ACCURATE MODELLING OF HEAT TRANSFER IN CONTINUOUS CASTING: MATHEMATICAL FORMULAS, PARAMETER STUDY AND EFFECT OF STEEL GRADE[1]

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Abstract

A lot of heat transfer models for continuous casting have been developed during the last years. They are easy to use and convenient for simulating the whole casting process. The accuracy of the models depends on many things as for instance on the boundary conditions, materials properties as well as on the model parameters, simplifications and assumptions. The general purpose of this presentation is to study the accuracy of the heat transfer simulations. A short review of the heat transfer models is presented as well as the items affecting the accuracy. The sensitivity of the important model parameters as well as the boundary conditions is studied using the two heat transfer models developed by UFRGS (Federal University of Rio Grande do Sul) and by TKK (Helsinki University of Technology). The effect and sensitivity of the steel material properties on the results is studied by making simulations with different steel grades. The material properties for steels are calculated using a specific model, IDS, developed by TKK. Industrial validations are also carried out. The results showed that the accurate simulations of heat transfer in continuous casting require accurate measurements to characterize the boundary conditions, temperature and alloy-dependent material properties, optimization of numerical and model parameters, and validation with plant measurements. The calculations also showed that both of the models (UFRGS and TKK) gave good and similar results and can be used for accurate simulations if the model parameters, boundary conditions and material properties are correctly defined.

Key words: Continuous casting; Solidification; Heat transfer; Numerical simulation.

MODELAGEM NUMÉRICA DA TRANSFERÊNCIA DE CALOR NO LINGOTAMENTO CONTÍNUO: FÓRMULAS MATEMÁTICAS, ESTUDO DE PARÂMETROS E EFEITO DA COMPOSIÇÃO QUÍMICA DO AÇO

Resumo

Muitos modelos de transferência de calor foram desenvolvidos durante os últimos anos. Eles são fáceis de serem usados e convenientes para simulação de todo processo de lingotamento. A exatidão dos modelos depende de muitas coisas como, por exemplo, as condições de contorno, propriedades dos materiais assim bem como de parâmetros, simplificações e suposições dos modelos. O propósito geral desse trabalho é estudar a exatidão das simulações da transferência de calor. Uma curta revisão de modelos de transferência de calor é apresentada assim como os itens que afetam a exatidão. A sensibilidade de importantes parâmetros de modelo assim como as condições de contorno foram estudadas usando os dois modelos de transferência de calor desenvolvidos pela UFRGS e pela TKK. O efeito e sensibilidade das propriedades dos materiais dos aços nos resultados são estudados fazendo simulações com diferentes qualidades de aços. As propriedades dos materiais para aços são calculados usando um modelo específico, IDS, desenvolvido pela TKK. Validações industriais também foram executadas. Os resultados mostram que a exatidão das simulações da transferência de calor no lingotamento contínuo requer medidas exatas para caracterizar as condições de contorno, temperaturas e propriedades dos materiais dependentes da composição química, otimização de parâmetros do modelo numérico, e validação com medidas em planta. Os cálculos mostraram também que ambos os modelos (UFRGS e TKK) deram resultados bons e similares e podem ser usados para simulações exatas se os parâmetros de modelo, as condições de contorno e propriedades dos materiais forem definidas corretamente.

Palavras-chave: Lingotamento contínuo; Solidificação; Transferência de calor, Simulação numérica.

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1 INTRODUCTION

The modelling of solidification systems is a problem of a great mathematical and industrial significance. Like most commercial processes, continuous casting involves many complex physical phenomena and no model can today include all of the phenomena at once. To develop a model, it is essential to select the most important phenomena and make the reasonable assumptions. In recent years, a lot of different kinds of heat transfer models for continuous casting have been developed. Simulations give important output data, such as strand temperatures and the shell thickness profile. Steady state heat transfer models are being increasingly used to improve the existing cooling systems, to improve the casting practices, and for process control. Most of the models are today one- or two-dimensional but three-dimensional models are also available. For better control over the whole continuous casting cycle, more attention has recently focused on developing real-time heat transfer models which are valid under transient casting conditions. The accuracy of the heat transfer models depends on many things as for instance on the boundary conditions, materials properties as well as on the model equations and parameters, simplifications and assumptions. The general purpose of this presentation is to study and discuss the accuracy of the heat transfer simulations. The study is partly made using the two heat transfer models developed by UFRGS and by TKK. The necessary material properties for steels are calculated using a specific model, IDS, developed by TKK. These three models are also shortly presented in this paper.

2 MATHEMATICAL FORMULAS AND GENERAL ASSUMPTIONS OF HEAT TRANSFER MODELS FOR CONTINUOUS CASTING

Continuous casting involves many physical phenomena. The main phenomena are: fluid flow, heat transfer, solidification, movement of the strand. Most of the thermal models developed are not calculating the fluid flow at all. In these models, it is assumed that the strand (solid and liquid) is withdrawn through the machine with a constant velocity field (= casting speed). The convective heat transfer generated by the fluid flow is taken into account by using an effective thermal heat conductivity method. This simplification is often done due to the fact that the fluid flow does not affect very much the results in the solid shell, but more on the results within the liquid pool. So, if the aim is to study the shell thickness profile, the location of the liquid pool end or the temperatures in the solid part of the strand, this simplification can be done and the models are simpler. The equation to be solved now is the basic partial differential equation of heat conduction including the removal of latent heat of solidification. In the case of steel continuous casting, the heat conduction in the casting direction is small and thus it can be ignored. This is due to the relatively high casting speed and low thermal conductivity. But in the case of copper or aluminium continuous casting, the heat conduction in the casting direction cannot be ignored. The thermal conductivity of these metals is much higher than that of steels and the casting speed is usually lower. So, most of the heat transfer models for steels are two-dimensional. The simulated geometry is a two-dimensional strand slice and the models simulate its movement at a constant casting speed through the machine. In these models, the casting direction is treated as time. The equation in these cases can be described by:

$$\rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{dx}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{dy}\right)+Q\,. \tag{1}$$

Actually the slice is not moving but the boundary conditions are changed as a function of time. The time is zero at the meniscus and below the meniscus it is calculated by equation t=z/v, where v is the casting speed and z the distance from the meniscus. In Eq. (1), ρ is the density, c is the specific heat, k is the thermal conductivity, and Q is a term describing the rate of energy released by phase transformations. For solidification phase change, it is usually defined as:

$$Q=\rho L\frac{\partial(f_s)}{\partial t}\,. \tag{2}$$

Here, L is the latent heat of solidification, and $f_s = f_s(T)$ is called the solidified fraction in the mushy zone. The later term describes the way in which the latent heat is released during solidification. This way depends strongly on the chemical composition of the material to be cast. The solid-state transformations can be treated in a similar way. Therefore, the material data needed are the density, the specific heat, the thermal conductivity, the latent heats, and the phase fractions during phase transformations. Eq. (2) can also be expressed in another form using a so-called enthalpy formulation. The enthalpy, H, is defined as the sum of sensible ($\int c\cdot dT$) and the latent heats (Q). The equation now becomes:

$$\rho\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{dx}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{dy}\right). \tag{3}$$

In this case, the necessary material data are the density, the enthalpy, and the thermal conductivity. The enthalpy now includes all the other data, except the density and the thermal conductivity. The steady state, three-dimensional models can be described by:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{dx}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{dy}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{dz}\right)+v\rho c\frac{\partial T}{\partial z}+Q=0 \tag{4}$$

The three first terms describe the heat conduction in the three spatial directions, the fourth term the convective heat transfer in the casting direction, caused by the movement of the strand. As mentioned above, the technique most often used to account for the convective heat transfer in the liquid and mushy zone due to the liquid flow is called the effective thermal conductivity or the enhanced conductivity method. The effective thermal conductivity is approximated by the following linear relationship:

$$k_{eff}=kf_s+Ak(1-f_s)\,. \tag{5}$$

Also other formulas are used, but the principle is the same. Here, k is the thermal conductivity of the solid material, A is a constant and $f_s(T)$ is the solid fraction in the mushy zone. If the constant, A, is 1, there is no increased heat transfer in the mushy zone or liquid regions due to the fluid flow. This means that the liquid pool is stagnant, i. e., there is no mixing in the liquid phase. Normally a value between 1-8 is used. It is difficult to define the value accurately. The value is also different in the mould than deeper in the pool due to the higher flow velocities close to the inlet nozzle. This value should be defined as a function of distance from the meniscus. Electromagnetic stirring also affects this value and the stirring can be taken into account by applying a higher value in the stirred area. The constant A should be fitted by experimental studies. The effective heat conductivity method assumes that fluid flow increases liquid pool heat transport isotropically, which is not the case, because fluid flow only contributes to heat transport in the flow direction.

The assumptions generally made in the heat transfer models are that (1) the solidus and the liquidus temperature, as well as other phase transformation temperatures, are constant, and (2) the solidification takes place by directional growth, (3) the material behavior is isotropic, and (4) in the case of only heat transfer models, the velocity is constant in the liquid and solid and it is the same as the casting speed, and (5) the effective thermal conductivity method is used. The models are relatively simple and assumptions do not affect very much on the results in the solid shell, but more on the results within the liquid pool. This is due to the fact that, the temperature gradients are small in the liquid pool and the liquid velocities effect much, for instance, on the liquidus isotherm. So, the results within the liquid pool are only relative and can be compared only with each other.

Boundary conditions. For the correct simulation of heat transfer, the determination of the boundary conditions describing the heat transfer phenomena taking place along the strand surface is of crucial importance. In the mould, there exists a thermal resistance between the shell and the mould because of the powder lubrication and the formation of an air gap due to the shrinkage during cooling. Heat transfer in the mould is controlled mainly by heat conduction across the interface between the surface of the solidifying shell and the mould. It is quite difficult to determine the heat transfer across this gap, which varies with time and position of the mould. The gap is a function of casting variables (casting speed, superheat, casting powder, etc.), steel composition, mould taper, etc. Advanced models simulate not only the strand but also the mould around the strand and the heat transfer across the gap is determined by the gap heat transfer coefficient. These advanced models actually consist of two models: the mould model and the strand model. The boundary equation for the strand model can be expresses as:

$$-k_{shell}\frac{\partial T_s}{\partial n} = h_g(T_s - T_m)\,. \tag{6}$$

And for the mould model:

$$-k_{mould}\frac{\partial T_m}{\partial n} = h_g(T_m - T_s)\,. \tag{7}$$

Here, T_s and T_m are the surface temperatures of the shell and the mould; h_g is the gap heat transfer coefficient. It is usually defined as a function of strand surface temperature $h_g = h_g(T_s)$. At the cold face of the casting mould, a convective heat transfer coefficient is used. It can be determined from the flow rate of the water and an empirical formula is often used. If the mould model is not used, it is difficult to know, what is the external temperature, T_m, in the boundary equation for the strand. The gap heat transfer coefficient can be determined using experimental measurements (thermocouple measurements in the mould and heat flux measurements of the cooling water). The mould heat flux (measured from the mould cooling water) can also be used directly as the boundary condition in the mould, but the accurate heat flux distribution is quite difficult to know.

Below the mould, water sprays and rolls extract heat from the surface and the boundary conditions are usually expressed as heat transfer coefficients. This, on the other hand, must be determined as a function of actual cooling parameters. This determination can be done in a laboratory set-up or directly in the casting machine using strand surface temperature measurements. A lot of empirical formulas have been derived in this way. However, the formulas are valid only for the particular type of casting machine and steel grade and cooling conditions, for which they are derived. They cannot simply be transferred directly to other casting machines. Below the mould, the heat flux from the strand surface to the environment is usually defined by the following equation:

$$-k\frac{\partial T}{\partial n} = h_{eff}(T_p - T_{ext1}) + \varepsilon\sigma(T_p^4 - T_{ext2}^4) \tag{8}$$

Here h_{eff} is the effective heat transfer coefficient, T_p the strand surface temperature, T_{ext} the external temperature for cooling water or air, ε is emissivity and σ the Stefan-Bolzmann constant. The effective heat transfer coefficient takes into account the other heat transfer mechanisms except radiation. The last term represents the heat flux by radiation. The input parameters in this equation are: h_{eff}, T_{ext} and ε. Before this boundary condition can be applied in actual computations, the relationship between the effective heat transfer coefficient and the cooling parameters must be determined.

Material data. To obtain reliable results from the heat transfer simulations, accurate data on the thermophysical material properties are also needed. Typical data needed are the density, the thermal conductivity, and the specific heat. Other important data are the phase transformation temperatures and the corresponding latent heats, and also the way in which the latent heats are released during the phase transformations. If the enthalpy formulation is used, the enthalpy values can be used directly if they are known. The enthalpy then includes all the other data except the thermal conductivity and the density. The material data are not only functions of the temperature and the chemical composition but also of the cooling rate. This is because the kinetics of phase transformations depends on the cooling rate and the thermophysical properties are related to the phases formed. Thus, for accurate simulation of solidification and cooling processes, one should know the material data as a function of temperature, composition, and cooling rate. Although material data have been measured for a great number of steel grades, most of these data are valid for special steel grades and/or for the low temperature region only and there are only a little data for higher temperatures up to the liquid phase. So it is seldom possible to find all the data needed. This is especially the case for carbon and low alloyed steel grades, because in these steels even smaller variations in the composition might have a significant effect on the phase transformations and so on the thermophysical material properties.

3 THE TOOLS USED IN THIS STUDY

The heat transfer calculations were carried out with the two in-house tools developed by UFRGS and TKK. They are called InALC+(1) and TEMPSIMU.(2) They are typical two-dimensional, steady state heat transfer models (slice model) for continuous casting (Eq. 1). They use the effective thermal conductivity method and the general assumptions follow the typical assumptions presented in the Chapter 2. InALC+ is based on explicit finite difference method but the TEMPSIMU on implicit finite element method. Both models are validated with industrial measurements. InALC+ also has a module called InALC+ Mold. This is used to determine the gap heat transfer coefficients (h_g in Eq. 6).(3) The material data in TEMPSIMU is defined as a function of temperature, but in InALC+ metal properties (specific heat, thermal conductivity, density) are constants in the liquid and solid phases. The changes with the temperature in the mush zone is calculated based on the lever rule concept. The necessary material data for TEMPSIMU is calculated using the in-house IDS tool developed by TKK. A 3-dimensional version of TEMPSIMU has also been developed (TEMPSIMU3D) according to Eq. 4. IDS tool(2) is a thermodynamic-kinetic-empirical tool for calculating of solidification phenomena from liquid to room temperature. The present version of the IDS module is valid for low-alloyed steels and stainless steels. It calculates among other things phases, phase transformations, segregations, material properties as a function of steel composition and cooling rate. The IDS package has been validated by comparing the calculations with experimental data.

4 CASE STUDIES

4.1 Handling of Density in Heat Transfer Models

In the heat transfer simulations the equations are usually solved using a fixed grid, i.e., the strand width and thickness are the same along the casting machine. This means that the contraction of the cast strand is not calculated and is not taken into account. When using this kind of model, it is important to take care that the mass and the heat balance are correct. One approximate and simple way to deal with this is to ensure that besides contraction, density is also not varied either. What value should then be used? The inlet energy is correct if the density of the inlet melt is used. However, during solidification the fluid in the interdendritic space is free to move and it more or less compensates the solidification contraction. To take this feeding more correctly into account in the mass and the heat balance, the density should be that of the solidus temperature rather than that of the inlet melt temperature. The TEMPSIMU model uses a fixed grid in the calculations. Some calculations with different density values are given below. The calculations were performed for a slab caster. The following calculations were carried out: 1) the density changes normally as a function of temperature, 2) the density is constant and that of the solidus temperature (ρ = 7300 kg/m^3), 3) or the density is constant and that of the room (or environment) temperature (ρ = 7800 kg/m^3). The calculation with temperature dependent density gave a shorter pool length of over 3m compared to the calculation with constant density (of solidus temperature) (Fig. 1a). As a second case, the effect of different constant density values was studied (Fig. 1b). Density values at solidus temperature for low-alloyed steels usually vary by around 7300 kg/m^3. This value was compared with a room temperature density of pure iron, 7800 kg/m^3. The crater end length was increased by over 2m in the case of the density value of 7800 kg/m^3.

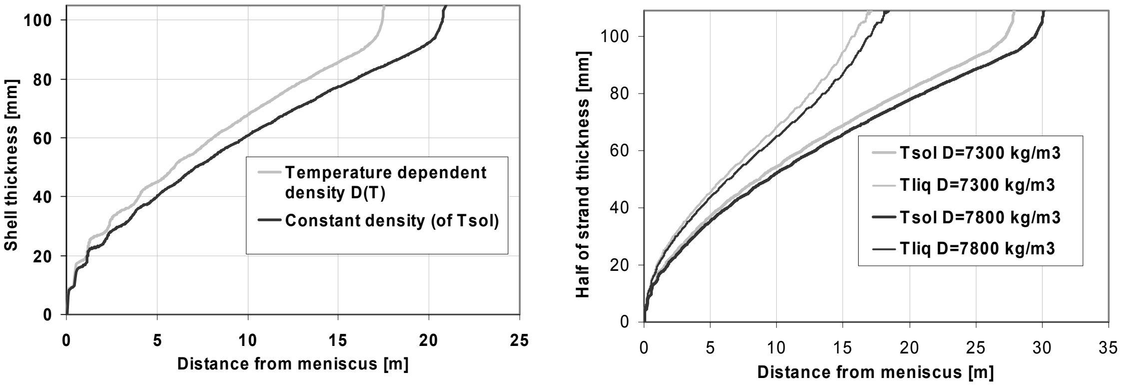


Figure 1. a) Shell thickness profile in the cases of temperature dependent and constant density, b) liquidus and solidus isotherms with different constant density values.

4.2 Fluid Flow Modeling

The technique most often used to account for the convective heat transfer in the liquid and mushy zone due to the liquid flow is called the effective thermal conductivity method (Eq. 5). As presented before (Chapter 2), normally a value between 1-8 is used, but it is difficult to define the value accurately. Test calculations were carried out using A=1.5 and A=5 in Eq. (5). The results for a steel slab caster are presented in Fig. 2. Parameter A has influence on the results, but more on the liquidus isotherm than on the solidus isotherm. Similar behavior was obtained with the studied copper alloys. Fortunately, the parameter A has a minor influence on the solidus isotherm or on the temperature of the solid strand. Models using an effective thermal conductivity method can be applied to study the temperatures in the solid shell and related data such as the shell growth and the location of the liquid pool end position, but the temperatures in the liquid pool cannot be calculated very accurately.

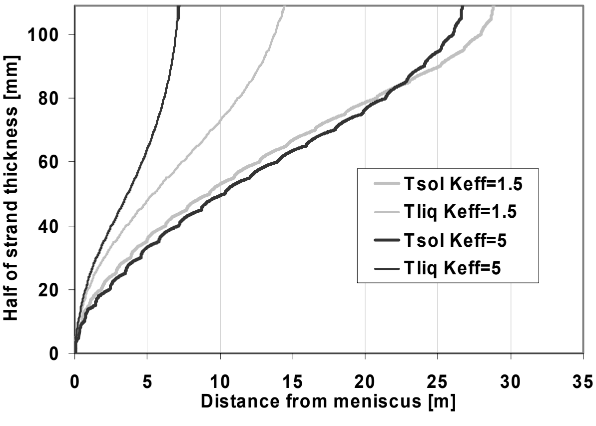


Figure 2. Liquidus and solidus profiles with A values of 1.5 and 5 in Eq. (5).

4.3 Effect of Material Data on Heat Transfer Simulations in Continuous Casting

The effect of material data on heat transfer simulations were studied by calculating firstly material data using the IDS tool and then calculating the heat transfer using the TEMPSIMU model. The casting machine used in the simulations was a vertical-bending slab caster from Ruukki Steel, Finland. Only carbon steels are cast with this machine, however the stainless steels were also simulated using this caster. In simulations, all process and machine data were the same and only the material data was changed. Thus, the effect of the composition on the results can be compared. The results are shown in Figure 3. As can be seen, the results are significantly different. For example, the length of the liquid pool varies several meters simply as a consequence of changes in the composition.

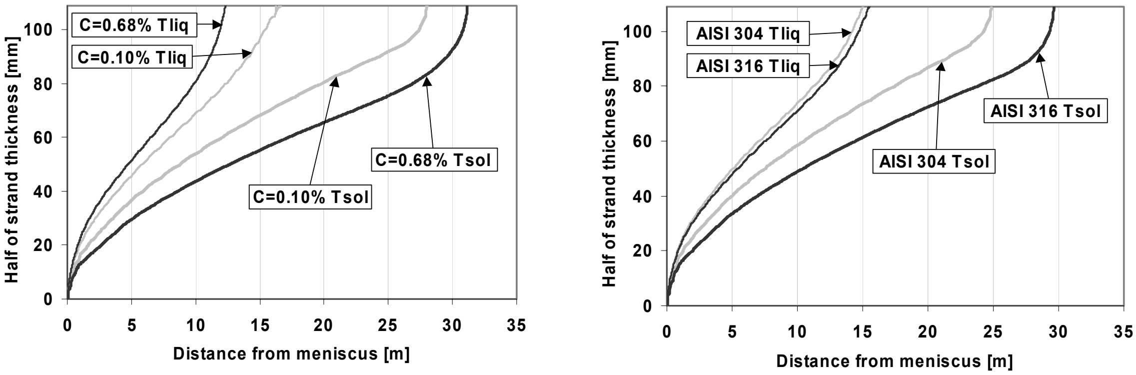


Figure 3. Liquidus and solidus isotherms of 1) the steels C=0.10% and C=0.68% (left) and 2) stainless steels AISI 304 and AISI 316 (right).

4.4 Effect of the Solid Fraction Curve During the Solidification

As mentioned before (see Eq. 2), $f_s = f_s(T)$ is called the solidified fraction in the mushy zone. It describes the way in which the latent heat is released during solidification and this way depends strongly on the chemical composition of the material to be cast. To study the sensitivity of its form, test calculations with a linear and bi-linear curves were calculated (Figure 4). As can be seen, the effect is higher in the liquid curve but smaller on the solid curve, but however the difference is about 1-2 meters. It is also good to mention that the solid curve can be much more nonlinear than the calculated bilinear used.

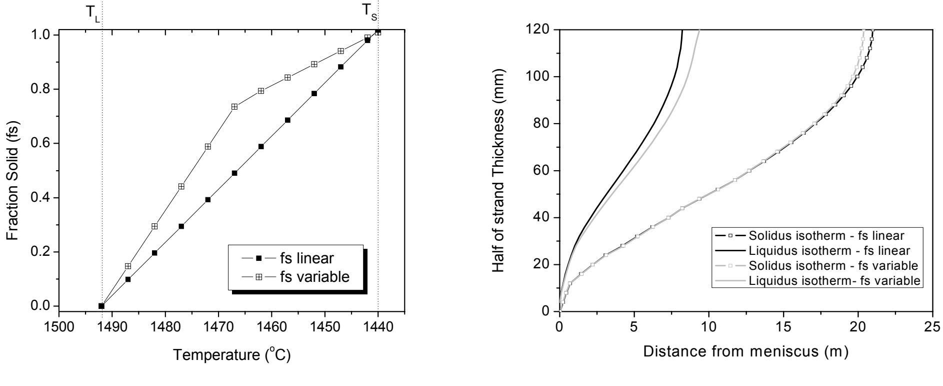


Figure 4. The effect of two solid fraction curves (linear and bilinear; left picture) on the results of the heat transfer calculations (right picture)

4.5 Heat Transfer Model Validations

The heat transfer models can be validated using strand surface temperature and shell thickness measurements. The mould model can be validated using mould thermocouple measurements. The strand surface temperature can be measured by pyrometers or by thermocouples. In the case of thermocouples, these are fed into the strand surface in the upper part of the machine and they move with the strand through the machine. The strand surface measurements are quite sensitive to external disturbance and the scale on the strand surface affects also the results. Usually, peak temperatures are used in the validation. The shell thickness can be measured with some methods, i.e.: the rivet pin shooting method, the so-called wedge method and adding alloying element into liquid pool. In the wedge method, a wedge is fed between two rolls of a caster. As the strand moves on, the wedge moves between the roll and the strand. The wedge causes tensile stress resulting in cracks in the solidification front of the strand (Figure 5). Shell thickness is then determined from the crack tip locations in the strand specimens. Another method to measure the shell thickness is analyzing the macrographs of the cross section of the strand. Both metallographic technique or Baumann method (sulphur print) can be used (Figure 6). If the caster has electromagnetic stirring (MEMS or FEMS), white band segregation is formed in the solidification front and so the shell thickness can be evaluated.

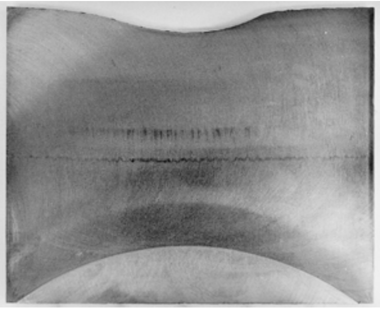
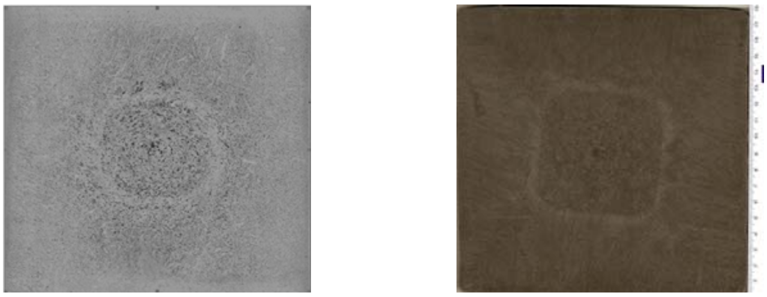


Figure 5. Wedge induced cracks in a slab specimen (slab thickness 210 mm).



(a) (b)

Figure 6. White bands formed by the FEMS. Macrograph obtained with (a) Baumann method and (b) metallographic technique.

TEMPSIMU tool was validated by measuring shell thicknesses and surface temperatures in different locations of the strand. Measurements were performed with a curved type slab caster at Ruukki Steel in Finland. Shell thickness was determined by using a wedge technique and temperatures were measured with pyrometers. During the experiments, casting conditions were kept constant for the whole casting history of the measuring locations. Material data for TEMPSIMU were calculated with IDS model. The simulations with TEMPSIMU showed good agreement with the shell thickness and temperature measurements (Fig. 7).

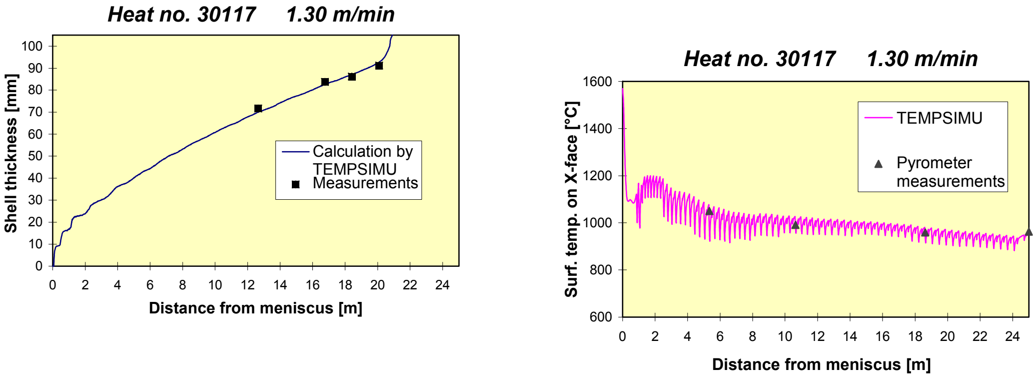


Figure 7. Measured and calculated shell thicknesses and surface temperatures (TEMPSIMU tool).

As TEMPSIMU, InALC+ was also validated by measuring shell thicknesses and surface temperatures in different locations of the strand and the mold wall. Measurements were performed with a curved type billet caster at Industrial Steel Plant in Brazil. Temperatures were measured with pyrometers on the strand surface and with thermocouple in the mold wall. Shell thickness was determined by using a metallographic technique and Baumann impression. The simulations with InALC+ showed also good agreement with the shell thickness and temperature measurements (Figure 8).

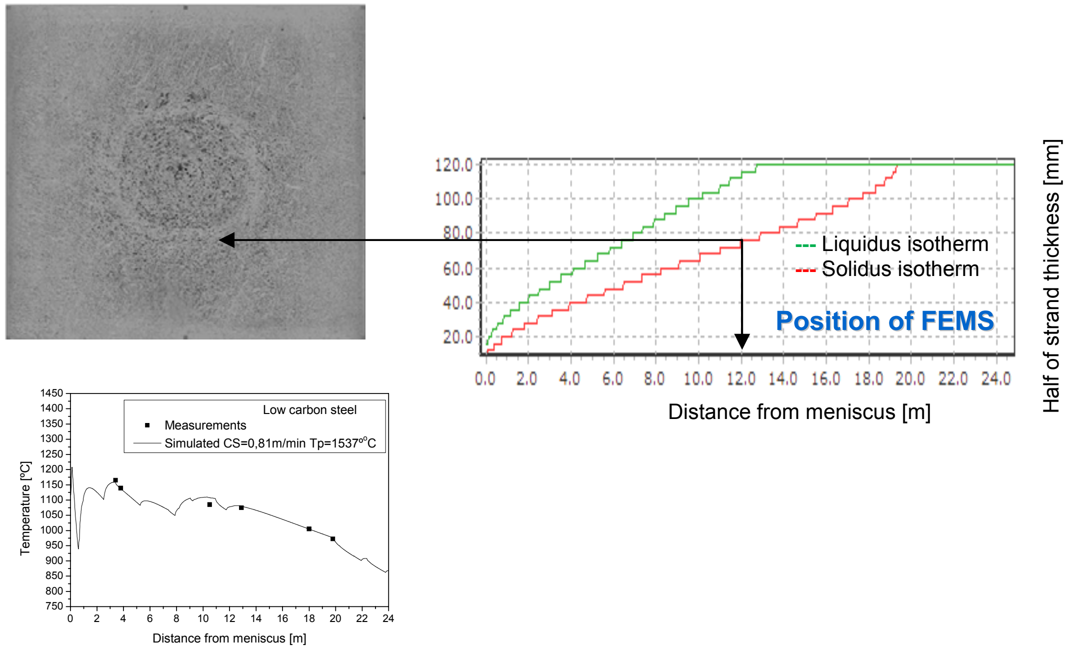


Figure 8. Measured and calculated shell thicknesses and surface temperatures (InALC+ tool).

5 CONCLUSION

The accurate simulations of heat transfer in continuous casting require accurate measurements to characterize the boundary conditions, temperature and alloy-dependent material properties, optimization of numerical and model parameters, and validation with plant measurements. If the data and parameters are not defined accurately enough, the error can be very large. It can easily be several meters in the length of the liquid pool. If fixed grid is used in the calculations, and the contraction of the cast strand is not calculated and is not taken into account, the density should also be fixed and constant and the authors suggest using the density value of that at the solidus. When using the effective thermal conductive method, it is important to define the parameter A (Eq. 5) accurately and in general the method can be applied to study the temperatures in the solid shell and related data such as the shell growth and the location of the liquid pool end position, but the temperatures in the liquid pool cannot be calculated very accurately. It is also important to have accurate material data including the solid fraction curve because these have a big influence on the results. It is also clear that the mesh density must be dense enough and the density depends much on the numerical solving methods used. Explicit methods need more accurate mesh than implicit methods and this is also the case if using specific heats in the equations (Eq.1) compared to enthalpies (Eq.3) in the equations. In general, the calculations showed that both of the models (UFRGS and TKK) gave good and similar results and can be used for accurate simulations if the model parameters, boundary conditions and material properties are correctly defined.

Acknowledgements

The authors would like to thank many people in industry and universities for cooperation, support and help. We would also like to thank agency National Council for Scientific and Technological Development of Brazil (CNPq) as well as Finnish steel industry and Finnish Technology Development Centre (TEKES) for the financial support.

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