insulation cushions on the ingot top. Similarly, efforts are being made to simulate in 3D the behaviour of the insulating powder in the case of asymmetric applications of the bags, resulting in an uneven distribution of the material in the insulation pads. The objective here is to develop appropriate guidelines for the correct application of this powder.

Conclusions and summary

These three examples of the use of simulation programs show that simulation has become part of everyday production practice in steel plants. The programs - Thercast and Solid – have been validated by the teams who work with them, and they have adopted them up to a point where they themselves determine their future technical content, for example when it comes to integrating the metallurgical capabilities of Solid into Thercast.

With respect to their implementation, the two programs are used in one of the plants as a means of systematization and documentation of experiences in the one-off production of good parts “right at first time”. In another company they serve to perform sensitivity analyses centred on the typical defects forming during solidification processes - such as shrink holes - as a function of process parameters. The third company utilizes solely Thercast to analyse problems related to continuous casting of certain steel materials and to use the findings to proceed to appropriate improvements.

Above all, the programs prove their usefulness in daily practice, helping to increase the quality of production by:

- Analysing the course of the pouring process in order to enhance the filling, to adjust the geometry and to adapt flow speeds in cases where otherwise erosion and a related increase in inclusion content might occur,
- Investigating the evolution of temperatures in order to better control the solidification, with the aim of minimizing porosity and the formation of undesirable phases, but also - in the case of ingots – reducing the amount of top and bottom scrap,
- Investigating macrosegregations which have a direct impact on product quality,
- Improving the capacity to address flaws occurring in production with lower cost and higher efficiency, as the simulation facilitates a deeper understanding of the processes.
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