FINITE ELEMENT THERMOMECHANICAL MODEL OF CONTINUOUS STEEL CASTING

F. Pascon, A. Habraken
Department of Mechanics of materials and Structures, University of Liege, Belgium

1 Summary

Problems in continuous casting of steel are numerous and have been leading producers to find ever more efficient solutions. We have developed a thermomechanical model of continuous casting, using a non-linear finite element code. Since a complete 3D discretization seemed impossible, the model has been based on a generalized plane strain state (2D½) and it includes at the same time thermal exchanges, mechanical behaviour of steel at very high temperature, the ferrostatic pressure and contact between the strand and the machine. This paper presents some results of two industrial applications. First results tend to prove the importance of some process factors (such as the mould taper) and local defects of the machine on the quality of cast products, according with observations.

Keywords: continuous casting, finite element, high temperature, industrial processes

2 Introduction

Since continuous casting has become the most efficient way to produce steel nowadays, all producers are looking for solutions that could help them to improve yield of casters and to reduce defects in cast products. Such kind of machine, which can be qualified as a big thermal exchanger, seems to be quite simple, but is in fact a high-tech device.

Liquid steel is first poured into a bottomless mould, where it is frozen in contact with the walls. A solidifying shell starts to grow and it must be thick and strong enough at the exit of the mould to withstand the hydrostatic pressure of the liquid pool. This is a first challenge that has been leading us to first developments of the model.

After the exit of the mould, the cooling of the strand is achieved thanks to water sprays, but it is not so fast as in the mould, so that when the product can be cut (i.e. when the whole cross section is completely solidified), the length of the product is generally about 20 to 25 meters for steel products. A vertical caster (as in copper or aluminium casting) is thus hopeless for steel casting (because of the hydrostatic pressure) and the knack to bypass such problem is to bend and straighten the steel strand. That way, longitudinal tensile stresses appear at the surface of the product (exterior face in bending zone and interior face in straightening zone). In a second time, we have continued to develop the model and we have focused on these tensile stresses, which are of prime importance in the straightening zone, where the temperature corresponds to the well-known lack of ductility (700-900 °C), which means higher risks of fracture.

3 Model

3.1 Global approach

The model has been worked out using a non-linear finite element code, called LAGAMINE, which has been developed since early eighties at University of Liege for large strains/displacements problems, more particularly for metal forming modelling [1]. Since a complete 3D discretization seemed impossible to manage (both because of numerical stability and convergence reasons, but also computing time), a 2D½ model has been developed.

We can summarise the approach as following: we model with a 2D mesh a set of material points representing a slice of the strand, perpendicularly to the casting direction. Initially the slice is at the meniscus level and its temperature is assumed to be uniform and equal to the casting temperature. Since this slice is moving down through the machine, we study heat transfer, stress and strain development and solidification growth, according to boundary conditions.

3.2 Mechanical model

From a mechanical point of view, the slice is in generalised plane strain state. That means that the thickness t of the slice is governed by the following equation:

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

The mechanical behaviour of steel is modelled by an elastic-viscous-plastic law. The elastic part is governed by a very classical Hooke's law. According to thermal variation of elastic properties (shear modulus G and bulk modulus χ), its integration over a time step (from configuration A to B) gives:

$$\sigma_{ij,B} = \left(\frac{G_B}{G_A} \cdot \hat{\sigma}_{ij,A} + 2.G_B.\hat{\dot{\varepsilon}}_{ij}.(t_B - t_A) \right) + \left(\frac{\chi_B}{\chi_A} \sigma_{m,A} + \chi_B.\dot{\varepsilon}_m.(t_B - t_A) \right) \cdot \delta_{ij} \quad (2)$$

where t is time and stress and strain rate tensors ($\hat{\sigma}_{ij}$ and $\dot{\varepsilon}_{ij}$) are decomposed into deviatoric part ($\hat{\sigma}_{ij}$ and $\hat{\dot{\varepsilon}}_{ij}$) and hydrostatic part ($\sigma_m$ and $\dot{\varepsilon}_m$).

In the viscous-plastic domain, we developed a Norton-Hoff type constitutive law, the expression of which (in terms of Von Mises equivalent values) is:

$$\bar{\sigma} = \sqrt{3}.p_2.e^{-p_1\bar{\varepsilon}}.(\sqrt{3}.\dot{\bar{\varepsilon}})^{p3}.\bar{\varepsilon}^{p4} \quad (3)$$

where $p_{1,2,3,4}$ are temperature dependent parameters, which can be fit on experimental curves. According to the assumption of a Von Mises yield locus, the expression (3) becomes in terms of tensors:

$$\dot{\hat{\varepsilon}}_{ij}^{vp} = \frac{J_2^{p_5} . e^{\frac{p_1}{p_3} . \overline{\varepsilon}} . \overline{\varepsilon}^{-\frac{p_4}{p_3}}}{2.\left(K_0 . p_2\right)^{\frac{1}{p_3}}} \cdot \hat{\sigma}_{ij} \quad (4) \qquad \text{where } J_2 = \frac{1}{2} \cdot \hat{\sigma}_{ij} \cdot \hat{\sigma}_{ij} = \frac{1}{3} \cdot \overline{\sigma}^2 \text{ and } p_5 = \frac{1 - p_3}{2.p_3}$$

and the integration of this constitutive law is based on an implicit scheme [2].

The liquid pool in the middle of the strand applies a hydrostatic pressure on the solidified shell. This pressure is called ferrostatic pressure p_f and it is equal to:

$$p_f = \gamma \cdot D \cdot \left(1 - f_s\right) \quad (5)$$

where γ is the volumetric weight of steel, D the depth under the meniscus level and f_s the solid fraction. Since the studied steel is not an eutectic composition, solidification occurs over a range of temperature limited by the solidus temperature (T_{sol}) and the liquidus one (T_{liq}). We assume a linear variation of the solid fraction according to temperature in this range:

$$0 \le f_s(T) = \frac{T_{liq} - T}{T_{liq} - T_{sol}} \le 1 \qquad \forall T \in \left[T_{liq}, T_{sol}\right] \qquad (6)$$

3.3 Thermal model

The heat transfer in the material is govern by the classical Fourier's law, expressing the energy conservation and taking into account the release of energy during phase transformation (solidification is exothermic):

$$\frac{\Delta H}{\Delta T} \dot{T} = \nabla \cdot (\lambda \nabla T) \quad (7)$$

where H is the enthalpy, T the temperature and λ the thermal conductivity of the material. The enthalpy H is given by:

$$H = \int \rho \, c \, dT + \left(1 - f_s\right) . L_F \quad (8)$$

where ρ is the volumetric mass, c the specific heat and L_F the latent heat of fusion.

Thermal shrinkage ε^{therm} due to solidification is also taken into account:

$$\dot{\varepsilon}^{therm} = \alpha(T) \cdot \dot{T} \cdot I \quad (9)$$

where I is identity tensor and α is the linear thermal expansion coefficient, which is thermally affected.

3.4 Boundary conditions

Different boundary conditions can occur, according to the position of the slice in the machine and the contact conditions. The following table summaries the different cases:

***Table 1**: boundary conditions*

position in the machine	contact conditions	mechanical boundary conditions	thermal boundary conditions
slice in the mould	contact with the mould	normal stress + tangential friction	large heat transfer (direct contact)
	loss of contact	free surface (no stress)	reduced heat transfer (through the slag)
under the mould	contact with the rolls	normal stress + tangential friction	heat transfer from the strand to the rolls (direct contact)
	between the rolls	free surface (no stress)	▪ radiation + convection or ▪ water spray or ▪ water flow

In case of mechanical contact, the normal pressure is calculated by allowing, but penalizing, the penetration of bodies into each other. The friction τ_c is then computed with the Coulomb's friction law:

$$|\tau_c| = \phi.\sigma_n \qquad (10)$$

where ϕ is the friction coefficient and σ_n is the normal stress.

The heat transfer q from the strand to the ambient is given by the simple relation:

$$q = h\left(T_{strand} - T_{ambient}\right) \qquad (11)$$

where h is the heat transfer coefficient according to the boundary conditions (**Table 1**).

4 Industrial applications

4.1 Influence of the mould taper

When the liquid steel is solidifying, it shrinks and this phenomenon is not of no consequence. Indeed, if it shrinks, the solidified shell loses contact with the mould and a gap appears in between, especially in the corners. This gap fill up with slag, the thermal conductivity of which is much less efficient than the one of the copper alloy constituting the mould walls. That leads to a lower cooling of the strand and the thickness and the strength of the solidified shell at the exit of the mould are considerably reduced. Such problem (which is of prime importance in case of high speed casting) can lead to cracks in the product or even to a breakout, freeing the liquid steel which flows in the machine.

In a first industrial collaboration, we have modelled the casting of a 125 mm wide squared billet and we studied different values for mould taper [3]. We compare here the results for two moulds:

- the first one has a single taper of 1% per meter
- the second one has a double taper: 2,5 %, then 1 %

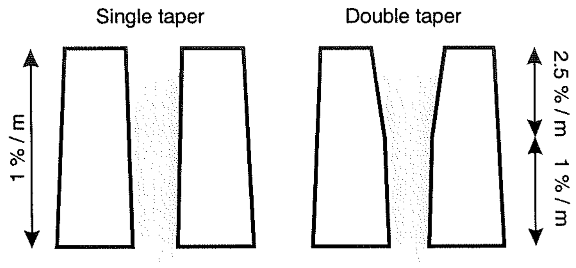

***Figure 1:** Examples of studied mould tapers*

Thanks to symmetry, only one quarter of the slice has been modelled. The comparison of temperature fields shows clearly the efficiency of the double taper, as shown on **Figure 2**. The thickness of the solidified shell is about 4 mm in the first case (on the left), while it reaches about 5.5 mm with the double taper (on the right).

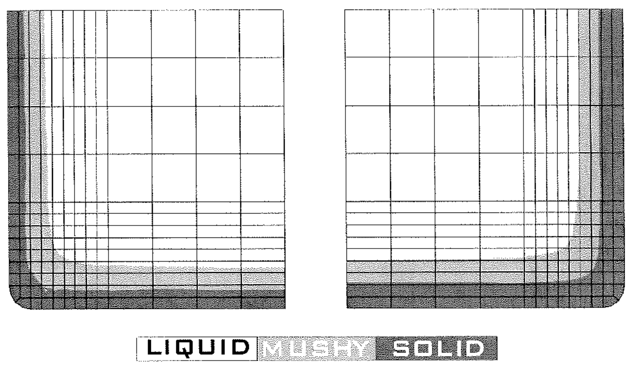

***Figure 2:** Solidified shell and mushy zone at the exit of the mould*

4.2 Study of the bending and straightening

This second industrial application tends to compare the risk of crack appearance in different cases. We have modelled (macroscopically) the complete casting using reference factors. That way, we have obtained results in terms of thermal and mechanical fields. We show on the **Figure 3** the predicted and measured temperatures at surface of the cast product: we can observe a good agreement between the two curves.

The **Figure 4** shows the extraction force, ie. the force that extracting rolls need to able to produce in order to extract the steel strand. This force originates in the friction of all rolls when spinning around their axis. There is a relation between this force and the pressure that the strand applies on the rolls. This pressure is due to the bulging of the strand between rolls (because of ferrostatic pressure), and it is increased by the supporting reactions of rolls when the strand is bent or straightened. As the **Figure 4** shows, there is a good agreement between the predicted force and the curve from the manufacturer in the straightening zone (which is the most interesting zone).

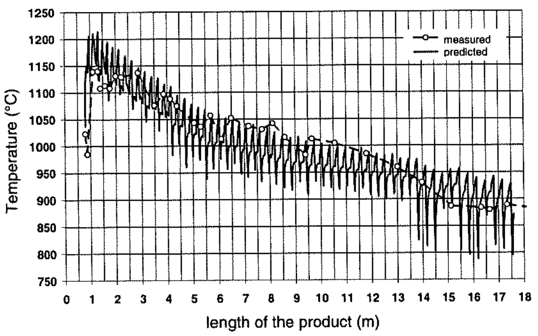

Figure 3: Predicted and measured temperature at the surface of the product

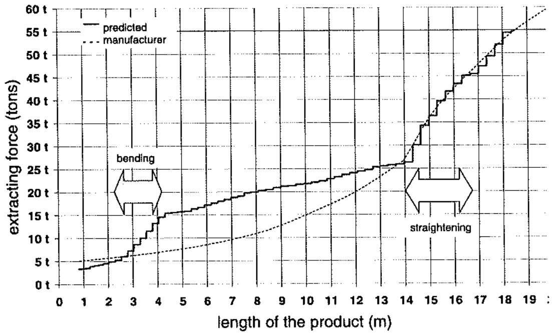

Figure 4: Extraction force (predicted and according to manufacturer)

This work is still in progress. The final goal is the analyse of various problems that can appear during the process such as misalignment of rolls, rolls locking or nozzles perturbations that modify the mechanical and thermal aspects of the contact. Other parameters will also be modified, such as the casting speed, the cooling rate and the steel grade. The way to compare the different cases is based on macroscopic fracture criteria, combining mechanical state (stress, strain, strain rate) and occurrence of low ductility (temperature between 700-900°C).

5 Conclusions

A F.E. thermo-mechanical model of continuous casting of steel has been developed in 2D½. Two industrial applications have been replicated using the model and the results of reference cases show a good correlation with respect to observations and measurements. In both studies, the model is usable now for prediction of behaviour. In the first case, the goal is the optimisation of the mould taper. In the second case, it is the prevention of appearance of cracks.

Acknowledgements

As Research Associate of National Fund for Scientific Research (Belgium), AM Habraken thanks this Belgian research fund for its support.

References

[1] http://www.msm.ulg.ac.be/
[2] Habraken A.M., Charles J.F., Wegria J., Cescotto S., Dynamic Recrystallization During Zinc Rolling, *Int. J. Forming Processes*, Vol. 1, n°1, pp. 53-73, 1998
[3] Pascon F., Habraken A.M., Bourdouxhe M., Labory F., Modélisation des phénomènes thermomécaniques dans une lingotière de coulée continue, *Mec. Ind.*, Vol. 1, p. 61-70, 2000.
[4] Modeling for casting and solidification processing, Kuang-O (Oscar) Yu Editor, 2002