FINITE ELEMENT MODELLING OF THERMO-MECHANICAL BEHAVIOUR OF A STEEL STRAND IN CONTINUOUS CASTING

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Abstract: An elastic-viscous-plastic constitutive law (Norton-Hoff type) is coupled to a contact law in a finite element code in order to model the behaviour of a steel strand in the mould of a continuous casting machine. Both thermal and mechanical type fields are computed. The objective is to compare for different industrial process conditions the thickness of the solidified shell as well as the stress and strain levels in this layer. More particularly, the model should lead to optimise the taper of the mould for different cross sections of steel strand.

Keywords: continuous casting; Norton-Hoff law; finite element method; mould taper

1. INTRODUCTION

Surface and internal quality of continuous cast products depends very much upon the behaviour of the steel strand in the mould. Among the parameters likely to influence this behaviour, the mould taper takes a prominent part [1, 2, 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. The consequences can be surface defects also in this case. 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.

In order to optimise this parameter for different cross sections, we have built a thermal-mechanical model. This analysis is based on a finite element approach, using the LAGAMINE code that has been developed since early eighties in the MSM Department of University of Liege. This code is a non linear finite element code and it belongs to the family of updated lagragian codes.

A slice of the strand is modelled and its evolution through the mould is observed. The main results are temperature field and solidification evolution, stress, strain and strain rate fields and losses of contact and returns to contact analysis. The model includes an elastic-viscous-plastic law to describe the behaviour of steel from liquid to solid state, a thermal-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 for the ferrostatic pressure according to the liquid or solid state.

This paper presents the model and its first results obtained with a relatively simple section (a 125-mm wide squared billet). This choice has been guided by the good knowledge of the optimal taper for such simple sections. The first step is thus to verify that the model provides the same optimal taper, then it will be applied to more complex sections (beam blanks), the optimal taper of which can only be determined with a flexible numerical technique such as finite element method.

2.3. Inner heat transfer

Liquid steel is poured in the mould at high temperature (casting temperature). The copper mould is cooled by an internal water flow near the surface. We assume that the temperature of the mould is constant and uniform (T_{mould}).

Since solidification is an exothermic process, energy is given off by the system during this phase transformation. This energy (latent heat) must be taken into account in the balance of energy. For a pure metal, this transformation occurs at a constant temperature, but for alloys (such as steel), the solidification starts at the liquidus temperature T_{liq} and finishes at the solidus temperature T_{sol}. Between these two limits, there is a mixture of solid and liquid states that is called mushy. We can notice an exception for eutectic alloys that solidify at a constant temperature.

In our model, liquidus and solidus temperatures are 1520 °C and 1470 °C. Even if the phase changing interval is relatively large according to temperature variation during time steps, we use the so-called enthalpy method. We use the enthalpy function $H(T)$, which takes into account all thermal energy involved in the material to heat it from the absolute zero (0 K) to the considered temperature T (in K):

$$H(T) = \int_{0K}^{T} \left(\rho c - \rho L_f \frac{\partial f_s}{\partial \theta} \right) d\theta \tag{2}$$

where ρ is the unit mass, c the specific enthalpy, L_f the specific latent heat of solidification and f_s is the solidified fraction. In a first approximation, we assumed a linear variation of the solid fraction with respect to the temperature:

$$0 \leq f_s(T) = \frac{T_{liq} - T}{T_{liq} - T_{sol}} \leq 1 \tag{3}$$

where T_{liq} and T_{sol} are respectively liquidus and solidus temperatures. In fact, this assumption is not too far from the observed evolution in equilibrium conditions, even if it is quite different of a non-equilibrium situation.

The main advantage of the enthalpy formulation is that the size of time step does not influence the result because the conservation of heat is always verified.

A classical Fourier-type law predicts the conductive heat flux (inner the strand):

$$\rho c \dot{T} = \mathrm{div}(\lambda \nabla T) + q \tag{4}$$

where λ is 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, one can express q by the equation:

$$q = \rho L_f \frac{\partial f_s}{\partial T} \dot{T} \tag{5}$$

Using the enthalpy formulation, the Fourier law can then be written as follows:

$$\dot{H}(T) = \mathrm{div}(\lambda \nabla T) \tag{6}$$

where the enthalpy is defined as:

and it is also thermally affected. During a time step, the thermal part of strain rate is classically given by:

$$\dot{\varepsilon}^{therm} = \alpha(T)\dot{T}\mathbf{I} \tag{10}$$

2.6. *Mechanical behaviour of the steel at high temperature*

The mechanical behaviour of the material is described by an elastic-viscous-plastic law for 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 dependent:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} = \frac{E}{1-2\nu}\varepsilon_m\delta_{ij} + \frac{E}{1+\nu}\hat{\varepsilon}_{ij} = 3\chi\varepsilon_m\delta_{ij} + 2G\hat{\varepsilon}_{ij} \tag{11}$$

where χ and G are respectively bulk and shear moduli. The integration of this over the time step Δt gives the stress tensor:

$$\sigma_{ij,B} = \left(\frac{G_B}{G_A}\hat{\sigma}_{ij,A} + 2G_B\hat{\dot{\varepsilon}}_{ij}\Delta t\right) + \left(\frac{\chi_B}{\chi_A}\sigma_{m,A} + 3\chi_B\dot{\varepsilon}_m\Delta t\right)\delta_{ij} \tag{12}$$

where subscripts A and B are used for beginning and end of time step. Unsubscripted values (strain rate) are assumed constant during time integration.

As usual in models of metals plasticity, we use criterion of Von Mises to define the yield locus f:

$$f = \frac{3}{2}\hat{\sigma}_{ij}\hat{\sigma}_{ij} - \sigma_0^2 \leq 0 \tag{13}$$

where σ_0 is the yield limit. This expression can be written using the (Von Mises) equivalent stress $\overline{\sigma}$:

$$\overline{\sigma} = \sqrt{\frac{3}{2}\sigma_{ij}\sigma_{ij}} \leq \sigma_0 \tag{14}$$

The plastic flow rule is associated to the yield locus:

$$\dot{\varepsilon}_{ij}^{pl} = \dot{\lambda}^{pl}\frac{\partial f}{\partial \sigma_{ij}} = \frac{3\dot{\overline{\varepsilon}}^{pl}}{2\sigma_0}\hat{\sigma}_{ij}^{pl} \tag{15}$$

where $\dot{\overline{\varepsilon}}^{pl}$ is the (Von Mises) equivalent plastic strain rate:

$$\dot{\overline{\varepsilon}}^{pl} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^{pl}\dot{\varepsilon}_{ij}^{pl}} \tag{16}$$

The viscous-plastic domain is described thanks to a Norton-Hoff type law, the expression of which is:

is obviously equal to zero. In the mushy zone, we assume a linear relationship between the pressure and the solid fraction f_s:

$$p_f = \gamma D(1 - f_s) = \gamma D\left(\frac{T - T_{sol}}{T_{liq} - T_{sol}}\right) \quad \text{when} \quad T_{sol} < T < T_{liq} \tag{21}$$

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

2.8. Mechanical contact

From the mechanical point of view, the contact between the strand and the mould induces both pressure (normal stress σ_n) and friction efforts in the plane of the slice and in the casting direction (respectively, tangential stresses τ_r and τ_s). The contact element is based on mixed variational principles and it has already been presented in a previous paper by Cescotto and Charlier [5]. It expresses the Signorini's conditions at its integration points:

$$\begin{cases} \sigma_n \le 0 & \text{unilateral contact} \\ \dot{\mathbf{u}} \cdot \mathbf{n} \le 0 & \text{no penetration} \\ (\dot{\mathbf{u}} \cdot \mathbf{n})\sigma_n = 0 & \end{cases}$$

where **n** is the external normal unit vector and $\dot{\mathbf{u}}$ the velocity in the **n** direction. Because of numerical considerations (infinite slopes, cf. **Fig. 3**), the no penetration condition is relaxed using the penalty method, allowing but penalizing penetration of the strand into the mould using the penalty coefficient K_p:

$$\sigma_n = -K_p u \tag{22}$$

where u is the penetration depth in the **n** direction.

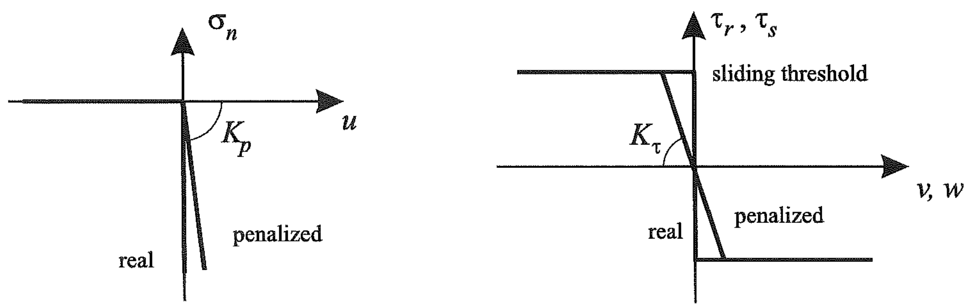

Fig. 3: Penalisation in mechanical contact

In the same way, a "reversible" sliding is authorized (**Fig. 3**), but a tangential stress withstand this move:

$$\begin{cases} \tau_r = -K_\tau v \\ \tau_s = -K_\tau w \end{cases} \tag{23}$$

where v and w are sliding moves (respectively in the plane and perpendicularly to it) and K_τ a second penalty coefficient.

The strand, more precisely the studied quarter of slice, is modelled with quadratic quadrangular elements (8 nodes) and 4 integration points with Gauss scheme for each element. The elements are of course larger in the centre of the slice and the 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).

The contact (or loss of contact) between the mould and the strand is modelled using (3 nodes-) contact elements. The particularity of these contact elements is that they use a three-dimensional law, even if the analysis is only two-dimensional. The reason of this is that we want to take into account the friction in the casting direction, that is perpendicular to the studied slice.

A rigid body represents the mould and it is mobile so that it is possible to define for each time step its position according to the taper of the mould. It can follow a single, multiple or parabolic taper.

2.10. 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/casting).

3. NUMERICAL SIMULATIONS

We present here some results obtained with two different tapers: the first one is a single (relatively low) taper and the second one is the one which is known as the optimal (recommended) one.

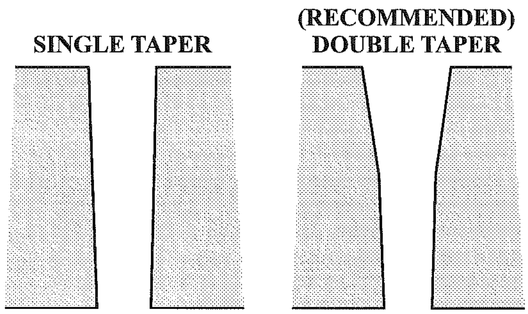

Figure 5: single and (recommended) double mould taper

The figure 6 shows the distance between the strand and the mould. When it is positive (in white), that means that there is loss of contact. At the opposite, contact occurs in grey when the distance is zero or less than zero (it can be slightly negative since we use penalty technique in the mechanical contact integration).

On the left, it clearly appears that the contact is not enough achieved. From this previous observation, one can guess that the cooling of the strand in the first case (single taper) should be worse than with the recommended taper. Indeed, the analysis of thermal fields shows that the solidified shell is 30 % less thick (ca. 4 mm vs. 5.5 mm).

Other results such as stress, strain and strain rate fields are also available. They can be introduced in different models of fracture criteria in order to evaluate the quality of the mould design. The integration of such criteria is going on in the model. Such results could help to optimise casting conditions (mould taper as well as any other parameter).