Thermomechanical model of the behaviour of a strand in continuous steel casting using finite element method

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1 Introduction

Continuous casting is the link between steelmaking and hot rolling processes. This modern technique is more and more important on the steel producers market because of its advantages compared to the older technique of ingots casting: energy and manpower savings, a better yield and improvement of steel quality.
Even if productivity leads producers to speed up the casting process, an appropriate casting speed remains an important factor of quality. If the speed is too high, the strand stays less time in the mould and the solidified shell is too thin, so that surface and subsurface cracks can appear or the strand can even break out. On the other hand, if the speed is too low, the solidified shell grows too much and that may lead to problems in the bending zone. The mould taper takes also a prominent part in this process. Many other parameters are also important for the quality of the product [1-3]. Among these parameters, one can mention steel chemistry and cleanliness, mould level, mould powder, mould oscillation, liquid steel temperature and the overall secondary cooling conditions.
The purpose of this study is to make a finite element model that describes the thermal-mechanical behaviour of the strand in the mould. This analysis is based on an finite element approach, using the Lagrangian LAGAMINE code that has been developed since early eighties in the MSM Department of University of Liège. More precisely we wanted to determinate for a given situation the temperature field, the stress and strain fields and the contact/friction between the strand and the mould.

2 Model description

2.1 *Approach of the problem*

A complete three-dimensional model seemed to be impossible (because of both numerical stability and convergence reasons, but also computing time), so a "two and a half" dimensional analysis was carried out. One can summarize this approach as follows: we model in a 2D mesh a set of material points representing a slice of the strand, perpendicularly to the strand axis. Initially the strand is at the meniscus level and its temperature is assumed to be uniform and equal to the casting temperature (1560 °C). Since this slide is moving down through the mould, we study heat transfer, stress and strain development and solidification growth.
From a mechanical point of view, the slice is in generalized plane strain state. That means that the thickness t of the slice is governed by the following equation where 3 degrees of freedom α_0, α_1 and α_2 appear:

(1) $$t(x,y) = \alpha_0 + \alpha_1 x + \alpha_2 y$$

The coefficient α_0 represents the thickness at the origin of the axes, while α_1 and α_2 are the slopes of the thickness value respectively along the axes x and y.
In our model, we considered that the coefficients α_1 and α_2 are constant during the simulation and equal to zero. That means that the thickness is only determined by the value of α_0, so that we can say that the thickness is uniform in the slice but variable in time. This assumption is a consequence of the double symmetry of the studied slice (see hereafter).

2.2 *Geometry of the problem*

In a first time, we worked with a simple geometry. We modeled the casting of a 125 mm wide squared billet. In order to avoid stress concentration, we rounded the corners of the section, using a 5 mm curvature radius.

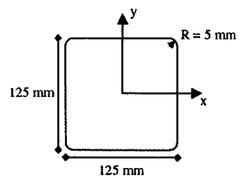

Figure 1: Cross section of the strand

The active height of the mould is 600 mm and the taper is 1.05 % per meter, so that the section is approximately 124.2 mm at the exit of the mould.

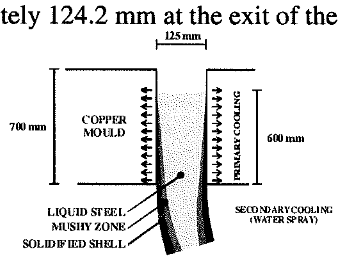

Figure 2: Mould geometry

The initial geometry of the strand is the same than the geometry of the mould (because of the liquid steel) and then it depends on the shrinkage.
Because of the double symmetry, we only studied

one quarter of the slice, applying the right boundary conditions along these symmetry axes.
The casting speed is relatively high speed and it is equal to 3.6 meter per minute or 60 mm per second.

2.3 *Thermal properties of the material*

Liquid steel is poured in the mould at 1560 °C (casting temperature). The copper mould is cooled by an internal water flow near the surface. We assumed that the temperature of the mould is constant, uniform and equal to 160 °C.
The heat flux in the material (the strand) is predicted by a classical Fourier-type law:

(2) $$\rho \cdot c \cdot \dot{T} = \mathrm{div}(\lambda \cdot \nabla T) + q$$

where T is the temperature field, function of coordinates (*x,y*), ρ is the volumic mass, c the specific enthalpy and λ the thermal conductivity of the material.
The parameter q is a heat source term that is equal to zero in our model, except in the mushy zone where it is equal to the latent heat. In this case, on can express q by the equation:

(3) $$q = \rho \cdot L_s \cdot \frac{\partial f_s}{\partial T} \cdot \dot{T}$$

where L_s is the latent heat of solidification and f_s is the solidified fraction.
In the case of an alloy, i.e. steel, the solidification does not occur at a single determined temperature, but only on a phase change interval from the upper temperature (liquidus) to the lower temperature of the domain (solidus). In our model, these temperatures are 1520 °C for liquidus and 1470 °C for solidus.
Even if the phase change interval is relatively large according to temperature variation during time steps, we use the so-called enthalpy method. We define an enthalpy function H(T), which takes into account all the thermal energy involved in the material to heat it from the absolute zero (0 K) to the considered temperature T (in K):

(4) $$H(T) = \int_0^T \left(\rho \cdot c - \rho \cdot L_s \cdot \frac{\partial f_s}{\partial T} \right) \cdot d\theta$$

The main advantage of this formulation is that the size of time step does not influence the result because the conservation of heat is always verified.
The Fourier law can be written as follows:

(5) $$\dot{H}(T) = \mathrm{div}(\lambda \cdot \nabla T)$$

One can notice that all the parameters (ρ, c, λ, q) are temperature dependant in the model.

2.4 *Heat exchange between the strand and the mould*

The thermal exchange between the strand and the mould depends very much on the contact conditions. Due to the thermal shrinkage, contact may be lost in some places, more particularly in the corners, as Figure 3 shows. When contact is lost, the thermal exchange decreases and the core of the strand tends to reheat the solidified shell so that the strand bulges and returns to contact with the mould.

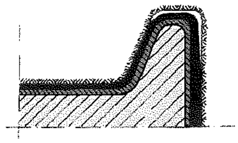

Figure 3: Gap appearance in the corners

Where the contact between the strand and the mould is established, the heat transfer q is based on the following expression:

(6) $$q = R \cdot (T_{strand} - T_{mould})$$

where R is the contact thermal resistance.
Where the contact is lost, a gap appears and the heat transfer is given by:

(7) $$q = h \cdot (T_{strand} - T_{mould}) + \varepsilon_r \cdot \sigma_B \cdot (T_{strand}^4 - T_{mould}^4)$$

where h is the heat transfer coefficient of convection mode, ε_r the relative emissivity of the strand and σ_B the Boltzmann radiation constant.

2.5 *Mechanical properties of the material*

The main mechanical effect of solidification is shrinkage the value of which is directly proportional to the temperature decreasing. The proportionality coefficient is the thermal expansion coefficient α and it is also thermally affected.
The mechanical behaviour of the material is described by a elastic-viscous-plastic law for both liquid, mushy and solid states.
The elastic domain is characterized by an elastic Young's modulus E and a lateral contraction coefficient ν (Poisson's coefficient) that are temperature dependant.
The viscous-plastic domain is described thanks to a Norton-Hoff type law the expression of which is in terms of equivalent values:

(8) $$\bar{\sigma} = K_0 \cdot e^{-p_1 \cdot \bar{\varepsilon}} \cdot p_2 \cdot \sqrt{3} \cdot \left(\sqrt{3} \cdot \dot{\bar{\varepsilon}}\right)^{p_3} \cdot \bar{\varepsilon}^{p_4}$$

where K_0, p_1, p_2, p_3, p_4 are temperature dependant parameters. Each parameter has its own influence on the curve shape:

- K_0 and p_2 influence the level of the curve;
- p_1 is mostly influent when $\bar{\varepsilon}$ is higher, in other words influence on softening;
- p_4 works on hardening;
- p_3 traduces the effect of strain rate, i.e. viscosity.

The variation of these parameters as functions of temperature allows to model the variation of mechanical behaviour of the material, including viscosity. Each parameter has been fitted at several temperatures corresponding to tensile tests that had been performed on a Gleeble device at several high temperatures (800 °C to 1475 °C) and strain rates (10^{-4} to 5 10^{-2} s^{-1}). The yield limit is defined as the intersection between the elastic straight line and the viscous-plastic curve.
The ferrostatic pressure p_f is also taken into account. In the liquid phase, it is given by the product of volumic weight γ and the distance D below the meniscus. In the solid phase, the pressure is

obviously equal to zero. In the mushy zone, we assume a linear variation. So we can summarize it:

(9) $$p_f = \gamma \cdot D \cdot (1 - f_s)$$

where f_s is the solidified fraction.

When two adjacent elements are in liquid state, the pressures are balanced so that there is no resulting force. But when the pressures are different, a resulting force takes place. In this way, the solidified shell is under ferrostatic pressure because of the liquid steel pool in the core of the strand.

2.6 *Mechanical contact*

From the mechanical point of view, the contact between the strand and the mould induces both pressure and friction efforts. The chosen contact element is based on a penalty technique and expresses the Signorini's condition at its integration points. The constitutive equation for the contact is a Coulomb-type law.

2.7 *Discretization*

The strand, more precisely the studied quarter of slice, is modeled with quadratic quadrangular elements (8 nodes) and 4 integration points with Gauss scheme for each element. The elements are of course larger in the center of de slice and smallest near the corner where most of the stresses and strains will grow. The mesh is composed of 560 nodes and 168 volume elements. Each node owns three degrees of freedom (coordinates *x* and *y* and temperature T).

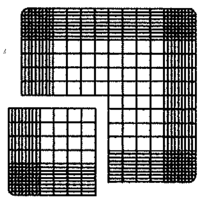

Figure 4: mesh for the studied quarter of slice

The contact (or loss of contact) between the mould and the strand is modeled using 3 nodes contact elements. The mould is represented by a rigid body so that its thermal distortion is not take into account. The geometry of the mould at each time step is defined by the taper that we impose. It can be a single, multiple or parabolic taper.

3 Results

3.1 *Temperature at the exit of the mould*

Figure 5 represents some isotherms in the slice at the exit of the mould. Temperature decreases to circa 1200 °C in the corner, while it is still greater than 1500 °C in most of the central zone (casting temperature is 1560 °C).

The thickness of the solidified shell is circa 3 mm and the one of the mushy zone is circa 5.5 mm. These values are close to reality (about 5 mm for each zone), but still too low for the solidified shell. This difference may be due to the thermal exchange coefficients that are relatively rough in a first time.

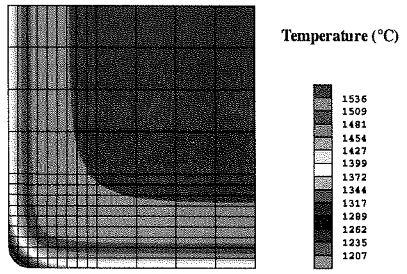

Figure 5: Temperature at the exit of the mould

3.2 *Stress, strain and strain rate fields*

The following figures represent the stress, strain and strain rate fiels in the slice at the exit of the mould. We do not analyse here these results in terms of absolute values because there is no interest to do that with this exemple. We just verify that the behaviour seems to be correct and that what we attempt to do is achieved.

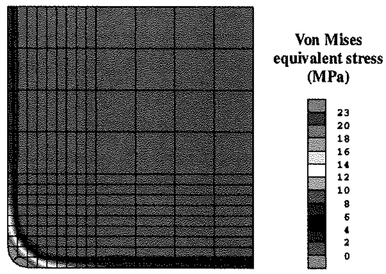

Figure 6: Von Mises equivalent stress field at the exit of the mould

Figure 6 shows the Von Mises equivalent stress field. Similarly to the temperature field, it is obvious that the maximum equivalent stresses are in the corner, in other words in the solidified zone. The reason is that the material is able to withdraw to larger loads in this region. Conversely, the liquid poll cannot withdraw and the stress in this area tends to zero.

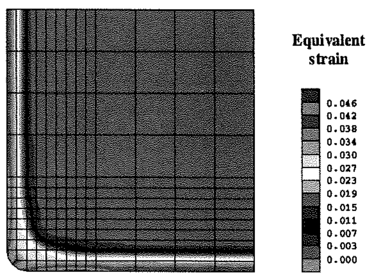

Figure 7: Equivalent strain field at the exit of the mould

Most of the strain is a thermal effect so the larger values are where the temperature decrease the most (in the solidified shell), as Figure 7 shows. In other respects, a corner effect appears: the equivalent is smaller in the corner than elsewhere on the surface.

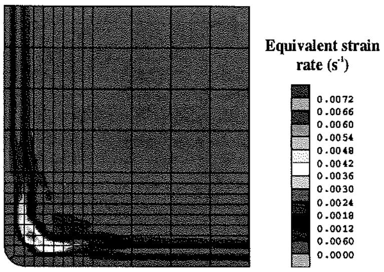

Figure 8: Equivalent strain rate field at the exit of the mould

Finally, the equivalent strain rate is given by Figure 8. The strain rate represent the variation of strain during the time step. What we can see is that the maximum value is not in the corner or the solidified zone (conversely to the previous figures), but in the mushy zone. As the principal strain is thermal strain, we can give different reasons to this field:

- first, most of the central region is still liquid and the thermal effect is not very large, so that strain rate is very low;
- in the solidified shell, temperature decreasing is more important, but the material "resistance" is greater than anywhere else and the strain remains low;
- last but not least, in the mushy phase, the temperature decreasing is quite important, but the thermal expansion coefficient is 20 times greater than the one of the solidified material and 28 times greater than the one of the liquid steel; that means that for a same temperature rate, the strain rate will be 20 or 28 times the one in the other phases.

3.3 Strand-mould contact

An important goal of the study is to manage to model the loss of / return to contact. Figure 9 represent the evolution of the distance between the strand and the mould during the simulation.

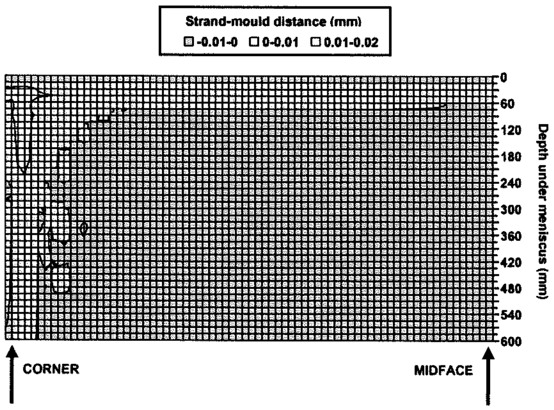

Figure 9: Evolution of the distance between the strand and the mould form the corner to the midface

The value of the distance is positive when there is loss of contact and negative when there is contact. A value can be negative because of the penalty technique in the contact computation.

We can see that in the first time the contact is lost everywhere along the outline of the cross section. Then, the contact returns over a large region (in the central part of the face), and it will not be lost anymore. At the opposite, the contact remains lost in the corner until the exit of the mould (600 mm under the meniscus). Lastly, in a region near to the corner, lost and returns to contact follows each other, that we can see with the orange and green marks.

4 Conclusion

The aim of the study was to build up a model of the thermal-mechanical behaviour of a steel strand in the mould of a continuous casting plant. The results we wanted to check were the temperature field and the solidified shell growth, the stress, strain and strain rate fields and finally the ability of the model to manage the loss of contact and returns to contact.

The presented results have been achieved for relatively simple section and the values are not to be put in parallel with experimental tests. But the overall behaviour of the simulated strand accords with what we can expect it should be.

The next step in the study is now to model another shape of strand, like a beam blank for instance, and to compare results with reality. This validation work is going on. Then we will be able to modify different parameters, such as mould taper, casting speed, mould and/or casting temperature, etc.

Acknowledgements

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