Finite element modeling of thermo-mechanical behaviour of a steel strand in continuous casting

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ABSTRACT: Surface and internal quality of continuous cast products depends very much upon the behaviour of the strand in the mould. Among the parameters likely to influence this behaviour, the mould taper takes a prominent part. In order to understand better the influence of this parameter, we have build up a thermo-mechanical finite elements model. The model includes an elasto-visco-plastic law to describe the behaviour of steel from liquid to solid state, a thermo-mechanical element that takes into account thermal expansion and mechanical behaviour of the strand, a unilateral contact element, a mobile rigid boundary element to model the mould and its taper and an adapted loading element to model the ferrostatic pressure according to the liquid or solid state.

Key words: continuous casting; solidification; mould taper; elasto-visco-plastic law; finite element

1 INTRODUCTION

Continuous casting can be schematically described as follows: liquid steel is poured into a bottomless copper mould that is kept at a relatively constant temperature thanks to a water cooling system. Liquid steel in contact with the mould hardens and a solidified shell starts to grow. This is called the primary cooling. Under the mould, some extracting rolls pull the strand out of the mould and make it moving forward in the caster while water sprays continue cooling the strand (secondary cooling). As fast as the strand is moving down the system, the thickness of the solidified shell grows until all of the section is solidified. Then the strand can be cut and sent to storage.

Numerous factors influence the quality of the product and many studies have already been performed. The behaviour of the strand in the mould takes a prominent part in the development of defects such as cracks and thus influences largely the quality of the cast product. Among other parameters, the determination of the mould taper is crucial [1-3]. In the case of totally convex sections (such as billets and blooms), the taper is positive on the whole outline. If the taper is too low, the contact between the strand and the mould can be lost and a gap appears, leading to a decreasing thermal exchange and defects. At the opposite, if the taper is too high, friction between the strand and the mould induces stresses and strains in the fragile solidifying shell. For more complex cross sections (i.e. beam blanks), the taper can be negative on a part of the outline. In the same way, a wrong taper design can be responsible of quality problems.

Many other parameters are also important for the quality of the product [4-7]. Among these parameters, one can mention casting speed, 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 thermo-mechanical behaviour of the strand in the mould. This analysis is based on a finite element approach, using the Lagrangean LAGAMINE code that has been developed since early eighties in the MSM Department of University of Liège.

If the optimal mould taper is well determined for simple sections (blooms and billets), it is rather more difficult for complex sections.

Finite elements are very helpful to solve this problem thanks to the interpretation of some numerical results such as the temperature field, the stress and strain fields and the contact/friction between the strand and the mould.

DEL DESCRIPTION

ometry of the problem

r to validate the model and since we know the ı of the problem for the following simple ry, we worked first with a 125-mm wide l billet:

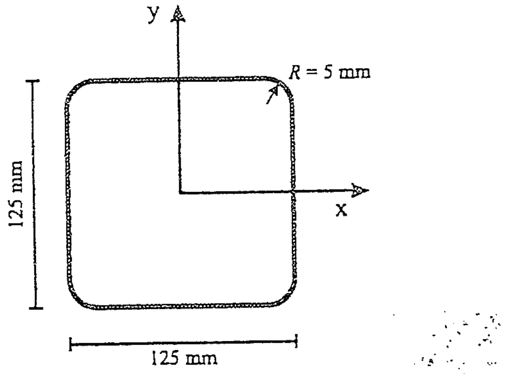


Figure 1: Cross section of the strand

ive height of the mould is 600 mm and the 1.05 % per meter.

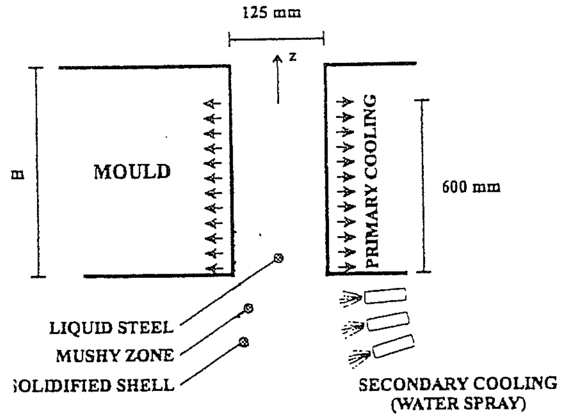


Figure 2: Mould geometry

e of the double symmetry, we only studied ırter of the slice, applying the right boundary ons along these symmetry axes. The casting s relatively high speed and it is equal to 3.6 ıer minute or 60 mm per second.

proach of the problem

olete three-dimensional analysis seemed to be ible (both because of numerical stability and gence reasons, but also computing time). We ed in a 2D mesh a set of material points nting a slice of the strand, perpendicularly to nd axis. Initially the slice is at the meniscus ıd its temperature is assumed to be uniform ual to the casting temperature. From a ical point of view, the slice is in generalized strain state; the thickness t of the slice is ed by the following equation:

$$t(x,y) = \alpha_0 + \alpha_1 \cdot x + \alpha_2 \cdot y \tag{1}$$

where α_0, α_1, α_2 are degrees of freedom of the problem. Because of double symmetry, $\alpha_1 = \alpha_2 = 0$. We dispose of a balance equation for this "third geometric degree of freedom" (the same for each node of the mesh), so that the generalized plane strain state include both strains and stresses perpendicularly to the plane.

2.3 Thermal model

The copper mould is cooled by an internal water flow near the contact surface. We assumed that the temperature of the mould surface is uniform, constant and equal to 160 °C.

A classical Fourier-type law predicts the heat flux in the material (the strand):

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

where T is the temperature field, 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:

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

where L_s is the latent heat of solidification and f_s is the solidified fraction.

Introducing the enthalpy function:

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

the Fourier law can be written as follows:

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

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.

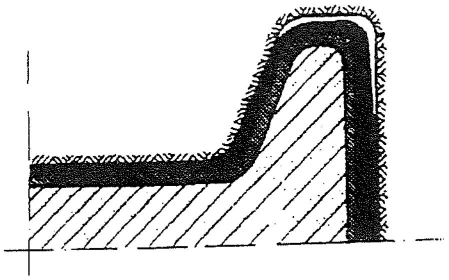


Figure 3: Gap appearance in the corners

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

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

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

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

where h is the heat transfer coefficient through the gap, ε_r the relative emissivity of the strand and σ_B the Stefan-Boltzmann constant.

2.5 *Mechanical properties of the material*

The main mechanical effect of solidification is shrinkage, the value of which is proportional to the temperature decreasing:

$$\dot{\varepsilon}^{therm} = \alpha(T) \cdot \dot{T} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

The mechanical behaviour of the material is described by an elasto-visco-plastic law for liquid, mushy and solid states. The visco-plastic domain is described thanks to a Norton-Hoff type law, the expression of which is:

$$\bar{\sigma} = K_0 \cdot e^{-p_1 \cdot \bar{\varepsilon}} \cdot p_2 \cdot \sqrt{3} \cdot \left(\sqrt{3} \cdot \dot{\bar{\varepsilon}}\right)^{p_3} \cdot \bar{\varepsilon}^{p_4} \tag{9}$$

where K_0, p_1, p_2, p_3, p_4 are temperature dependant parameters. This expression allows to model both hardening and softening and an implicit integration scheme has been used. Moreover, the parameters at high temperature can be chosen in such a way that the law degenerates to model a fluid behaviour.
Using a plastic flow rule associated to the von Mises criterion, the tensor relationship is:

$$\hat{\dot{\varepsilon}}^{vp}_{ij} = \frac{(J_2)^{\frac{1-p_3}{p_3}} \cdot (\dot{\bar{\varepsilon}})^{\frac{p_4}{p_3}} \cdot e^{\frac{p_1 \cdot \bar{\varepsilon}}{p_3}}}{2(K_0 \cdot p_2)^{\frac{1}{p_3}}} \cdot \hat{\sigma}_{ij} \tag{10}$$

with

$$J_2 = \frac{1}{2} \cdot \hat{\sigma}_{ij} \cdot \hat{\sigma}_{ij} = \frac{(\bar{\sigma}_{VM})^2}{3} \tag{11}$$

The ferrostatic pressure p_f is also taken into account. Its value is given by:

$$p_f = \gamma \cdot D \cdot (1 - f_s) \tag{12}$$

where g is the volumic weight and D the depth under the meniscus.

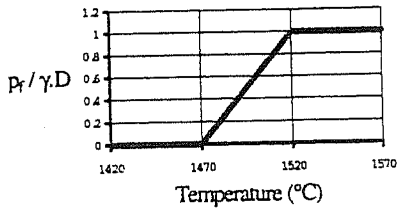


Figure 4: Ferrostatic pressure vs. temperature

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 [8] 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 [9].

2.7 *Type of analysis*

The resolution of the problem is achieved using a staggered analysis. Such an analysis was necessary because of very expensive CPU time and loss of stability in the case of a fully coupled analysis. It has been used many times previously for different kinds of problems and what has been concluded is that the results are not too much affected with right strategy parameters. Literature also provides many examples of using staggered analysis for such thermo-mechanical coupled problem, including phase transformation and contact (such as in foundry).

3 NUMERICAL RESULTS

We present here some results obtained with two different tapers:

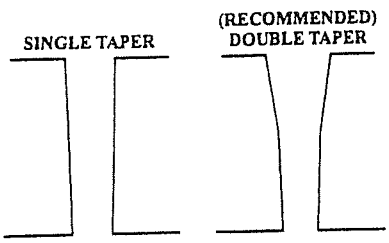
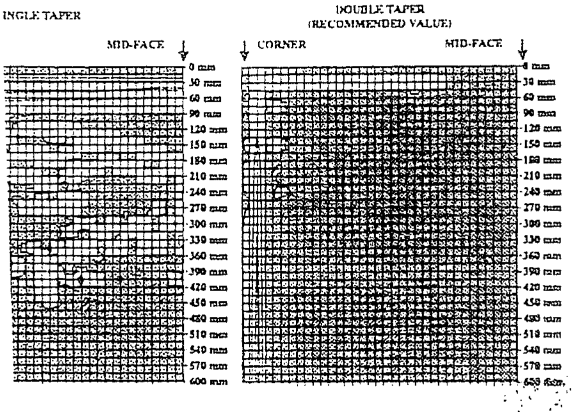


Figure 5: single and (recommended) double mould taper

ure 6 shows the distance between the strand mould. When it is positive (in white), that :hat there is loss of contact. At the opposite, occurs in grey when the distance is zero or n zero (it can be slightly negative since we ıalty technique in the mechanical contact on).



Contact mould-strand according to the depth under cus (0 mm: meniscus - 600 mm: exit of the mould)

ft, it clearly appears that the contact is not :hieved.

; previous observation, one can guess that ıg of the strand in the first case (single ›uld be worse than with the recommended eed, the analysis of thermal fields shows olidified shell is 30 % less (ca. 4 mm vs.

ılts such as stress, strain and strain rate also available. They can be introduced in models of fracture criteria in order to :he quality of the mould design. The ı of such criteria is going on in the model. ults could help to optimise casting (mould taper as well as any other to quantify the quality of the mould design, which is essential in order to optimise (and to use an inverse method).

.USION

f the study was to make a model of the :chanical behaviour of a steel strand in the continuous caster.

tend to prove that the model prediction is observations.

ɜp in the study is to model more complex ɜam blanks) and to optimise the mould

ɔment and integration of fracture criteria ɜteel at very high temperature will guide

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References

[1] S. Chandra, J.K. Brimacombe and I. Samarasekera, "Mould-strand interaction in continuous casting of steel billets – Part 3 Mould heat transfer and taper", Ironmakinig and Steelmaking, 1993, vol. 20, No.2, pp. 104-112.

[2] M.R. Ridolfi, B.G. Thomas and U. Della Foglia, "The optimization of mold taper for the Ilva-Dalmine round bloom caster", La Revue de Métallurgie – CIT, Avril 1994, pp. 609-620.

[3] M. Bourdouxhe, A.M. Habraken and F. Pascon, "Mathematical modelisation of beam blank casting in order to optimise the mould taper", 3rd European Conference on Continuous Casting, October 20-23, Madrid 1998

[4] J.E. Kelly, K.P. Michalek, T.G. O'Connor, B.G. Thomas and J.A. Dantzig, "Initial development of thermal and stress fields in continuously cast steel billets", Metallurgical Transactions A, vol. 19A, October 1988, pp. 2589-2602.

[5] M. El-Bealy, N. Leskinen and H. Fredriksson, "Simulation of cooling conditions in secondary cooling zones in continuous casting process", Ironmaking and Steelmaking, 1995, vol. 22, No.3, pp. 246-255.

[6] R. B. Mahapatra, J.K. Brimacombe, I. Samarasekera, N. Walker, E.A. Paterson and J.D. Young "Mold behavior and its influence on quality on the continuous casting of steel slabs : Part I. Industrial trials, mold temperature measurements, and mathematical modeling", Metallurgical Transactions B, vol. 22B, December 1991, pp. 861- 874

[7] R. B. Mahapatra, J.K. Brimacombe and I. Samarasekera, "Mold behavior and its influence on quality on the continuous casting of steel slabs : Part II. Mold heat transfer, mold flux behavior, formation of oscillation marks, longitudinal off-corner depression, and subsurface cracks", Metallurgical Transactions B, vol. 22B, December 1991, pp. 875- 888

[9] Cescotto S., Charlier R., "Frictional contact finite element based on mixed variational principle", Int. J. for Numerical Methods in Engineering, vol. 36, 1993, pp. 1681-1701.

[10] Habraken A.-M., Radu J.-P., Charlier R., "Numerical approach of contact with friction between two bodies in large deformations", Contact Mechanics International Symposium, Lausanne, October 92.