Continuous Casting Simulation

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1. Introduction

The cast houses are showing a remarkable development and technological evolution in processing of metals. The strong competition among cast houses has led engineers to overcome important challenges such as increasing casting velocities, reducing production costs, shrinking the time required for a new geometry and alloy modification while steadily improving the cast product quality. New communication technologies have facilitated this impressive development over the past decade. Electronic file transfers, computer assisted design (CAD), computer assisted engineering (CAE) and process simulation are new tools which contribute to this evolution.

The development of a new product and the change of alloy composition for a novel billet, slab or sheet are associated with a revision of the process set-up. Depending on the situation, the mould dimension should be modified, the cooling system redesigned and the temperature in the furnace adapted. Furthermore, as most of the continuous cast products are intended for further processing, typically such as rolling or extrusion, various metallurgical aspects need to be finely controlled. In this case, issues like grain structure, hot tearing, cold cracking, distortion, chemical homogeneity or surface segregation, just to mention a few of them, are features which need to be controlled during production. These quality requirements have to be integrated early in the development stage of the new cast product. If not, the cast product might present an inadequate microstructure (even though it looks as a sound defect free casting), and it can generate tremendous costs in downstream processes.

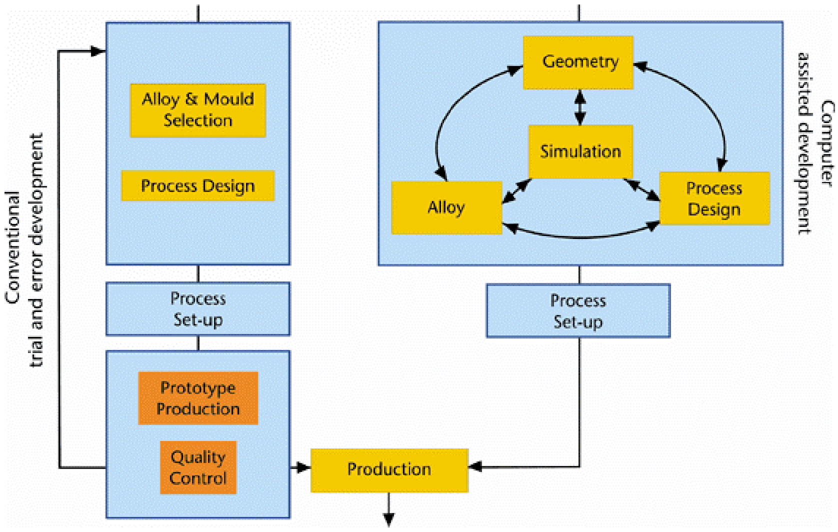

Figure 1: Schematic flowchart presenting the conventional trial and error development and the computer assisted development.

Traditionally, the set-up of adapted casting conditions for a new product has been done based on past experiences. Engineers have been taking decisions based on their know-how. This valuable approach can nowadays be complemented by casting simulation. Indeed, computer simulation enables the cast house engineers to visualise rapidly the effect of design decisions, and to identify which are the most influencing parameters. The castability of a new alloy can be tested early in the development stage, and the impact of a geometry change can be assessed before a modified processing route is chosen.

Decisions that influence the final quality of the product can be taken rapidly, thereby drastically reducing costly trial and error developments. Customer requirements can be analysed more efficiently and at low cost, thereby enabling the sales department to prepare accurate commercial quotations in the pre-study phase. Increasingly, casting simulation becomes also a prerequisite, included in the quality management policy of a company, in the selection of its cast product suppliers.

Casting simulation has many other beneficial applications, as it is a powerful educational tool. Indeed, the computer can be used as a laboratory in order to test challenging solutions and to certify processing windows. Furthermore, new collaborators can rapidly be made aware of the importance of specific casting parameters, by simulating the continuous casting process.

2. Solidification: Temperature & Shell Growth

A natural application of simulation in the field of continuous casting is the computation of the solidification behaviour of the liquid metal, which is entering into the mould. For this purpose, the presence of a graphite insert, the dimension of the cooler and the amount of water flow through the mould needs to be described. The geometrical description of the casting set-up is generally transferred from a CAD system, and meshed into finite elements. The computation further includes important processing parameters, such as the amount of secondary cooling (water jet), the casting temperature and the casting speed.

Figure 2 presents a calculation, which simulates the continuous casting of steel. The first figure (coloured in yellow and brown) shows the temperature evolution along the cast metal. It is visible, for instance, that the edges are cooling more efficiently than the large faces. This computation takes into account the full complexity of the cooling system. Indeed, besides the primary cooling in the mould, the influence of the guide-rolls (only a few are displayed on the figure), the radiation between the rolls and the impingement of the water jets is analysed.

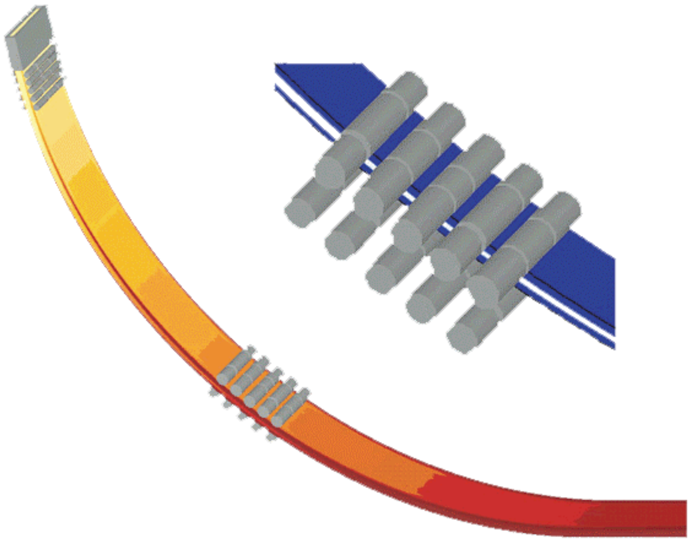

Figure 2: Continuous casting of steel. The larger figure presents the temperature evolution at the surface of the cast metal (yellow is warm and brown is cooler). The magnification shows the evolution of the fraction of solid in a central cross section (blue solid, white liquid). Calculation realised with calcosoft®-3D.

The magnified picture in Figure 2 (blue and white gradation) shows the evolution of the fraction of solid in a cross-section. The fraction of solid in the cast bar is linked to the temperature distribution. However, it is depending also on the alloy composition. Indeed, the melting temperature, the solidification interval, the heat conductivity and the latent or specific heat are influenced by the alloying elements. Therefore, casting simulation allows one to study the influence of alloy specifications on the evolution of the fraction of solid. In particular, as it is shown in Figure 2, the precise location of the liquid metal and the thickness of the solidified crust at a specific location can be predicted. These features are difficult to assess by experiments, and might be crucial when casting new alloys.

Simulation can be used to easily predict shell growth. It provides an analysis tool capable of looking inside the core of the casting at any time. Shell thickness can only be determined experimentally using expensive and complicated technology. Simulation on the other hand can easily predict shell thickness related to a certain set of casting parameters. Possible problems, such as strong re-heating, can be observed and corrected on the computer prior to going to the cast shop.

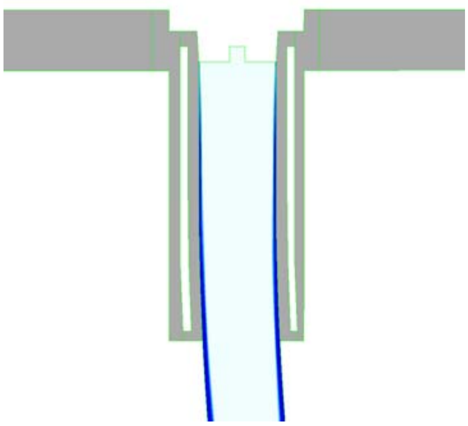

Figure 3: Shell thickness for curved continuous casting of steel. Liquid is shown in light blue and solid in dark blue.. Calculation realised with calcosoft®-2D.

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Shell growth can be observed either statically by means of crosscuts in a full 3D calculation or dynamically using travelling sections. Figure 3 represents a lateral crosscut showing the shell thickness at the exit of the mould for a steel bloom. Figure 4 represents several successive transversal crosscuts showing the thickness of the solid layer.

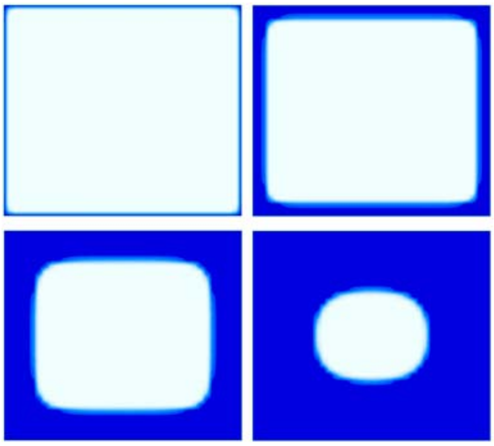


Figure 4: Simulated crosscuts of a steel bloom, from the level of the mould to the end of the casting. Calculation realised with calco*soft*®-2D.

Figure 5 presents similar results, but for a horizontal continuous casting process of a copper alloy. The temperature distribution in the cast metal, in the graphite insert and in the mould components can be studied. The location of the mushy zone (interval within which the metal is gradually changing from liquid to solid, i.e. white to dark blue) can be precisely identified. The influence of the casting speed or of the cooling system design on the positioning of the liquid pool within the graphite insert can be studied.

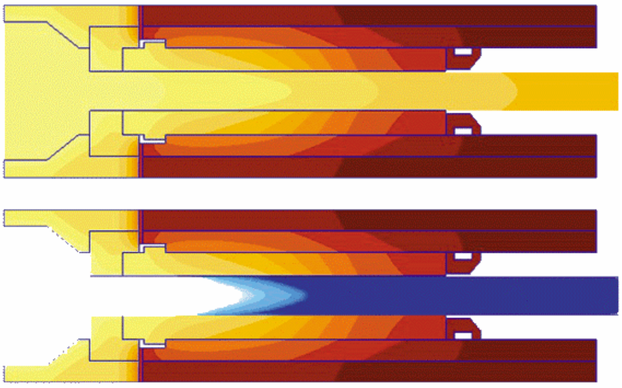


Figure 5: Horizontal continuous casting of copper. The top figure shows the temperature distribution, while the lower figure shows the fraction of solid. Calculation realised with calco*soft*®-2D.

Optimal cooler designs can be developed, by testing new solutions on the computer. For instance, in Figure 5, a computation can be realised, where the maximum casting speed is calculated by directly cooling the liquid metal with a water jet (thereby removing the description of the mould and of the graphite insert). This solution, which can obviously not be tested in practice, will show what the maximum theoretical casting speed is. An iterative analysis can afterwards be realised, where essential components are added to the simulation (such as, obviously, the insert or the mould). However, these components can be optimised in a systematic manner. In practice, various industries have achieved a gain of more than 25% in productivity using such simulation supported approaches.

3. Influence of Metal Flow

Liquid motion is a very important issue related to casting quality. The control of the fluid flow in a continuous casting process has a direct incidence on the final product. Strong turbulence close to the liquid surface tend to introduce more oxide particles in the casting. On the other hand, if the liquid metal is not mixed properly, segregation problems tend to appear. Unfortunately, fluid flow is not as easy to measure as temperature, thus making the control of liquid metal motion nearly impossible. Liquid motion is generated by convective phenomena which can be separated in two categories:

- Forced convection
- Natural convection

Forced convection is created by the metal inlet through the nozzle and by possible mechanical or electromagnetic stirring. Natural convection is created by differences in density within the liquid. Those differences can have two origins, either thermal (difference in temperature) or solutal (difference in concentration). Gradients in temperature as well as gradients in concentration appear close to the solid shell. Therefore, it is extremely important that solidification is taken into account for fluid flow modelling.

An example of the type of help simulation can provide through fluid flow modelling is given below. Liquid motion and turbulence created at the inlet strongly depend on the shape of the nozzle. In the specific case described here, the problem which needed to be solved was a hot spot on the casting and consequent mould wear. Fluid flow analyses showed that, due to the inlet geometry, the hot liquid metal was bouncing against the wall, re-melting the solid shell. Figure 6 shows the liquid speed at the inlet, the bouncing against the wall and the consequent re-melting of the solid shell.

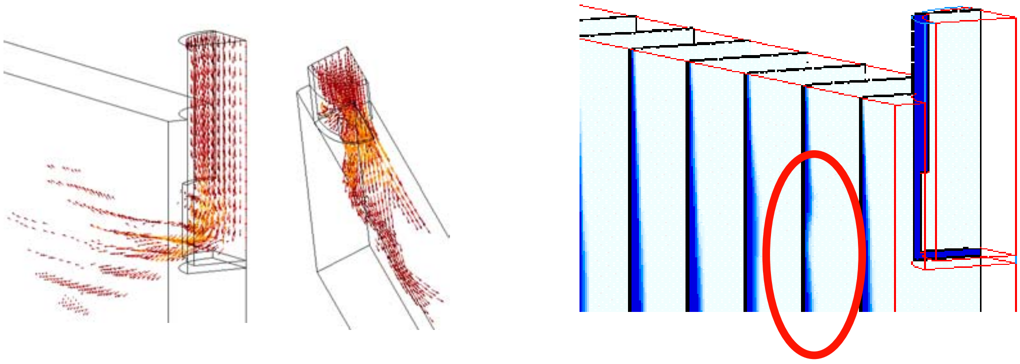


Figure 6: Left: Vectors related to the inlet speed. Bouncing effect against the surface of the mould. Right: Crosscuts showing shell thickness at various locations. Re-melting of the shell highlighted in red. Calculation realised with calco*soft*®-3D.

The inlet geometry has been modified on the computer until the bouncing could be suppressed. It appeared that a slight change in the size of the inlet could avoid the re-melting. Figure 7 shows the two inlet geometries and their effect on the re-melting of the shell. Fluid flow is strongly related to the quality of the final product. As it is difficult to measure convective forces in a liquid, simulation becomes an essential tool for quality control.

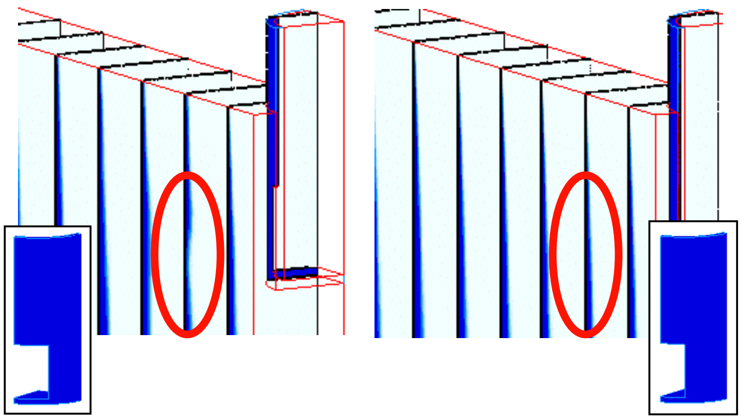


Figure 7: Effect of the nozzle opening size on the surface re-melting. Left: Large nozzle opening, re-melting highlighted. Right: Small nozzle opening, no re-melting can be observed. Calculation realised with calco*soft*®-3D.

4. Chemical Distribution - Macrosegregation

Continuous casting simulation can also predict the distribution of chemical species. Applications can be found for instance in the time required for a tundish to reach a new steady state (i.e. constant chemical composition), while the alloy composition has changed. Another field of application is the investigation of the chemical homogeneity of the cast product itself.

Figure 8 presents the evolution and the mixing in the tundish of two alloy compositions, during continuous casting of steel. In practice, this simulation represents the operation where the alloy composition is modified during the process. As the casting equipment is not turned off during this stage, this results in a part of the casting which needs to be cut off, as its alloy composition gradually changes from the old to the new composition.

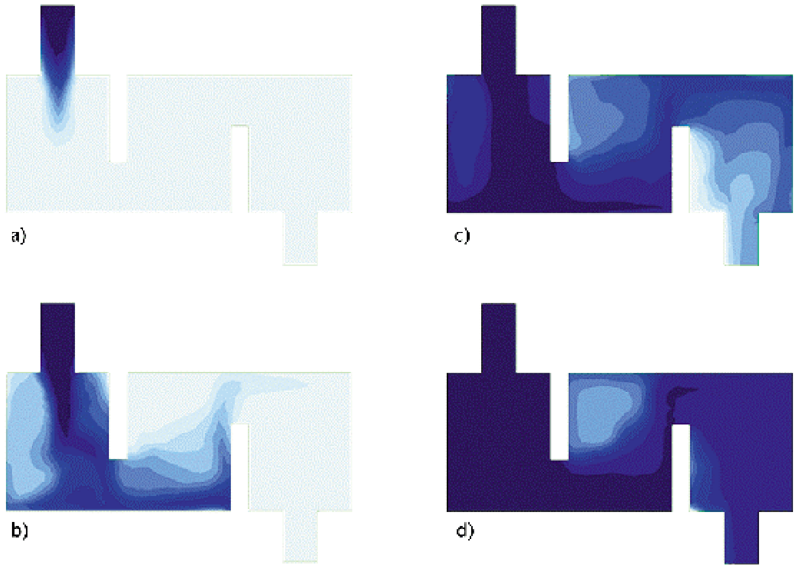


Figure 8: Calculation of the composition evolution in the tundish, when the alloy composition is changed during the continuous casting process of steel. Calculation realised with calcosoft®-2D.

The simulation shown in Figure 8, could be compared to a tundish initially filled with water (first steel grade), where the water is gradually replaced by ink (second steel grade). The time, which is required for the water to be completely replaced by ink, can be predicted, which eventually corresponds to the section of the final cast product that needs to be removed. This approach can obviously be extended to a tundish supplying several casters, where the time for each caster to have completely reached the new alloy composition might differ. Clearly, the fact that the tundish is emptied in practice to a certain extent before the new alloy is poured, can also be taken into account in the simulation.

When the computation of the chemical distribution is coupled with the metal flow and solidification computations, then it is possible to predict macrosegregation. This results in a change in alloy composition over the thickness, for instance, of the final cast product. This feature, which leads to a non-homogeneous casting, is linked to the fact that some alloying elements are segregating during solidification, due to a modification of the solubility during cooling. This local modification of the alloy composition eventually leads to in-homogeneities over the scale of the casting, when liquid motion (convection) transports these species.

Figure 9, for instance, presents macrosegregation results for a direct chill casting of two aluminium alloys. The left figure shows the influence of alloying elements on the shape of the melt pool (the left half is an Al-Mg alloy, and the right half is an Al-Cu alloy). The figure on the right shows the resulting chemical distribution for the same two alloys. Clearly, the alloy composition is disturbed close to the centreline of the ingot, as well as next to the surface.

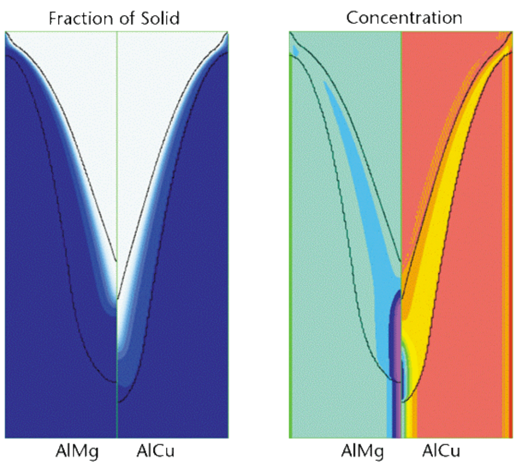


Figure 9: Macrosegregation calculation in a direct chill casting of aluminium. The effect of alloying element on the shape of the melt pool (left), and on the concentration profile (right) is presented. Calculation realised with calcosoft®-2D.

In most of the cases, a homogeneous cast ingot is required. Therefore, casting simulation can be used in order to optimise casting parameters, such as the efficiency of secondary cooling and casting speed, or the influence of the geometry of the distributor bag, of magnetic stirring or of a hot-top.

5. Grain Structure - Microstructure Formation

Advanced modelling in continuous casting operations can predict the microstructure as well. For instance, the phase compositions (i.e. the amount of austenite, perlite, ferrite or martensite) can be forecasted for steel castings. The influence of processing parameters on the resulting grain structure or dendrite morphology can be studied as well.

Figure 10 shows the grain structure in a transverse cross-section of a cast bloom. All figures show an outer columnar grain structure with a central equiaxed region (except the figure on top left, which is fully columnar). These figures are calculated for different conditions, namely a change of alloy composition, the usage of grain inoculation and the increase in the casting speed. Clearly, the columnar to equiaxed transition is drastically influenced, leading in some cases to large columnar grains, or to finely dispersed equiaxed grains. As further processing operations, such as rolling, are largely influenced by the grain structure, it is safer and more cost effective to be able to control theses microstructural features early in the development stage.

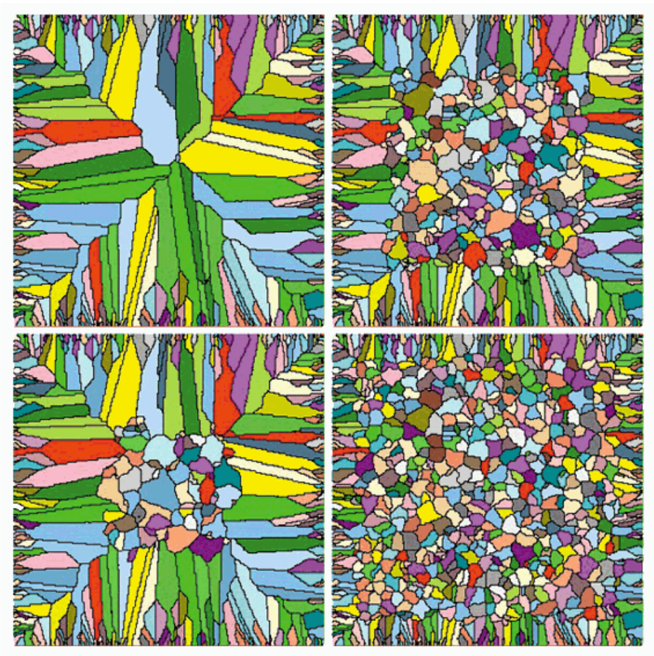


Figure 10: Stochastic modelling of the grain structure in a transverse cross-section of a bloom. The effect on the columnar to equiaxed transition of inoculation, alloy concentration and casting speed is shown. Calculation realised with calcosoft®-2D.

Figure 11 presents some advanced modelling results, showing the evolution of the dendrite structure, as a function of time, during solidification. With such computations, it is possible to predict the fine chemical distribution between the dendrites, their size and morphology and the appearance of interdendritic phases such as precipitates for instance.

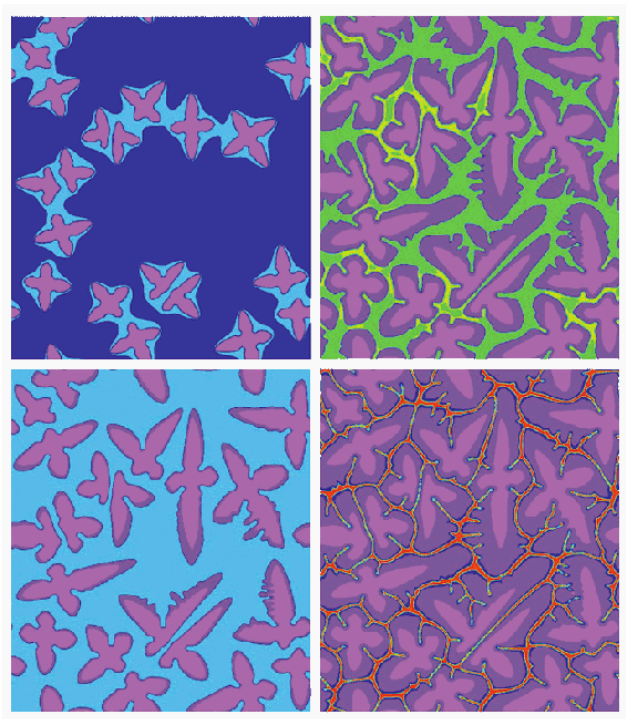


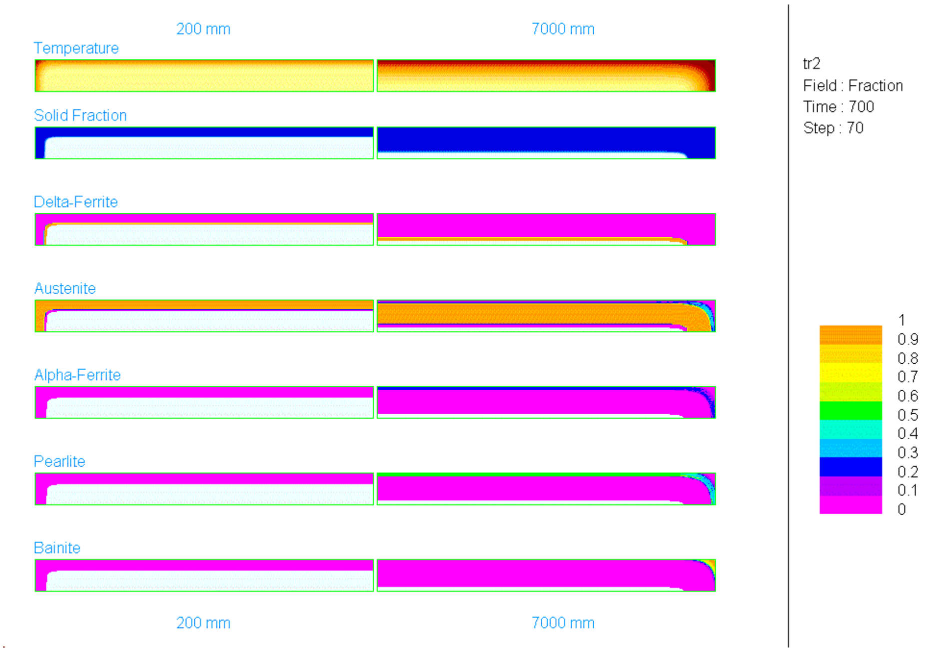
Figure 11: Calculated microstructure evolution, where the concentration field is presented at four different times. The microsegregation patterns and the dendritic morphology of the Al-Si-Mg alloy are shown. Calculation realised with calcosoft®-2D.

Further modelling tools allow nowadays to predict defects related to microstructural features, but also to stress generation and deformation, such as the formation of hot tears and cold cracks. Various attempts are also underway, which aim to directly link the material properties (essentially mechanical and electrical) to the as-cast microstructure. By doing this, the full range of metallurgical properties and casting defects can be predicted based on the knowledge and the simulation of the processing conditions.

6. Solid state transformation

A continuously cast steel slab will not be homogenous but will present different phases from the surface to the core. The presence of different phases is explained by the solid state transformation occurring during cooling. The solid state transformations can be modelled using the appropriate simulation tool. Figure 12 presents the appearance of the different phases, 200 and 7000 mm. below the liquid level. The fractions of delta-ferrite, austenite, alpha-ferrite, pearlite and bainite are shown. The liquid is drawn in white.

Figure 12: Phase analysis of a steel slab at two different locations during the casting process. Left: analysis at 200 mm



below the liquid surface. Right: analysis at 7000 mm below the liquid surface. The fraction of each phase is given in accordance to the colour scale. Calculation realised with calco*soft*®-2D.

This tool can be coupled to an electromagnetic heating simulation package to provide a modelling package for heat treatment. This type of tool is commonly used to predict martensitic transformation in hardening operations.

7. Software: calco*soft*®

The calco*soft*® package is the only software on the market which is truly tailored for the needs of continuous casting processes. This computer simulation package is fast, easy to use and accelerates the development of evolving industrial applications. This software gives a new perspective in finding solutions to novel casting processes and alloy selection.

The calco*soft*® package is the result of intensive collaborations, initiated in 1985, between Calcom SA and the Swiss Institute of Technology in Lausanne. It has been designed to solve different type of problems:

- Temperature, solidification prediction,
- Analysis of the shell growth
- Fluid flow
- Macro- and micro-segregation problems
- Grain structure prediction
- Hot-tearing
- Induction heating and heat treatment

Different modules have been developed to answer specifically each of the above mentioned subjects. All the modules can be coupled to guarantee optimal results. The package exists in a 2D and in a 3D version. Inverse calculation capabilities have also been developed to set real boundary conditions and accurate material properties. The aim of calco*soft*® is to provide the industry with a powerful, easy-to-use package, which will help cast better products. All the simulations in this chapter have been realised with calco*soft*®.

8. Investing in Casting Simulation

Casting simulation has been in existence for more than 20 years, and it is now recognised as a standard in the shape casting industries. However, several cast houses that concentrate on continuous casting are still evaluating the payback of a potential investment in this modern technology.

A critical stage is to launch the investment at the right time. If a company waits too long, it takes the risk of being left behind by competitors, which have succeeded in making casting simulation work to their advantage. On the other hand, if the company launches it too early, then it might suffer unnecessary through the painful and expensive lessons associated with deploying a technology for which the company is still immature.

An investment decision should at least rely on the following questions:

- Which problems need to be solved;
- Are the right persons available;
- Are the cast house engineers ready to integrate a new tool.

The selection of the right partner is the second decision the company has to overcome. Whereas some companies have initiated simulation activities with multi-purpose simulation packages (for either thermal-, flow- or mechanical-computations, rarely all three together), most recognise nowadays the advantage of having a professional and dedicated software such as calco*soft*®, which enables coupled thermal-, flow- and metallurgical-analysis of continuous casting processes.

Without being comprehensive, some features are listed which need to be verified for the selection of the right software:

- Clarity of the software, friendliness of the user interface;
- Reliability of the results, computation speed;
- Automatic mesh generation, possible CAD and CAE file transfer formats;
- Current modelling capacities and extension possibilities;
- Material databases;
- Dynamic visualisation tools, web interfaced results;
- Competence of the support team;
- Reference customers in the same industry field.

Once a simulation software has been introduced in the cast house, then it should not be used for troubleshooting right away. As any new tool, some experience is required before full profit can be taken from it. Therefore, it is important that simple cases are solved with success first, before gradually moving on more complex ones.

9. Conclusions

Casting simulation will never replace an experienced engineer. Nevertheless, it is currently the only tool, which permits to visualise what is happening in the mould and what causes defects and microstructure formation during solidification. It is also the only way to effectively do radical experiments. In this respect, simulation is an invaluable partner for the development and the optimisation of casting processes. Cost can be saved, experience earned and a marketing message can be achieved by first casting it on the computer.