In Light Metals 2002, Ed. W. Schneider , TMS.2002, p. 703-708.

THERMO-MECHANICAL MODELING TO PREDICT SHRINKAGE, SHAPE AND MOLD OPENINGS FOR DC-CAST ROLLING INGOTS

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Abstract

The traditional way to design mold openings of DC-cast rolling ingots is based on measured values of shrinkage combined with interpolation methods. Difficulties arise, when the basic measured values are far from the shape and casting speed desired, as extrapolation on this basis does not work. On the other hand, available thermo-mechanical simulation tools for the DC-casting process are based on purely physical models. After validation using a given ingot size and casting speed such a model should be capable to predict the correct shrinkage even far away from the validation point at quite different ingot shapes and casting speeds.

Here, a 3-D thermo-mechanical model, based on the general purpose software Abaqus, which takes into account relevant material behavior, was tested for its ability to predict the ingot shrinkage for both, large and small ingot sizes and additionally different casting speeds after evaluation of the model for a medium size ingot. Resulting shapes are compared with measured data and the influence of ingot size, casting speed and cooling conditions on the accuracy are discussed.

Introduction

An important demand on aluminum sheet ingots is keeping the scalping scrap as small as possible. The typical cast length has changed from roughly 4m in the past to 9m on most of the modern pits, and also scalping machines have been improved e.g. with faster and more precise measuring equipment. So the achievement of a good surface appearance combined with an optimized ingot contour has become even more important. As described above, the traditional way to calculate the necessary mold opening needs measured data of cast slabs, which have a similar size, alloy and casting speed as the new or to be optimized ingot. Such an optimization method for the calculation of the expected shrinkage of a new slab size from given data was presented by C. Weaver [1] about ten years ago. In his conclusions on this empirical extrapolation model he assumed the predicted shrinkage to be valid within a certain given accuracy for the same alloy group. Results will be correct within a range of ±60-150mm ingot width, ±50mm ingot thickness and ±10mm/min casting speed around the original measured input values. The basic equation of this model includes casting speed, thermal contraction and an additional factor called pull-in constant, which is alloy and ingot size dependent. More recently, a further improvement of this model has been presented by A. Håkonsen [2], where the rolling faces pull-in is considered in a more sophisticated way, which includes the influence of the width to thickness ratio of the ingot and therefore extends the validity range of the model, but still depends on an alloy dependent constant and measured data. According to the authors own experience, this simple model works surprisingly well and can easily be programmed e.g. into an Excel sheet, but of course relies on precisely measured data.

A good example of the limits of these models and the necessary procedures to achieve acceptable results beyond already known sizes is revealed in the work of Grealy, et al. [3] on the development of a new mold design for extremely large rolling ingots. Here, the authors describe the necessary iterative process of measurements and following adjusting of the constants of the model, when the planned mold opening is far wider than the validity range.

On the other hand, in the last decade thermo-mechanical simulation tools of the aluminum DC casting process experienced as well a remarkable improvement [4-8]. Although most of the models concentrate on the correct calculation of the butt curl during the start-up phase, they are as well capable to predict the shrinkage of the ingot during the steady state conditions [7,8].

One of these kind of models is the outcome of a larger project aimed at getting a package of simulation tools for aluminum DC-casting. Since the end of this project in 2000 these tools are going to be adapted by the participating aluminum companies for internal use. At VAW aluminium AG this is carried out by integrating a 3D-thermo-mechanical model into their toolbox, which is based on the development work of J.-M. Drezet et al. [7,8] and further modifications and refinements within this larger project [9].

The adaptation on the VAW mold technology and its exemplary verification was firstly done for a given ingot size of 1650x600mm [10]. But this size is very close to the ingot size of 1750x600mm, which was used for the validation during the larger program [9]. As the main advantage of these numerical models is the physically based description of the material properties and behavior, it is expected, that after this adaptation the model yields reasonable results even beyond the rather limited range of sizes and casting speeds defined for the validity of the above shown empirical models. The aim of this paper is to prove this assumption and to test the capability of the physics based model. This is done by calculating the shape of a larger ingot of 2200x600mm cast at 60mm/min and of a smaller one of 1100x500mm at 74mm/min using the material property data set of the exemplary verification and accordingly adjusted boundary conditions. Both resulting shapes are then compared with measured data coming from corresponding full size casts and finally the accuracy of the simulations are concluded.

Model Description

The above mentioned 3D-model is realized with the general purpose software Abaqus. A more detailed description of the model implementation and the assumed simplifications can be found in [7-12], but a brief presentation of the concept will follow. Based on a finite element formulation to compute the stress build-up within the solidifying ingot, the model calculates the time-dependent development of temperatures, stresses and stress induced deformation. The stress-strain dependency is described by a viscoplastic material model within Abaqus using a rate dependent plasticity analysis. The model allows to predict the butt curl as well as the rolling faces pull in. Although fluid flow influence on temperatures is not included in the governing equations, it is taken into account by an accordingly increased heat conductivity in the molten state.

Geometry

The computational domain is limited to a quarter of an ingot because of assumed symmetry. An important point regarding the application of the model as a mold design tool is the enmeshment of the solution domain. An appropriate distribution of calculation nodes is achieved, when a stable mathematical solution of the problem is reached within a minimum computation time, and this solution is unaffected by further refinement of the mesh.

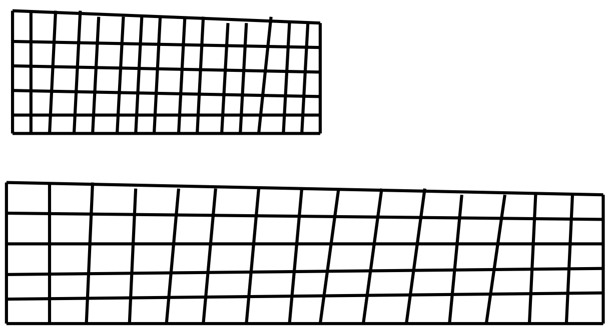

Figure 1: Enmeshment used in the modeling of a quarter of an ingot; top : 1100x500mm, bottom: 2200x600mm

In case of the pull-in modeling concept, the principal design of the mold opening and the enmeshment of the ingot as well as the bottom block are fixed. In the actually used model the grid is made of layers of a constant number of 96 nodes, with 16 nodes along the rolling side and 6 nodes along the narrow side. This is sufficient to get the previously mentioned accuracy. The positions of the outer nodes follow the desired shape of the mold opening. With a typical thickness of 30mm per layer the length of the ingot is then defined by choosing an appropriate number of layers. Fig. 1 shows horizontal cross-sections of the mesh representation for both investigated cases, the 1100x500mm ingot and the 2200x600mm one. As a consequence of the fixed grid concept the enmeshment of larger ingots is quite coarse, but from the viewpoint of mold opening design the capabilities of geometry modification are still satisfactory.

In order to ease the usage of the model with regard to mold design, a special pre-processor [13] is part of the VAW toolbox for easy modification of shape data, cooling conditions, casting speed etc. The appropriate material data for the alloy to be cast are selected from an integrated data base.

Initial and boundary conditions, solution strategy

As the basic formulation of the solved equation is time-dependent, the calculation always begins with the transient start-up phase of casting. Then the simulation is continued until steady state conditions are reached. As the start-up itself has no influence on the steady state rolling faces pull-in, at which the mold design optimization aims, the start-up is strongly simplified. Only the first lower layer is defined as bottom block. Between this simple bottom block and the ingot the boundary conditions assume full contact heat transfer or an air gap developing according to the butt curl. During the early stage of casting (up to 300mm cast length) the direct cooling boundary conditions defined for the steady state are reduced by a given factor, while later on it is increased to full strength. In addition, the cast always starts with the final casting speed. A detailed description of the definition of the boundary conditions and the material properties data can be found in [10,11]. Finally, after reaching a satisfactory cast length for achieving the steady state ingot contour, a one hour cooling is applied in order to get ingot values at ambient temperatures, which can be compared with the measurements.

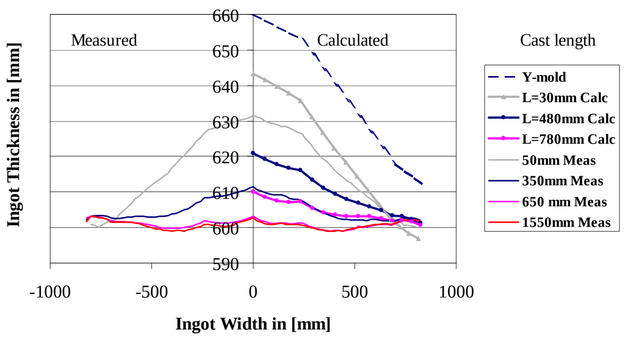

Figure 2: Measured and calculated contour results during start-up of a 1650x600mm ingot size (Y-mold is the mold opening used for modeling and measuring) [10]

Adaptation to VAW mold technology

As mentioned above and described in detail in [10], the model was adapted to the in house technology and tested for the start-up of a 1650x600mm hot top cast ingot. The calculated ingot shape was compared with the measured contour in the butt area (c.f. Fig.2) and a reasonable agreement was achieved. But in that case, the main attention was paid to the start-up phase, especially regarding the heat transfer to the bottom block and to the cooling water. As the model is rather based on physical descriptions of material properties than on empirical found laws, it should deliver comparable good results with cases of quite different size and casting speed, which are the most common changes besides the alloy type.

Though the outcome of the model at different aspect ratios and casting speeds was tested and compared with results of different other models [14] and was regarded as reasonable, it was so far not compared with measured ingot shapes. Therefore, here the adapted boundary conditions and material data of the 1650x600mm case are combined with existing mold openings to calculate the steady state ingot contour for a 2200x600mm hot top ingot cast at 60mm/min and for a 1100x500mm hot top ingot cast at 74mm/min, and then compared with related measurements.

Results and Discussion

The 3D model delivers an abundance of resulting data, e.g. stresses, strains, deformations and temperatures. Concerning the mold design problem, the most important parameter is the development of the ingot geometry as a result of the contraction of the rolling face. Key values to demonstrate this are development of the ingot thickness at the center of the rolling face along the entire length and the ingot contour or shrinkage at given cast lengths. In the following sections these values are used to present and discuss the simulation results and later on to compare with real ingot shape measurements.

Case 2200x600mm

As a first result of the calculation Fig.3 shows the changing ingot thickness at the center of the rolling face of the 2200x600mm ingot from bottom to the top. It starts at about 650mm thickness at the bottom of the ingot, which approximately corresponds with the mold opening at this position and is due to the extremely different heat flow mainly directed into the bottom block at this stage. As the sump profile develops according to the changing cooling conditions during start-up, the thickness begins to reduce at 200mm and it has reached an almost constant thickness of around 608mm after 810mm. The localized thickness oscillation at about 400mm is related to the change of the cooling conditions from start-up to steady state at this cast length. Finally, at the end of the simulation close to 1500mm, the thickness slightly increases, what is also known from practical experience with hot top molds [15].

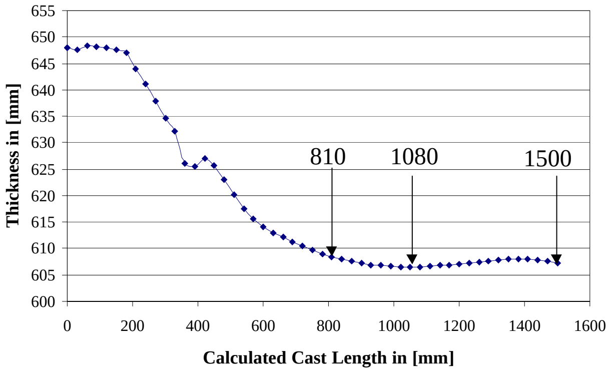

Figure 3: Calculated ingot thickness along the center line of the rolling face of a 2000x600mm ingot cast at 60mm/min.

The three indicated cast lengths of 810mm, 1080mm and 1500mm in Figure 3 are selected for the evaluation of the full ingot contour (c.f. Fig.4). Because of the assumed symmetry, only one half of the contour is shown. Thickness values at about 1100mm width correspond to the size at the edges of the ingot and those at zero width to the measure at the center of the rolling face. Additionally, the mold opening used in the calculation is shown as well as a mold opening, which was optimized using the empirical methods mentioned above based on experimentally cast and measured ingots of this size. This optimized mold opening is expected to deliver an optimal, completely flat 600mm thick ingot as indicated in Fig. 4, too. The calculated ingot contour at the three selected positions show really minor differences and are nearly identical, which again proves that steady state conditions are reached. At the center, the deviation from the optimal flatness is about 8mm. This corresponds very well with the deviation of about 7mm between the mold opening used in the calculation (660mm) and the optimized mold opening based on the experiments (~653mm). At a width of about 350mm the calculated thickness meets the 600mm, and accordingly the two mold openings show coincident values. Halfway to the edge, the calculated ingot shows its minimal thickness of about 595mm, which again agrees very well with a deviation of about 6mm between the mold opening used in the calculation and the optimized one. Further towards the edges the difference between calculated and optimum size again is very small, but the direct correspondence between the simulation and empirically derived mold shape is no longer valid. The calculated thickness reaches the targeted size of 600mm at about 1000mm width, while the two mold openings meet each other at about 900mm. Directly in the ingot corner area measured data are missing, because the real edge of the ingot is round while the calculated ingot assumes a rectangular corner shape due to the implemented finite element approach.

This direct comparison between calculated and measured ingot thickness is useful to judge an ingot contour in concern of the related customer specification.

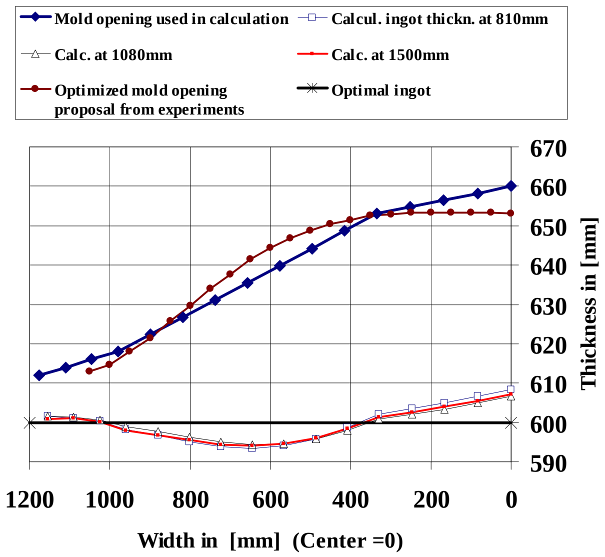

Figure 4: Calculated ingot contour at the 3 cast lengths indicated in Fig. 3, mold design used in the calculation and optimized mold design for a 600mm flat ingot revealed from experiments

A more convenient way to visualize these differences between measured and calculated results is the comparison of the non-dimensional ingot shrinkage normal to the mold width $S(x_D)$, which can be derived from mold opening $MO(x_M)$ and related ingot thickness $D(x_D)$, using the following equation:

$$S(x_D)=\{1-D(x_D)/MO(x_M)\}*100 \qquad (1)$$

where x_M is a position on the mold and x_D is the corresponding position on the ingot taking as well into account the shrinkage in direction of the ingot width (This can be calculated from the mold opening of the narrow side and the ingot's width).

This shrinkage $S(x_D)$ is shown in Fig. 5 for the 2200x600mm case using all three calculated and the measured data, which are the basis for the optimized mold opening displayed in Fig. 4. In general, the agreement between the data achieved from the measurements and from simulation is acceptable well. In the center of the ingot, shrinkage in the model seems to be slightly underestimated compared with real data. Vice versa, shrinkage is higher than the measured values close to the narrow faces of the ingot. Nevertheless, as a maximum difference of about 0.3% means an approximate error of 2mm in ingot thickness, this is an excellent result, because it is about the error one can sometimes find in measured data coming from the cast houses.

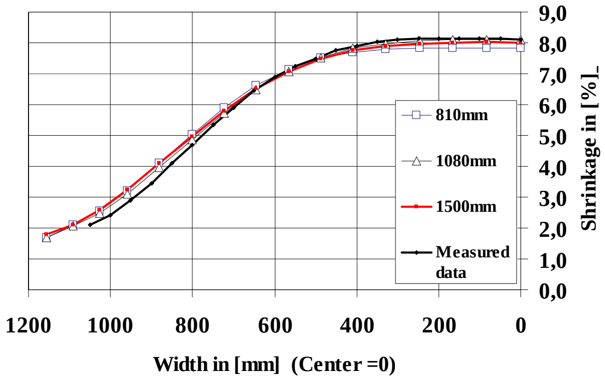

Figure 5: Calculated and measured ingot shrinkage for a 2200x600mm ingot cast at 60mm/min

Case 1100x500mm
The other case used to test the validity range of the model assumes a typical small mold (1100x500mm) in combination with a significantly higher casting speed of 74mm/min, but the same hot top mold technology. According to the identical mold design boundary conditions for the cooling remain unchanged.

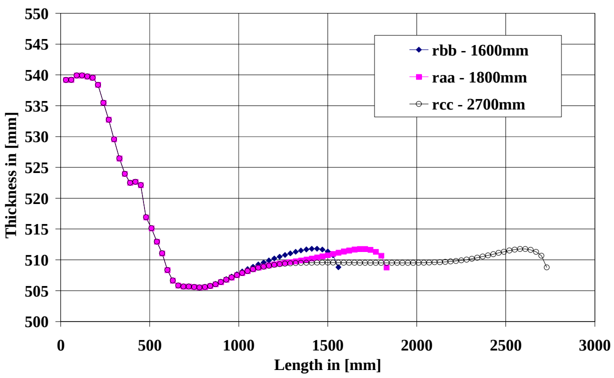

Figure 6: Calculated ingot thickness along the center line of the rolling face for the same ingot size of 1100x500mm and casting speed 74mm/min simulating three different cast lengths

Regarding to the substantial increase of the casting speed, an achievement of steady state conditions at a simulated cast length of 1500mm revealed impossible owing to the more pronounced transient start-up and ending phases. So, additional calculations with larger ingot lengths of 1800mm and 2700mm were carried out. The development of the ingot thickness along the center line of the rolling face for these three simulation runs (c.f. Fig. 6) indicates clearly, that for a higher casting speed a longer ingot needs to be modeled. Up to 1000mm the three curves are identical and the principal thickness reduction is governed by the same influences as described in the case of the large 2200x600mm ingot.

But then, the result of the 1600mm long case shows no evidence to reach a zone with constant thickness, which would indicate steady state conditions, while the curve of the slightly longer ingot indicates a decreasing change in ingot dimension between about 1300 to 1400mm. Eventually, the calculation of a much longer (2700mm, rcc) ingot develops an easily visible zone of an almost constant thickness between 1400 to 2200mm. And again, the different casting and solidification conditions at the top seem to slightly exaggerate the already, in case of the larger ingot, described thickening within the last 300 to 500mm of the ingot.

On the basis of these results it can be derived, that in this case a length of about 2100mm should be sufficient to establish a small steady state zone, which is of practical importance as the solution time for solving this problem is a function of the squared number of layers.

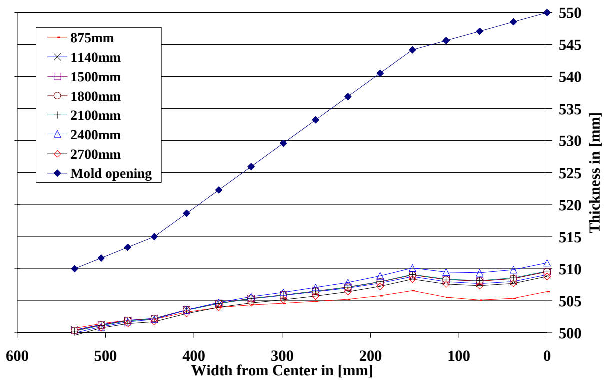

Figure 7: Calculated ingot contour at several cast length (case rcc) and related mold opening for a 1100x500mm size ingot cast at 74mm/min

For selected cast lengths of the longest case rcc, Fig. 7 shows the ingot contour and the related mold opening. Except for the contour closest to the butt at 875mm and that near the top of the ingot at 2400m the ingot profile remains constant as expected from the results displayed in Fig. 6. The ingot contour in the butt area is of minor interest, since it depends strongly on the shape of the bottom block, the related cooling and the start-up procedure, which are simplified in this calculation as explained in the model description. The differences regarding the ingot contour in the top area near the center of the rolling face, where the head experiences a thickening, correspond, as already stated, with cast house experience.

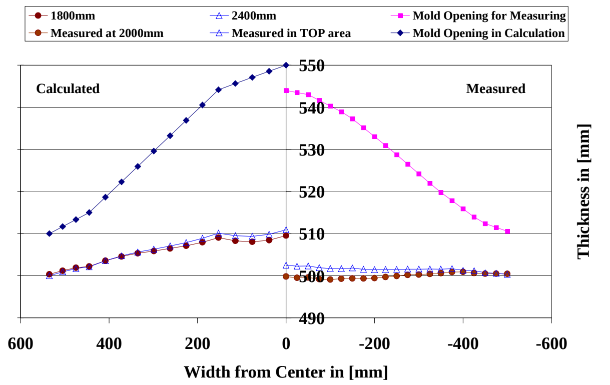

Figure 8: Calculated and measured ingot contour in steady state regime for a 1100x500mm size ingot cast at 74mm/min together with the mold opening used for the calculation and for the experimental cast

Corresponding to the 2200x600mm case the simulation results are compared with real cast ingots using a comparable mold design. In Fig. 8 the right hand side shows as well the mold opening for this 1100x500 mm ingot size as the ingot contours achieved with this mold for steady state conditions (at a cast length of 2000mm) and close to the top, while in the left part of this figure the mold opening used in the calculation (case rcc) and the ingot profiles at 1800 and 2400mm are displayed. In the center of the rolling face, the difference between measured and calculated ingot thickness is about 10mm, but the difference in the mold opening is only approximately 7mm. This again indicates that in case of the center region of the ingot the simulated shrinkage is slightly too small (c.f. Fig. 9) as it is illustrated in Fig. 5 for the large ingot. Towards the edges, the difference between both curves decreases to almost zero, which is an even better coincidence than in case of the bigger size.

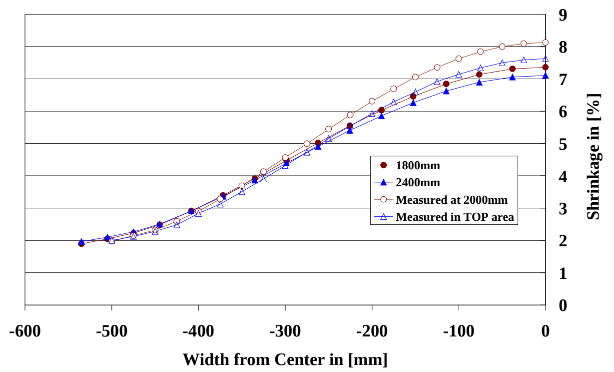

Figure 9: Calculated and measured shrinkage in the steady-state regime and in the top region for a 1100x500mm ingot cast at 74mm/min

In the top area, the measured ingot thickness in the center of the rolling face is about 3 to 4mm thicker than in the steady state zone. Also the calculated profiles similarly increases towards the center of the rolling face, but with less magnitude. On the other hand, the model output of all displacement data is only available at previously selected simulation steps in order to minimize necessary data storage on the computer. As can be seen from Fig. 6, the available 2400mm profile does not fully represent the maximum thickness in the top area. Therefore, on the basis of the results presented in Fig. 6, the maximum increase for the complete ingot thickness compared to the steady state case is about 2 to 3mm, which is in excellent agreement with the measured 3 to 4mm.

In Fig. 9, the comparison of the derived shrinkage of the measured and simulated ingots using the above mentioned function given in Eq. (1) strictly supports these findings. In the outer area of the ingot, starting from 300mm until the edge value of 600mm, all curves show a very good agreement. Towards the center, a slightly increasing difference can be detected, which reaches a maximum of about 0.6% in the center itself corresponding with the already described difference of 10mm between the mold openings and 7mm between the ingot thickness.

Conclusions

The accuracy of the calculated results compared with measured data is surprisingly good, even in the top region of the ingots, where the model should be considered as not fully applicable, due to the lack of a realistic fluid flow and feeding description. The overall difference in thickness between the simulations and the measurement is within about 1%. A part of this error might even result from inaccuracies in the measurement of the real ingot and mold sizes. The calculated results are obtained with even not fully optimized boundary conditions in the case of the casting speed of 74mm/min and though the model does not include fluid flow within the sump. The chosen constant enmeshment for the different sizes of the modeled ingots reveals to be adequate for the problem solved. Both examples show a tendency of a slightly underestimated shrinkage towards the center of the rolling face. This might be again triggered by the missing consideration of the fluid flow influence on the sump depth. The results demonstrate, that the model based on the physical material data properties can be used within a wide range of casting parameters far beyond the dimensions and conditions of the reference case, which was used for validation, as long as the physical data are valid.

In spite of these rather positive conclusions, the practical usefulness of the model still needs to be improved.

First of all, depending on the simulated cast length, the CPU time necessary to run one calculation is still quite long at the moment, but with the current increase in CPU speed, this will be no restriction in the near future.

As well, the future demands on ingot contour accuracy aim at maximum deviations from the desired contour of about 1mm for a 500mm to 600mm thick ingot. This is an accuracy of roughly 0.2 to 0.3%, which still can be obtained with the empirically based methods mentioned in the introduction. But this means the costly and time consuming process of building a mold, doing a cast, measuring the ingot and building an improved mold.

On the other hand, if there exist no measured data close to a size and casting speed of an ingot to be produced, the model is already now a powerful tool, with a good chance to reveal a close to optimum first mold opening design for the targeted contour. Future parallel use of the model and the conventional method to design a mold shape will help to improve the accuracy.

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