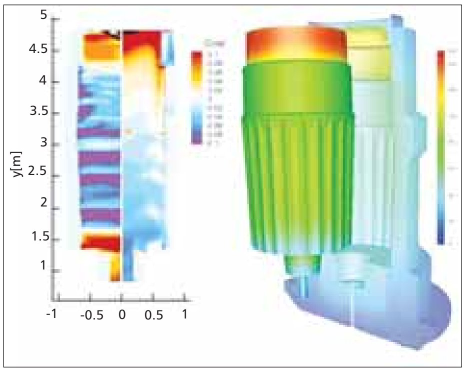
Experience with pouring simulation in three French steel mills

Significant progress has been achieved with respect to the degree of maturity of software to predict solidification behaviour during casting as well as the speed of the computers needed to solve the 2D and 3D models. To assess the current usefulness of simulation in 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. **By Klaus Vollrath***



Predicted macrosegregation and temperture in a 65t bottom poured ingot using simulation software (Graphic from Industeel)

SINCE the first introduction of software to simulate the pouring and solidification of steel, opinions on its usefulness have been divided. Three examples are provided of the application of two simulation programs – 2D 'Solid' and 3D 'Thercast' – which show that simulation has become part of everyday production practice in steel plants. The programs have been validated by the teams who work with them, and they have adopted them up to the point where they themselves determine their future technical content, for example when it comes to integrating the metallurgical capabilities of Solid into Thercast.

In the first example, the company uses Thercast to analyse problems related to continuous casting of certain steel alloys and to use the findings to proceed to appropriate improvements.

In the second example, the two programs are used in another plant as a means of systemising and documenting the experiences in the production of 'one-off' good castings 'right first time'.

In the third example, the two programs serve to perform sensitivity analyses centred on the typical defects formed during solidification of ingots as a function of process parameters.

Continuous casting at Ascométal

Ascométal in France is a specialty steel manufacturer with a workforce of approximately 2250 employees. It produces a wide range of special steels in the form of long products.

The Company has 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 UHP electric arc furnaces (EAF) followed by ladle refining and vacuum degassing. The range of grades mainly includes special alloy steels with many variants, some of which are patented. Most steel is poured by continuous casting in a vertical caster with submerged nozzles in dimensions of between 95 to 300mm, but casting is complemented by the production of ingots with weights ranging from 5.2 to 7.5t.

Objectives when using simulation

Joëlle Demurger, Research Group Manager Process Simulation at Ascométal Creas comments "We use the simulation programs 'Thercast' and 'Solid' to analyse problems impeding the casting process and to improve production and product quality". With the help of these programs, the researchers try to get a better understanding of phenomena such as the formation of macro segregations 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.

With respect to productivity in the steel mill 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. Also, the software serves to characterise materials by determining thermophysical 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 temperature.

Improving continuous casting

At Ascométal Hagondange works, problems have been experienced during continuous casting 240 x 240mm billet in certain sensitive alloys which develop internal cracks in the corners as well as with melt break-outs below the mould. 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 break-outs are the result of tensile stresses developing 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 to compute and verify the stresses in accordance with the model stipulated by Thercast. The continuous caster was fitted with sensors to monitor the parameters determining the process. These data were then used as input for a 3D model of the process. Once 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 model (**Fig 1**).

A sensitivity analysis of the process (equipment and operating conditions) delivered the proof that the risk of defects forming immediately after the strand has left the mould could be reduced either by extending the length of the mould or by fitting the caster with an additional supporting roller set (**Fig 2**). It was 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 the mould – which also has to take account of the specifics of the alloy currently used.

Ingot casting

As many of Ascométal's alloys are used for components with high demands regarding fatigue strength, a high level of purity is a primary criterion of quality. The high cycle fatigue strength of the parts produced thereby essentially depends on a low inclusion content. As part of the strategy to reduce this, Ascométal therefore relies on a long-term R&D programme, which aims to identify and reduce the causes of such inclusions in cast ingots. Ingot casting is by uphill pouring (**Fig 3**). In the context of this multi-parameter approach, pouring simulation using the Thercast software plays an important role.

The inclusions found in ingots are partly of endogenous (internal) and partly of exogenous (external) origin. Endogenous inclusions have a size distribution that significantly differs from that of exogenous inclusions. While exogenous inclusions have a much greater detrimental influence on the fatigue properties of the components, to achieve useful results it is necessary to adopt a holistic approach taking the complex interactions between the two types of inclusions into account.

One of the main sources of inclusions are chemical reactions between the melt and atmospheric oxygen. To investigate this 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,

*Schnitt-Stelle Redaktionsbüro, Bünteweg 21, CH-4912 Aarwangen, Switzerland Tel +41 62 923 4490 Mobil-Tel +41 79 6639405 e-mail KVollrath@bluewin.ch

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 offering products found to be more resilient with respect to this type of attack.

The key factor to reduce the content of both endogenous and exogenous inclusions continues to be the prevention of contact between the liquid steel and the atmosphere during pouring. Pouring is therefore always performed under inert gas. Additionally, the surface of the melt in the ladle is protected using a covering powder to further prevent any contact with the air. If however the flow 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 from the refractory materials and to suck liquid or solid contaminants from the surface down into the ingot, where they are often trapped. To optimise the related parameters, a computational fluid dynamic model has been created using Thercast, which simulates the effects of different diameters of the duct through which the steel flows into the mould (**Fig 4**). This simulation clearly showed that a larger diameter duct at the base of the ingot mould 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 (**Fig 5**).

Simulation at Industeel France

Industeel France is part of the Arcelor Mittal Group and provides alloys and high-quality products for industry sectors such as power generation, mould and toolmaking. The four industrial sites of the group – two in France and two in Belgium – each have specialised production programmes and produce ingots, sheet and sand castings – some of the latter being of very high mass and made in small quantities.

Isabelle Poitrault, Manager, Steel Process Section in the Research Center Le Creusot (France) 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 ingots with weights between 2t and 300t in a large variety of geometries: flat, cylindrical, fluted, rectangular, and even circular (**Fig 6**). This product segment also encompasses the vacuum-casting of cylindrical ingots weighing between 90t to 260t. 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 90 to 400t of molten steel need to be available.

Other products of Industeel are continuously cast slabs with a thickness between 220 to 300mm and a width of 2000mm produced in a curved mould radius continuous caster. As can be expected in view of the wide range of products and application fields, the alloy band width is wide and encompasses carbon steels, low to high alloy Mn-, Cr-, Ni-, Mo- and V-steels through to super alloys and nickel base alloys (**Fig 7**).

Right first time

"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 with each casting every time. In this context, the systematic recording of experience is a very important aspect since the time period between orders for two similar products can sometimes exceed ten or more years. After such long intervals, people have often forgotten the experiences gained at the time – assuming they are still employed at the company. Her responsibilities thus include the documentation of the know-how of all staff involved in production.

The modelling of the casting process – whether it involves the casting of ingots in moulds or sand casting – is of crucial importance, since this process step basically determines the quality of the part, thus also affecting all subsequent operations along the production process chain. The investigation of the casting process must include all aspects relating to the emptying of the tundish 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

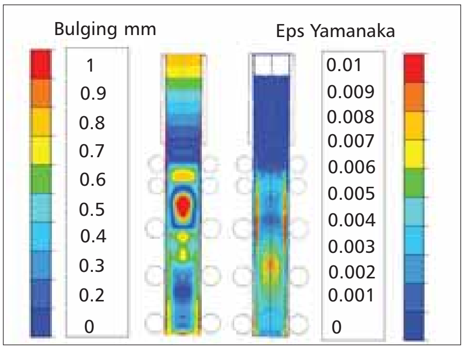


Fig 1 Simulation using Thercast made it possible to establish the mathematical relationship between the bulging of the outer skin of the continuously cast bloom (left) and the Yamanaka criterion **(Graphics : Ascométal)**

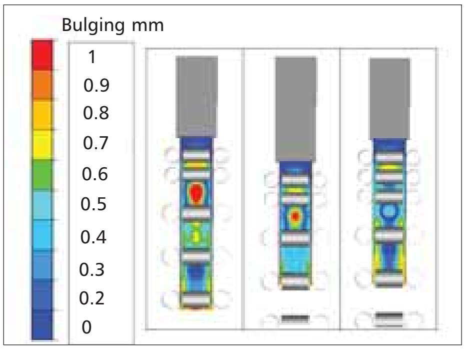


Fig 2 Analysis of the possible modifications to the continuous caster to prevent bulging of the strand: initial situation (left), use of an elongated mould (centre) or installation of an additional support roll below the mould (right) **(Graphics: Ascométal)**

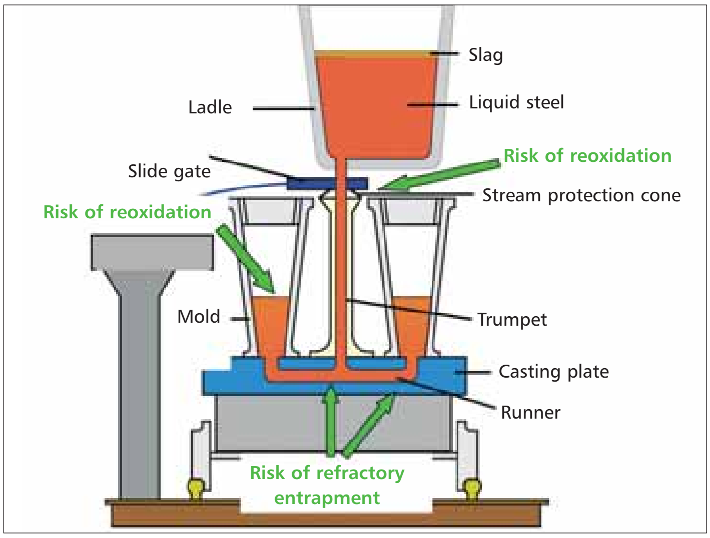


Fig 3 Main sources of inclusions in cast ingots and the countermeasures taken to minimise their occurrence **(Graphics : Ascométal)**

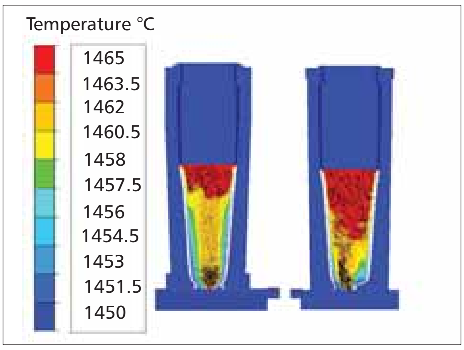


Fig 4 Visualisation of the melt flow velocity speeds and directions and temperature profile in a half-filled bottom pored ingot mould for two different diameters of the runner channel **(Graphics: Ascométal)**

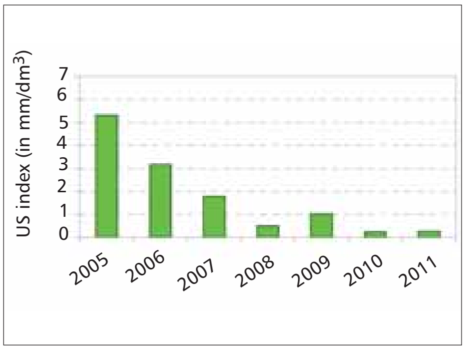


Fig 5 Reduction of the internal defects detected in rolled wire rod using ultrasonic testing (10MHz) over a period of seven years **(Graphics : Ascométal)**

Fig 6 Industeel produces cast ingots in nearly 50 different sizes weighing between 2t to 300t by bottom pouring (Photos: Industeel)

and Thercast. The results achieved with both programs are regularly compared to reality, for example by casting an ingot and sectioning it afterwards for analysis, or by fitting it with sensors in order to record vital parameters of the phenomena to be investigated (**Fig 8**).

Objectives when using simulation software

Despite the fact that the Solid program is limited to 2D, it is quite useful in the field of metallurgy for estimates of segregation and microstructure. Thercast with its 3D approach is 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", says 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, solidification, the distribution of inclusions, the formation of shrinkage holes and the stresses within the solidified component.
- Reducing costs by minimising 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 minimise 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.
- Solving 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 Time-Temperature-Transformation (TTT) diagram that favour their occurrence. In these cases, 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 (**Fig 9**).
- Solving 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.

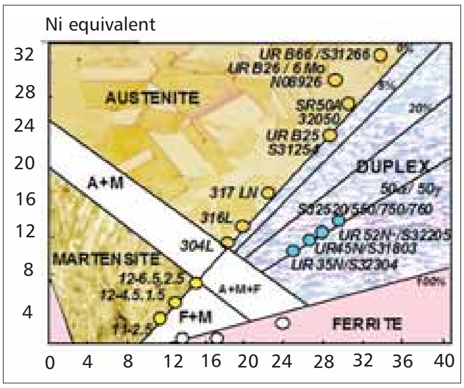


Fig 7 Steel grades produced by Industeel (Graphics: Industeel)

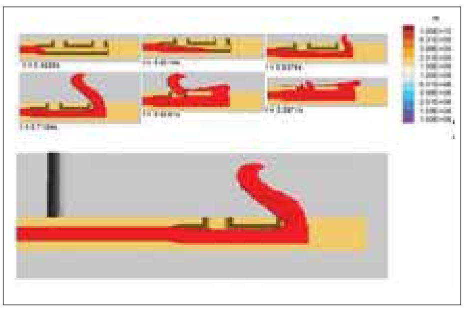


Fig 8 Analysis of the filling process of a flat ingot using simulation software (Graphics : Industeel)

Aubert & Duval

Aubert & Duval in Ancizes, France 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. The Company has a workforce of around 4000 in ten locations where it specialises in the development, melting and hot forming of special steels, super alloys and non-ferrous metals such as aluminium and titanium. These are delivered to customers in the form of components or long products. 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 either in electric arc furnaces or under vacuum in induction furnaces (VIM). Steel made in the EAF is subsequently refined in a ladle furnace or, for high Cr alloys, an AOD converter and alloyed to the required composition. Ingots are bottom poured and after solidification and stripping are either passed on for downstream processing or remelted by Electro slag refining (ESR) or Vacuum Arc Refining (VAR) for further removal of inclusions and segregation. Vacuum induction melted steel is directly poured into moulds, and the ingots thus produced exclusively serve as input material for the ESR and VAR units.

Production of ingots

Jessica Escaffre, Melting Process Development Engineer at Aubert & Duval says:

"The team I belong to mainly focuses on understanding and optimising processes for alloy production and casting ingots, while another team deals with downstream processes such as rolling, open die forging or drop forging,". Her team has to differentiate between bottom pouring ingots and remelted ingot.

For bottom poured ingot, 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 2t to 27t, with either round, square or octagonal cross-sections. The alloy spectrum includes 250 grades ranging from low alloy steels to super alloys.

To minimise the formation of shrinkage 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 the surface of the steel as it rises up the mould. In the top region of the ingot, the insulating effect of the powder may be further enhanced – according to requirements – by 'hot top' insulating plates or by adding an exothermic powder with the aim of keeping the surface molten to feed internal shrinkage porosity as the ingot solidifies.

Defect types

"We have to deal with the whole range of defect types that can arise during the casting of ingots," explains Escaffre. The three main problem groups are oversized shrinkage holes, porosity and inclusions. The latter can be of either of 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 sources such as the refractory lining of the furnace, the ladle or the runners. Another

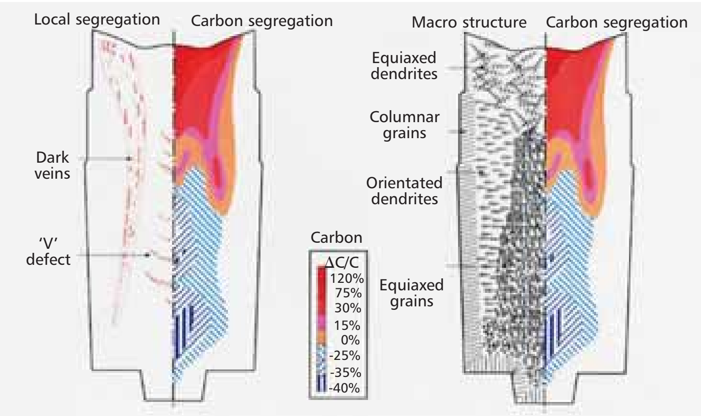


Fig 9 Prediction of macro segregations and the structure of an ingot (Right side of each ingot = Carbon segregation; Left side macro segregation and structure)
(Graphics : Industeel)

source of defects occurring from time to time and often resulting in the total loss of an ingot are cracks and hot tears. An additional class of problems that have to be tackled is due to segregation, which leads 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", 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, models in 3D and works on the basis of finite element (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 at 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 between the mould and ingot resulting from contraction of the ingot during cooling. These air gaps insulate the hot ingot from 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 minimise shrink holes (**Fig 10**).

Advantages & limits of simulation

"The advantage of the 3D modelling used by Thercast is that you can also perform calculations on ingots with geometry which would be difficult to depict in 2D," says Escaffre. Depending on requirements, both simulation 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 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, a particular type of defect should be selected and the parameters of the process varied to influence this flaw: this is a measure of the sensitivity of the analyses. The results thus provide information on how single parameter variations affect the defect being 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, such simulation will in any case help to drastically reduce the number of trials necessary 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 (**Fig 11**).

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 Escaffre. The project partners include the Centre de Mise en Forme des Matériaux of the École des Mines de Paris (CEMEF). 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 eg 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 positioning 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.

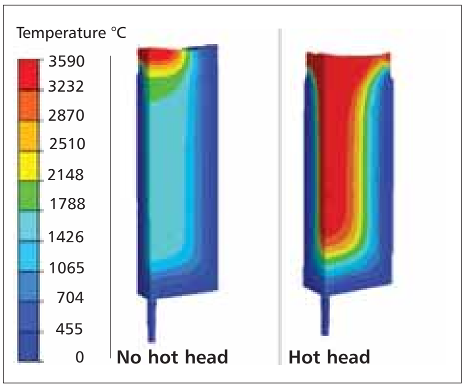


Fig 10 Use of Thercast when optimising pouring parameters: influence of ingot head insulation on the macro segregations in an ingot with rectangular cross section
(Graphics : Aubert & Duval)

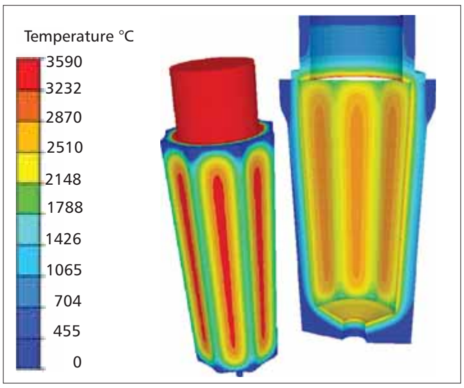


Fig 11 Prediction of temperatures in an octagonal ingot as well as in the related mould (right) using Thercast
(Graphics : Aubert & Duval)

Conclusions

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 to enhance mould 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 to better control the solidification, with the aim of minimising porosity and the formation of undesirable phases, but also, in the case of ingots, improving yield by reducing the amount of top and bottom scrap.
- Investigating macro segregations 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. ■

Contacts
Ascométal Creas, BP 70045, Avenue de France, 57301 Hagondange Cedex, France, www.ascometal.com
ArcelorMittal - Industeel France, 56 rue Clémenceau, B.P. 19, 71201 Le Creusot Cedex France, www.arcelormittal.com
Aubert & Duval, Tour Maine Montparnasse, 33, avenue du Maine, 75755 Paris Cedex 15, Tél +33-1 45 38 38 88, www.aubertduval.com