Sensitivity Analysis of a Thermo Mechanical Process Model for Shell Formation in Continuous Casting

J. Wendelstorf

Clausthal University of Technology, Robert-Koch-Str. 42, D-38678 Clausthal-Zellerfeld, Germany, E-Mail: jens.wendelstorf@tu-clausthal.de

ABSTRACT: The strand shell formation in the continuous casting mould and the early stages of secondary cooling is critical for the process reliability and the overall process performance as well as the quality of the near surface part of the strand. Reliable process models with significant extrapolation capabilities are still under development.

This paper attempts to identify the set of process parameters of highest relevance and demonstrates the sensitivity analysis of continuous casting process models.

Due to the fact that the heat fluxes and shrinkages in the plane perpendicular to the casting direction are dominant, a 2-D process model for the strand shell formation is a good starting point. It includes thermal shrinkage data from the TCFE6 database, the modelling of a self consistent gap and the resulting heat transfer to the mould surface. After some validation against experimental data on mould heat flux, a sensitivity analysis of this model provides quantitative information about the effect of the controllable process parameters on the strand shell properties related to the overall process productivity and safety.

These sensitivity results from an ABAQUS/THERMOCALC based process model for billet and slab casting are critically discussed, especially with respect to the practical relevance. The importance of plant data (e.g. from mould instrumentation and break out shells) for model parameter identification is highlighted. Finally the role of the interface heat transfer coefficient (IHTC) in model development and corresponding laboratory experiments are discussed with respect to model validation and practical application.

Introduction

Continuous casting is the most important process for the primary shaping of steel. For an introduction and the state-of-the-art see [1], especially chapters 4 and 5 as well as [2]. As a conclusion, experimental and numerical research work has demonstrated the importance of the initial solidification taking place in the continuous casting mould (primary cooling). The local heat flux between the inner mould surface and the outer strand shell surface is the result of a complicated self organisation process (see *Figure 1*), which can be simulated (to some extend) by CFD methods ([3],[4]) for the meniscus region and which has to be included into self consistent thermo-mechanical FEM models of the strand shell formation (see e.g. [5]).

The modelling activities are manifold and have led to very sophisticated thermo-mechanical models (e.g. [5], [6], [7] and references therein) and CFD models of the fluid flow phenomena (e.g. [4], [8] and [9]), as well as multi-physics models (e.g. [10]). Coupled experimental and numerical investigations (e.g. [11]) have shown the importance of the local interface heat transfer coefficient (IHTC) on the driving force of the process and the heat flux from the strand shell surface towards the mould surface. With increasing shell thickness, the heat conduction through the steel shell itself becomes another limiting factor for the heat transport.

This paper exemplifies the sensitivity analysis for a 2-D thermo-mechanical FEM model using the ABAQUS[i] solver and material properties deduced from the TCFE6 database by THERMOCALC[ii] [12].

After identification and discussion of the relevant process parameters, these are classified into groups and the sensitivity of some measureable variables describing the resulting shell formation with respect to a variation of these process parameters are calculated and discussed. Finally, the impacts on the overall model validation as well as the direct practical consequences will be summarized.

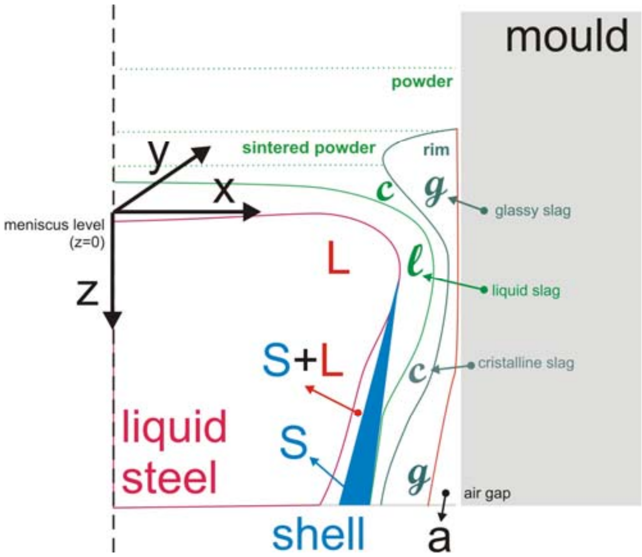

Figure 1: Schematic of the strand shell formation in the continuous casting mould.

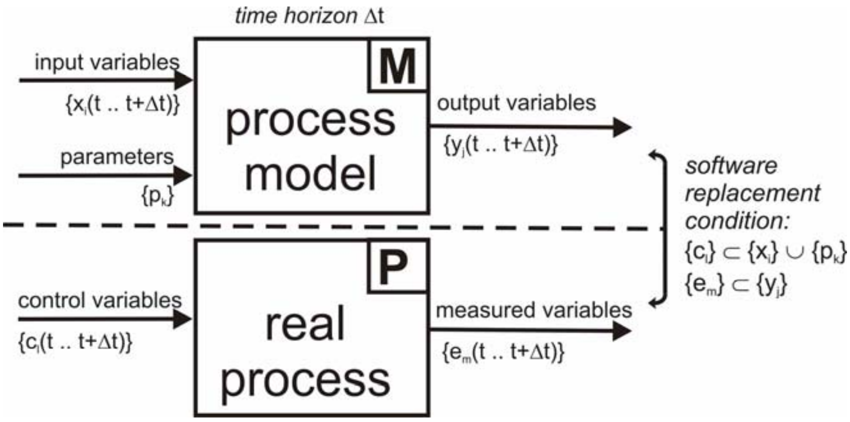

Figure 2: Definition of a process model as simulator of the real process [13].

Parameters

In general, a process model can be seen as a software replacement for certain aspects of the real process being simulated using the model. Some input parameters x_i are time dependent while others p_k are not. The (time dependent) output variables y_j should coincide with variables which can be measured in the real process, while the inputs should coincide with the control variables of the real process (*Figure 2*, [13]). As a conclusion, the x_i, p_k and y_j have to be defined for a certain process independently of a specific model implementation[iii]. A subset of the definitions used for the continuous casting process can be used for the parameterization of the melt flow and primary cooling process within the mould. A further subset is relevant to the strand shell formation process and will be discussed here.

Initial solidification and primary cooling in the mould is crucial for stable operation at maximum productivity and the final (near) surface quality of the slab or billet. The driving force is the heat flux between the outer strand and the inner mould surface. In the meniscus area, this heat flux can be seen as a result of the complicated casting powder (slag) infiltration mechanisms taking place within each oscillation cycle [3]. There is no direct external setscrew for the local heat flux in general and especially its maximum value in the meniscus area. With growing local thickness of the strand shell, it can withstand the ferrostatic pressure and the thermal shrinkage becomes an important factor for the interface heat transfer coefficient (IHTC) too. At the latest when the strand surface temperature is below the resolidification temperature of the flux powder, the liquid flux can not fill the shrinkage gaps and gas filled gaps may form, further decreasing local heat flux. The following ***input variables*** x_i ***and parameters*** p_k can be influenced by the caster designers and/or operators:

- Mould dimensions (d_{wall}, $l_{x,y,z}$ and taper $\Delta l_{x,y}$), water cooling (e.g. α_{H2O}) and oscillation parameters.
- Casting velocity v_C.
- Lubricant (oil or powder) properties, e.g.

λ*(phase,T)*.

- Steel Grade/Melt composition determining the thermodynamic and mechanical properties during solidification.

Up to now, the following relevant ***output variables*** y_j can be measured to some extend:

- The heat flux q as a function of position in the mould, especially:
  - o Maximum heat flux (wide face $q_{x,Max}$, small face $q_{y,Max}$).
  - o Mean heat flux (wide face $q_{x,avg}$, small face $q_{y,avg}$).
  - o Mould exit heat flux (wide face $q_{x,end}$, small face $q_{y,end}$).
- Strand surface temperature at mould exit (wide face $T_{s,x,end}$, small face $T_{s,y,end}$).
- Strand shell thickness (e.g. $d_{ws=0.65}$ at mould exit).

Modelling provides a number of additional results, e.g. on local stress/strain distributions, but their experimental testability is insufficient. The lubricant (powder or oil) consumption can be determined experimentally but is also prescribed somewhat by the operators. For local quantities like the heat flux, the model values have to be taken at the same positions as the measurements.

During shell formation, mainly thermal shrinkage causes stresses and strains within the solidified shell. These can be computed by models like those discussed here and these stresses can be measured (see e.g. [14]). No published data was found for steel breakout shells. As a result of these stresses, cracks may form within the shell as well as at the strand surface (see e.g. [15]).

The model and experimental validation data

The model used for this paper is a simplified 2-dimensional thermo-mechanical strand shell formation model similar to that of [5] using the FEM solver ABAQUS with the following details:

- The calculation region is a L-shaped downwards moving slice of the strand and it's corresponding part of the mould (see *Figure 3*). A discussion of this widely used method can be found in the literature (e.g. [5]).
- The thermodynamic data is taken from the TCFE6 database using Thermocalc[ii] software [12].
- The thermal shrinkage data is calculated from the specific density data provided by the TCFE6 database (see *Figure 4*).
- The elastic and plastic material properties and the heat conductivity of the strand shell are taken from the literature (e.g. [16] and [17]).
- The heat transfer between strand and mould surface is modelled by a user defined function (GAPCON) including the following effects: λ*(phase,T)* functions for all slag phases, air gap formation, heuristic modelling of the meniscus shape etc…

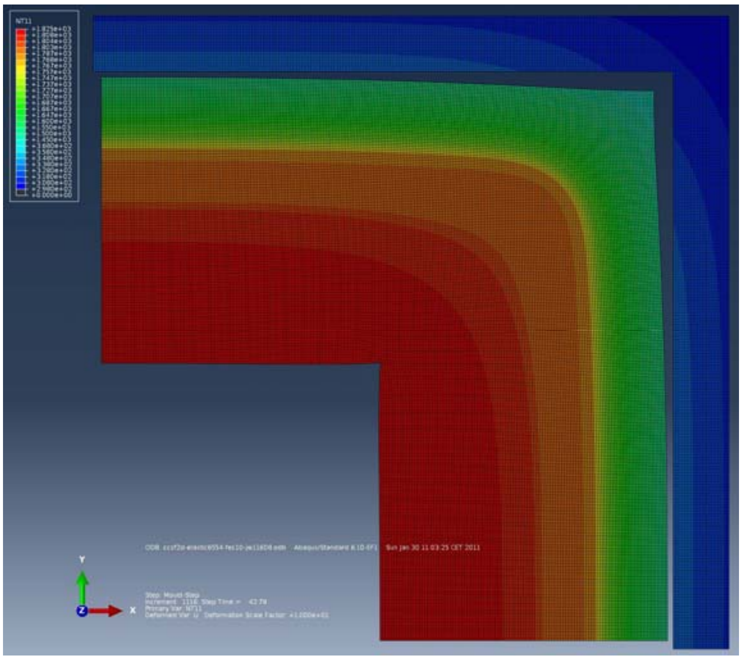

Figure 3: Calculated temperature distribution at the mould exit (parameters from melt 262 of [18], shrinkage amplified by a factor of 10).

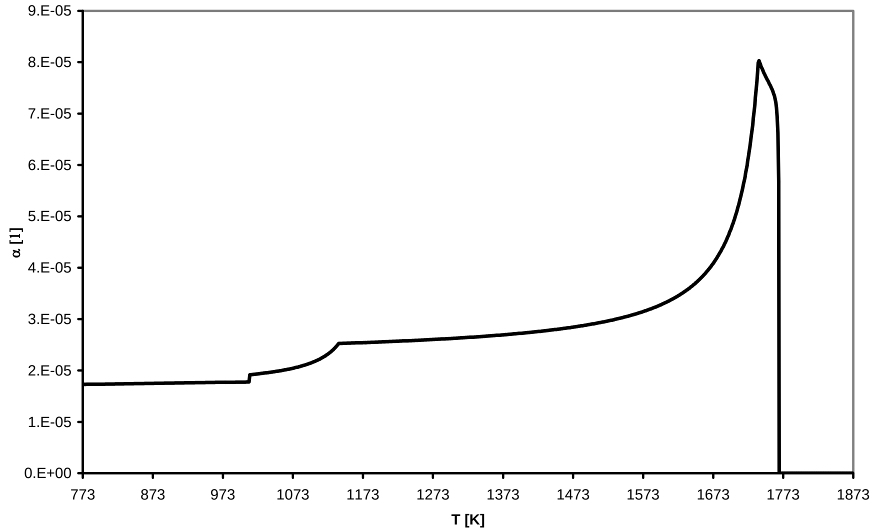

Figure 4: Thermal expansion coefficient calculated from TCFE6 data (Fe+0.11%C, reference temperature 1767.53K).

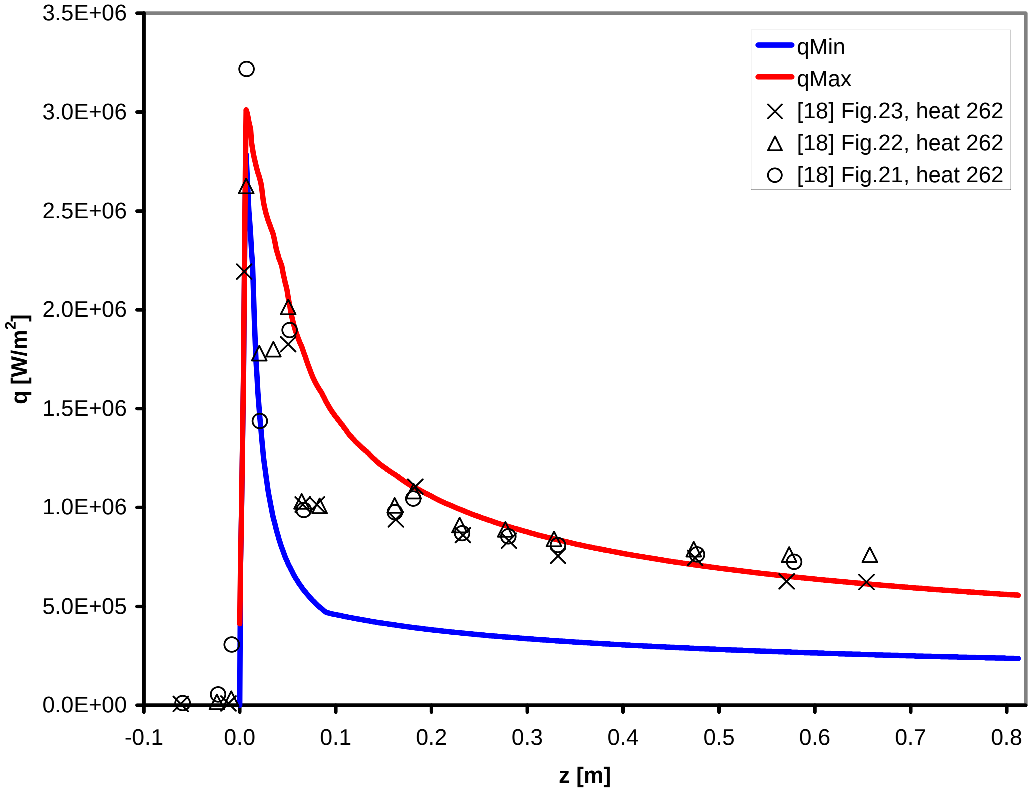

Figure 5: Heat flux in the mould as a function of vertical position (see text).

Special care is taken on the treatment of the liquid material, as discussed by the other authors cited above and with respect to the results from [19]. As stated above, this paper is dedicated to a determination of the parameter sensitivity of strand shell formation by numerical modelling. For motivating the accuracy and practical relevance of the data, the modelling data has to be compared with measurements. An early approach to measure the heat flux towards the mould as a function of vertical position is a segmented cooling system [20]. A number of authors investigate the primary cooling process by instrumenting their moulds with thermocouples and attempting to determine the local heat flux density to the mould surface by inverse modelling (e.g. [21]). From these measurements, exemplary data for billet is taken from [18]. For slab casting, some shell growth profiles were found [22] and some heat flux measurements were taken from [23]. With some exceptions (e.g. [18]), the heat flux data available in the literature suffers from the incomplete specifications of the casting parameters. The positioning of the thermocouples as well as the IHCP methodology determines the accuracy of the results and it is difficult to find measurements with substantiated accuracy. Additionally, the continuous casting process often shows fluctuations in the meniscus level and the mould oscillation further complicates both heat flux measurements as well as modelling.

While it is not the objective of this paper to obtain the best fit to experimental data by optimization of the model parameters, the limitations of both, the measurements and the process model can be discussed by plotting the driving force of the process, the horizontal heat flux density into the mould surface against the distance from the steel meniscus level. As shown in *Figure 5*, there is considerable agreement between the measured [18] and calculated heat flux densities. For square billet casting, the model predicts a heat flux density near the q_{max}-line with larger deviations at the edges (q_{min}-line). The limitation of the measurement is the large measurement error for q, the limiting factor of the model is e.g. the heuristic sub-model for the self consistent determination of the local heat flux through the temporarily and spatially varying layer system between strand and mould surface, as sketched in Figure 1. In practise, there is a lot of scatter in the local behaviour of the slag layer. In the meniscus region, its behaviour is determined by the mould oscillation and at least when the strand surface cools below the solidification temperature of the flux, the solidified slag may form cracks due to phase transformations and residual stresses. Rather than forming a solid coating on the strand surface, the mould flux consumed during the process leaves the mould downwards filling the oscillation marks and by rinsing through the gaps formed due to shrinkage of the shell.

The sensitivity of some of the modelling results on the properties and behaviour of the mould flux will be discussed below, but it is obvious that before such a model is used in practise, parameterizations are required using as much of the available experimental data as possible. This validation and parameterization of the model benefits from the following measurements taken from casting process settings as close as possible to that to be predicted:

- Strand surface temperature at the mould exit.
- Local heat flux measurement by solving the IHCP using local thermocouple data and/or separated cooling channels.
- Residual stress measurements, e.g. as described in [14].
- Shell thickness data from breakout shells.

Such measurements require smooth meniscus level and powder feed control and the results may be a function of the mould oscillation parameters as well as of the powder used.

Sensitivity Analysis

A sensitivity analysis of a non linear system is a complex task requiring a significant number of experiments or simulations. For the continuous casting process, the experimental data in the open literature is limited and an experimental sensitivity analysis is restricted by the scatter or unavailability of accurate measurements. Process modelling provides a large amount of details but is bounded by computational complexity and the lack or intractability of a model including all physical phenomena in all sub-regions simultaneously. As a result, all models have *external* parameters which have to be determined by laboratory experiments or inverse modelling using plant data. Additionally, not all real process parameters have a specific meaning for a specific model, e.g. the mould oscillation parameters are not direct input parameters for the shell formation model used here.

Beneath the immediate relevance of the results, a sensitivity analysis is part of the major task of process optimization and the computation of the process feasibility for novel designs or novel steel grades. It is required for determining the most promising set screws. Additionally the results provide detailed data for the evaluation and validation of the model itself.

The local sensitivity s_{jk} of an output (i.e. measurable value) variable y_j with respect to a process parameter p_k is defined by (e.g. [24])

$$s_{jk} = \frac{\partial y_j}{\partial p_k} \quad (1)$$

The interpretation of sensitivities is easier, if they are normalized, i.e. using typical values $\tilde{p}_k$ and $\tilde{y}_j$

$$\bar{s}_{jk} = \frac{\partial y_j}{\partial p_k} \cdot \frac{\tilde{p}_k}{\tilde{y}_j} \quad (2)$$

A sensitivity analysis is an effective mean to determine the critical model parameters but one has to keep in mind the locality of the definitions presented above. In general, the sensitivities are functions of the x_i and p_k itself and a global sensitivity analysis is an extensive venture [25]. As the process is simulated by a rather sophisticated model, the available computer capacity limits the number of data sets x_i and p_k where simulations can be performed. Therefore, the local sensitivity will be calculated for two typical casting situations (billet and slab) using parameter settings as close as possible to those used in the mould heat flux measurements reported in [18] for billet casting and [23] for slab casting. The sensitivities will be calculated by approaching equations (1) and (2) by their finite difference approximations.

Numerical Parameters

All thermo-mechanical models of strand shell formation are based on simplifications and the solution is obtained using a numerical grid with limited resolution – they thus contain numerical parameters. While the impact of the physical simplifications will be investigated in the next section, this section deals with the computational parameters. With some exceptions, the numerical accuracy of complex FEM solvers can not be set *a priori*, it has to be controlled *a posteriori*. The main numerical parameter affecting accuracy is the spatial and temporal discretization. The spatial grid size and the minimum realizable time step is limited by the available computing resources and the wall clock time constraints. The sensitivity of the quantities to be computed with respect to these numerical parameters determines the predictive power of a specific numerical model with respect to a specific quantity. As shown in *Table 1*, the numerical accuracy is much better than the measurement accuracy currently feasible.

The computational complexity (e.g. computing time) also depends on the treatment of the mechanical problem. By proofing the differences in the results to be small enough, an ideal plastic or even elastic calculation is sufficient for most measureable y_j.

Process parameters

The major benefit of a process model should be its ability to investigate the effect of process parameter variations. In reality, the effect of a (small) parameter variation if often difficult to measure, because of the limited instrumentation of the process or the big statistical scatter due to process instabilities or scattering of control parameters. Process modelling avoids these difficulties.

The calculated sensitivity of the most important measureable quantities with respect to the major operational as well as design parameters of the continuous casting process can be found in *Table 2* and *3*. The maximum heat flux q_{Max} is always observed at the meniscus and thus reacts sensitive to a change in the pouring temperature. If the casting temperature is increased by 1% (≈18K), q_{Max} will also rise by ~1.5%, while the average heat flux density will increase by ~5% and the shell thickness at the mould exit will decrease by ~10%. A significant increase of the heat transfer towards the mould by changing the mould design parameters is not possible except for the trivial case of increasing the mould length. Increasing casting speed by 10% will decrease the shell thickness at the mould exit by ~3%. All calculated sensitivities agree with the few available experimental observations so that the model seems to be validated from this point of view.

External Parameters

All thermo-mechanical models of strand shell formation are based on physical simplifications and require powder/slag property data which is difficult to determine experimentally. The calculated sensitivities with respect to some of the major external parameters can be found in *Table 4*. These sensitivities have to be discussed with respect to the accuracies of the corresponding laboratory measurements or the data scatter obtained by comparing the best fit results for different sets of process parameters.

The first parameter owes its existence from the simplified treatment of liquid steel. For numerical treatability of the model, the inner boundary condition has to be set somewhere in the liquid region and the overall thickness of the calculation domain $d_{SimpleFlow}$ therefore affects the results somewhat. The consistency of the model can be enhanced by using CFD models for determination of the inner boundary conditions in an iterative setting, since the CFD models require heat flux boundary conditions being self consistent with the shell shrinkage.

The maximum heat flux is decreased by increased thickness of the (solidified) slag layer d_{slag}, although there is still ongoing research on a self consistent prediction of the thickness of this layer [4]. Its determination is related to the heat transfer coefficient of the solid slag/copper interface which is modelled by its equivalence to a gas filled gap of thickness r_{Mould} (~100µm). A more applicable result is the sensitivity of q_{Max} on the Solidus temperature $T_{S,Slag}$ of the casting slag. A significant increase in $T_{S,Slag}$ will decrease q_{Max} and the average heat flux q_{Avg} so representing a set screw for milder cooling. A similar effect is found for the Liquidus temperature $T_{L,Slag}$ and the glas transition temperature $T_{C,Slag}$.

Another well known factor is the heat conductivity of the different phases of the casting slag as a function of temperature. The model demonstrates the importance of flow phenomena in the meniscus region ($\lambda_{Slag,Multiplier}$). The dependency on the heat conductivities of the solid slag fractions ($\lambda_{Slag,T=TC}$, $\lambda_{Slag,T=TGC}$) is found to be damped and therefore such models can deliver reasonable predictions for mould powders with sufficiently well-known properties.

Finally, the surface tension between the slag and the melt $\Delta\gamma_{slag,melt}$ determines the meniscus shape but has only a small effect on the shell formation.

numerical parameter	*Min.*	*Max.*	Δq_{Max}	Δq_{avg}	Δq_{end}	$\Delta T_{s,end}$	$\Delta d_{ws=0.65}$
Δx	400 µm	1.4 mm	<0.5%	<0.8%	<0.3%	<0.2%	<0.4%
ΔT_{Max} *per* Δt	1 K	8 K	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Δt_{Out}	50 ms	250 ms	0.5%	<0.5%	<0.4%	<0.2%	<0.4%

Table 1: Calculated numerical sensitivity data for casting 208x208 mm billet at 1.14 m/min (0.1%C).

s for: parameter:	q_{Max}	q_{avg}	q_{end}	$T_{s,end}$	$d_{ws=0.65}$
C%	0.6 %	6 %	6 %	-0.1 %	13 %
$d_{Mould\ wall}$	-0.3 %	-0.2 %	<±0.1%	<±0.1%	<±0.1%
l_{Mould}	<±0.1%	-2 %	-53 %	-1.3 %	62 %
$T_{Cast\ (e.g.\ Tundish)}$	150 %	~500 %	~500 %	12 %	~ -1000 %
v_{Cast}	-2 %	5 %	47 %	0.7 %	-32 %
$\alpha_{Cu\text{-}water}$	<±0.1%	-0.2 %	<0.1 %	<±0.1%	<±0.1%
d_{Slab}	3 %	-4 %	-7 %	-0.2 %	22 %

Table 2: Process parameter sensitivity data for casting 208x208 mm billet at 1.14 m/min (0.1%C).

s for: parameter:	q_{Max}	q_{avg}	q_{end}	$T_{s,end}$	$d_{ws=0.65}$
C%	-7 %	-1..2 %	~ -1 %	-0.2%	-6 %
$d_{Mould\ wall}$	-2 %	-0.4 %	-0.2%	<±0.1%	<±0.1%
l_{Mould}	<±0.1%	-0.4%	-50 %	~ -1.5 %	31 %
$T_{Cast\ (e.g.\ Tundish)}$	120 %	500..2800%	500..1000%	-14..+22%	-1000 %
v_{Cast}	-3 %	-4 %	28..43%	1..2 %	-40 %
$\alpha_{Cu\text{-}water}$	0.6 %	-0.2 %	<±0.1%	<±0.1%	0.1%
$d_{Slab,\ wide}$	3 %	-8..+5 %	-7..+32 %	-4..+8 %	3 %
$d_{Slab,\ narrow}$	<±0.1%	-14..+0.5 %	9 %	-1..+1 %	43 %

Table 3: Process parameter sensitivity data for casting 790x120 mm slab at 0.65 m/min (0.07%C).

s for: parameter:	q_{Max}	q_{avg}	q_{end}	$T_{s,end}$	$d_{ws=0.65}$
$d_{SimpleFlow}$	1..3 %	1 %	-18..-3 %	-1 %	~ 25 %
d_{Slag}	-80 %	-13 %	-4..-1 %	1..2 %	-3 %
r_{Mould}	-4..13 %	-0.6 %	-0.3 %	0.14%	-0.3..+1.6 %
$T_{L,slag}$	<±0.1 %	-244%	~ -250 %	~60 %	~ -135 %
$T_{S,slag}$	~ -280 %	-78%	~ -40 %	~16 %	~ -40 %
$T_{C,slag}$	-13 %	-8%	~ -6 %	1..2 %	-3..+17 %
$\lambda_{Slag,Multiplier}$	~80 %	~10 %	-1..+5 %	~ -1.5 %	4..11 %
$\lambda_{Slag,T=TLiquid}$	~80 %	~10 %	1..5 %	~ -1.5 %	6..11 %
$\lambda_{Slag,\ T=TC}$	5 %	1 %	1 %	-0.3 %	1..4 %
$\lambda_{Slag,\ T=TGC}$	<±0.1 %	-0.2..+0.7 %	<±0.1 %	<±0.1 %	<±0.1 %
$\Delta\gamma_{slag,melt}$	0..2 %	0.4 %	0.8 %	-0.2 %	0..4 %

Table 4: External parameter sensitivity data for continuous casting of billet and slab (see text).

Ignored and correlated Parameters

An important issue in the analysis of real world processes is the role of unknown parameters and the correlations between the parameters. The analysis or a mathematical model of a complex process often includes a number of parameters initially ignored and found to be significant later on. Another problem is the correlation of parameters and the mathematical stiffness of the fitting problem to be solved when obtaining parameters from plant data.

A good example is the heat transfer coefficient in secondary cooling by spray water. Nowadays, reliable data on the local HTC as a function of spray parameters, surface temperature and condition is available from laboratory measurements (e.g. [26] and [27]). Additionally to the larger scatter in the laboratory data, some decades ago, something like a mean effective spray cooling HTC was reasoned by inverse modelling techniques (e.g. [28] or [29] and references therein). As a rule of thumb, the accurate measurement of a specific material property or behaviour of a sub-system is better obtained from laboratory measurements than by extensive fitting of inaccurate plant data in an environment, where often the number of unknown parameters is larger than the number of uncorrelated measurements.

Another important parameter is the mould taper. A thermo-mechanical model can predict the optimum taper for a specific casting parameter set by an iterative procedure: Initially, the calculation without any taper provides the gas gap data to be minimized by the mould taper. Deducing the mould taper from this data is a good starting point for the determination of the optimum mould taper. As casting speed, pouring temperature and steel grade may vary using the same mould, a static optimum taper design is a compromise often enhanced by active mechanical actors integrated in the mould design to minimize gas gap formation – a detailed discussion is beyond the scope of this paper.

Discussion

The local self consistent interfacial heat transfer coefficient (IHTC) between the strand and the mould surface determines the solidification conditions inside the continuous casting mould. In the meniscus region, the IHTC is dominated by complex slag entrainment within the oscillation cycle [4] while with increasing thickness of the strand shell, the thermal shrinkage becomes important. The sensitivity analysis has validated the model and quantified the role of some of the most important process parameters, e.g. pouring temperature and casting speed. Some knowledge on the detailed properties of the casting slag is required but a measurement of e.g. its heat conductivity as a function of temperature with an accuracy of better than 10% is not a prerequisite for predicting optimum casting conditions by thermo-mechanical modelling. The parameters for the initial heat transfer conditions in the meniscus area and the convective heat flow within the slag may also be determined by CFD modelling, laboratory experiments and inverse modelling using the data from instrumented moulds – if the measurement of the local heat fluxes is set-up very carefully. The self consistent computation of the local heat transfer is possible using quite coarse numerical grids, while the accurate prediction of the stress-strain history may require finer numerical resolutions.

The calculated sensitivities are local quantities and have to be determined for each specific setting of casting parameters and steel grade. The later is possible, because the thermodynamic data is taken from a general purpose database.

Conclusion

The sensitivity analysis of a thermo-mechanical process model of strand shell formation based on the FEM solver ABAQUS has demonstrated the predictive power as well as the fundamental limitations of such models. The major advantage are the correct predictions of the model with respect to the major process parameters and its ability to calculate the stress-strain history of the strand shell, e.g. allowing for the prediction of parameter regimes with increased sensitivity to cracking. There are also a number of simple direct applications, e.g. the prediction of the required decrease in casting speed due to a specific increase in pouring temperature – as it can be calculated for a specific parameter setting by such a thermo mechanical shell formation model.

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