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▶ **To cite this version:**

HAL Id: hal-00576637

https://hal-mines-paristech.archives-ouvertes.fr/hal-00576637

Submitted on 15 Mar 2011

Finite element thermomechanical simulation of steel continuous casting

R. Forestier[1], Frédéric Costes[2], Olivier Jaouen[2], Michel Bellet[3]

[1]ASCOMETAL CREAS, Avenue de France, B.P. 70045, 57301 Hagondange Cedex, France
[2] Transvalor SA, Sophia Antipolis, France
[3] Mines ParisTech, CEMEF – CNRS UMR 7635, Sophia Antipolis, France

Keywords: continuous casting, thermal-mechanical modelling, air gap, stress-strain, hot tearing

Abstract

In continuous casting (CC), thermomechanical simulation is essential to analyze important issues: gap formation; stress and deformation of the solidified shell; bulging of product between supporting rolls in the case of steel CC; size of final product, butt-curl defect in direct chill casting of aluminium. The numerical simulation package THERCAST has been developed with the objective of supplying an accurate analysis of those phenomena, permitting to define relevant process actuators. In this paper, some characteristic features especially developed for steel continuous casting are presented and illustrated by examples of industrial application.

Introduction

During CC, deformations are induced by thermal heterogeneity, bending, unbending, contact with rolls, bulging of the solidified shell. These deformations can cause hot tearing or cracking. Then, the casting speed has to be reduced for sensitive grades. Within this framework, thermal-mechanical modelling is of interest as it can help steel producers to adjust the process parameters to improve casting productivity while maintaining a satisfying product quality. The use of such models is economically interesting since plant trials are very expensive and time consuming.

This kind of simulation is quite complex. First, it requires many input data regarding thermal exchanges in the mould and in secondary cooling, as well as mechanical properties of steel at high temperature and under very low strains and strain rates. This needs many experimental characterisations and researches in literature. Second, it is a numerical challenge. As steel undergoes stiff thermal gradients, its properties dramatically change throughout the solidified shell, requiring very fine meshes, and then long computational times.

However, thermal-mechanical modelling of CC is nowadays used to solve concrete industrial problems. For example, Park et al. [1] studied the impact of mould corner radii on the formation of corner cracks using a finite element method. Triolet et al. [2] studied the impact of process parameters on slab bulging. Won et al. [3] developed a hot tearing criterion and applied it to the solidification of a strand under different process parameter conditions. Recently, Saraswat et al. [4] studied the impact of mould flux properties on the thermal-mechanical behaviour of a billet.

The present paper focuses on the numerical methods implemented in THERCAST and on the way this software can be used in industrial research centres. The software THERCAST – based on 3D finite element methods – has been used for all the examples presented here. The input data – constitutive equation and boundary conditions as well – are presented. The model is applied to simulate air gap formation inside the mould. The deformations under the mould are also computed and analysed and the impact of process parameters on hot tearing criteria is discussed.

Non Steady-State Thermal-Mechanical Modelling of Continuous Casting

THERCAST is a commercial numerical package for the simulation of solidification processes: shape casting (foundry), ingot casting, and direct-chill or continuous casting. It includes a 3D finite element thermal-mechanical solver, based on an Arbitrary Lagrangian Eulerian (ALE) formulation [5]. In order to take into account the complex behaviour of solidifying alloys, a hybrid constitutive model is considered. In the liquid (respectively, mushy) state, the metal is considered as a Newtonian (respectively non-Newtonian) fluid. In the solid state, the metal is assumed to be elastic-viscoplastic. Solid regions are treated in a Lagrangian formulation, while liquid regions are treated using ALE.

In the computations presented in this paper, the submerged entry nozzle (SEN) is not modelled. The meniscus is defined as an injection surface (nodes are considered as Eulerian) and the dummy bar is modelled by prescribing the casting speed along the lower face of the product (figure 1). This Global Non Steady-state approach, initially proposed by Bellet and Heinrich [6] permits a global thermomechanical modelling of the cast product. It overcomes the limitations of the classical "slice method", in which the only possible mechanical boundary conditions (plane stress, plane strain, generalized plane strain) are not relevant, and which does not give access to bulging prediction. Using this GNS formulation, it is necessary to use a remeshing method, since the computational domain is continuously expanding during the simulation. Remeshing only affects the extreme upper zone of the domain, near the meniscus, and is performed using a local extraction/remeshing strategy in order to minimise remeshing duration [7][8].
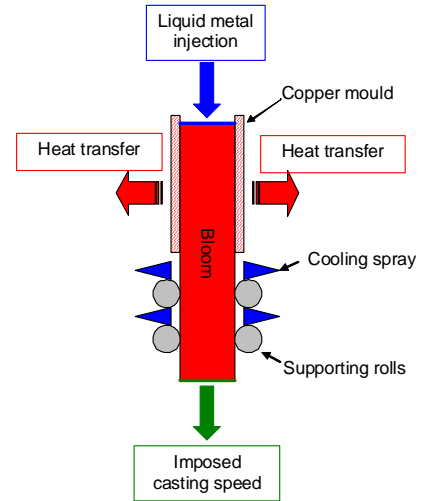

Figure 1. Global non steady-state modelling of CC

Contact with mould surface (including mould deformation) and with supporting rolls is taken into account using a specific penalty method [9][8].

Input Data

Constitutive Equations

Rheological data are necessary to perform thermo-mechanical calculations. The acquisition of rheological data at high temperature, small strain and very low strain rate is a difficult problem. One can cite the works of Kozlowski et al.[10], of Pierer et al. [11] and of Seol et al. [12], who identified models and parameters for different carbon steels. The behaviour of δ-ferrite and of austenite was also studied by Seol and al. [12] and Kim et al [13], showing that δ-ferrite hardens less than austenite. In the computations presented here, the constitutive data are taken from Kozloswki et al. [10] who identified rheological models with respect to the carbon content for strain rates between 10^{-3} et 10^{-6} s^{-1}, and for temperatures between 950 °C and 1400 °C. The law II of Kozlowski et al. [10] can be reformulated as follows:

$$\overline{\sigma} = K_s(T)\overline{\varepsilon}^{n(T)}\dot{\overline{\varepsilon}}^{m(T)}$$

where $\overline{\sigma}$ is the von Mises flow stress, $\overline{\varepsilon}$ the equivalent plastic strain, $\dot{\overline{\varepsilon}}$ the equivalent plastic strain rate, T the temperature, n the strain hardening coefficient and m the strain rate sensitivity coefficient. In the present study, this law is used below the solidus temperature T_S. For the liquid steel, over the liquidus temperature T_L, a Newtonian behaviour is considered:

$$\overline{\sigma} = K_l(T)\dot{\overline{\varepsilon}}$$

Between solidus and liquidus temperatures, it is considered first that steel over the coherency temperature T_C behaves like liquid steel. Then, we interpolate the constitutive law between the coherency and the solidus temperature using a multiplicative law:

$$\overline{\sigma} = \left(K_s(T_S)\overline{\varepsilon}^{n(T_S)}\dot{\overline{\varepsilon}}^{m(T_S)}\right)^{\frac{f_s - f_c}{1 - f_c}} \left(K_l(T_C)\dot{\overline{\varepsilon}}\right)^{\frac{1 - f_s}{1 - f_c}} \quad \text{i.e.} \quad \overline{\sigma} = \widetilde{K}\overline{\varepsilon}^{\widetilde{n}}\dot{\overline{\varepsilon}}^{\widetilde{m}}$$

$$\text{with} \quad \widetilde{K} = K_s(T_S)^{\frac{f_s - f_c}{1 - f_c}} K_l(T_C)^{\frac{1 - f_s}{1 - f_c}} \qquad \widetilde{n} = n(T_S)\frac{f_s - f_c}{1 - f_c} \qquad \widetilde{m} = m(T_S)\frac{f_s - f_c}{1 - f_c} + \frac{1 - f_s}{1 - f_c}$$

where f_c is the solid fraction at the coherency temperature and f_s the solid fraction. This law permits a smooth transition between solid and liquid behaviour. Nevertheless, the solution of the mechanical problem is tricky since the consistency of steel drops over coherency temperature.

Thermal Boundary Conditions in the Context of Continuous Casting

At the mould/product interface, the extracted heat flux q is expressed as follows:

$$\begin{cases} q = \dfrac{1}{R_{eq}}(T - T_{mld}) \\[2mm] q = -k\dfrac{\partial T}{\partial n} = -k_{mld}\dfrac{\partial T_{mld}}{\partial n} \end{cases} \quad \text{with} \quad \begin{cases} R_{eq} = \dfrac{1}{\dfrac{1}{R_{cond}} + \dfrac{1}{R_{rad}}} + R_{flux} \quad \text{if } e_{air} > 0 \\[4mm] R_{eq} = R_{flux} \text{ if } e_{air} = 0 \end{cases}$$

$$R_{flux} = \frac{e_{flux}}{\lambda_{flux}} \qquad R_{cond} = \frac{e_{air}}{\lambda_{air}} \qquad R_{rad} = 1/\left(\sigma\varepsilon_{eq}(T^2 + T_{mld}^2)(T + T_{mld})\right) \text{ with } \varepsilon_{eq} = \frac{1}{\dfrac{1}{\varepsilon} + \dfrac{1}{\varepsilon_{mld}} - 1}$$

where e_{air} and e_{flux} denote respectively the air gap and the mould flux thickness, λ_{air} and λ_{flux} the air and the mould flux heat conductivity, T and T_{mld} the product and the inner mould surface temperature, ε and ε_{mld} the emissivity of steel and copper, and σ the Stefan-Boltzmann constant. These equations permit to model heat conduction and radiation inside the air gap (when it exists) and conduction through the mould flux. The flux layer thickness is determined by use of a decoupled 1D resolution based on Reynolds equation. This model permits to determine a heat flux density inside the mould, which is in good agreement with in situ measurements. At the interface between the cooling water and the mould, a convection-type boundary condition is used: $q = h(T_{mld} - T_{water})$.

In secondary cooling, heat extraction is modelled using the spray diagrams and heat transfer models depending on the water surface density [14][15][16]. The cooling due to the contact with the rolls is also modelled using heat transfer coefficients from the literature [16].

Hot Tearing Criteria

Various hot tear criteria can be found in the literature. Some are just based on thermal calculations, others use as input stresses and/or strains and/or strain rates. Cerri et al. [17] proved that the criterion of Yamanaka et al. [18] is pertinent to forecast the location of hot tears in solidification conditions. This criterion is expressed as follows:

$$\varepsilon_c = \int_{f_{s1}}^{f_{s2}} \hat{\dot{\varepsilon}}\, dt$$

where f_{s1}, f_{s2} are two characteristic solid fractions and $\hat{\dot{\varepsilon}}$ denotes a norm associated to the damaging components of the strain rate tensor, that is those exerted orthogonally with respect to the crystal growth direction [19]. The critical value ε_c depends on steel composition. It should be noted that Won et al. [3] introduced a critical deformation depending on the brittle temperature range and on strain rate. As it can be seen in its definition, such a criterion is

obtained by time-integration of tensile strain rates inside the brittle temperature (typically [0.9;0.99]. Yet, inside the mould or just below the mould exit, the thermal gradient is important and then, the mushy zone is relatively tiny. It is then necessary to use very fine meshes.

Applications

Study of Air Gap Formation

The simulation of CC of round and square blooms of alloyed steel grades was performed with THERCAST. During casting, metal shrinks and air gap forms, generating heterogeneous cooling. Hence, such a modelling can be used for the study of the influence of the mould taper. As shown hereunder, air gap forms very differently for round and square products.

Round Section Casting. In this case, a partial contact between the mould and the metal is observed when the mould taper is not well adapted. Then, a polygonalisation of the solidification front may appear and some longitudinal defects can even form. These phenomena are reproduced with THERCAST (figure 2 and figure 3). As heat transfer depends on air gap width, an irregular solid skin may form, leading to such a longitudinal defect (figure 4). This example shows how the thermal-mechanical model can reproduce some classical casting defects. Of course, the defect disappears with an appropriate mould taper, which prevents air gap formation.
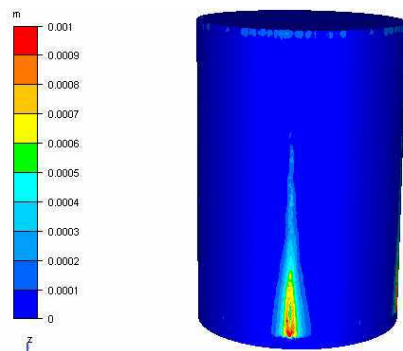

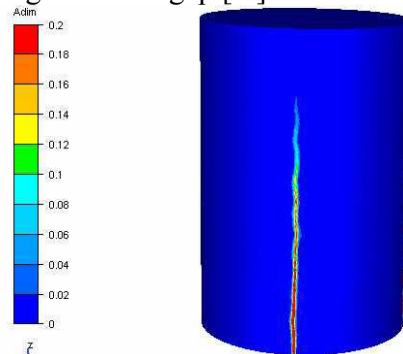Figure 2. Air gap [m] formed in the mould

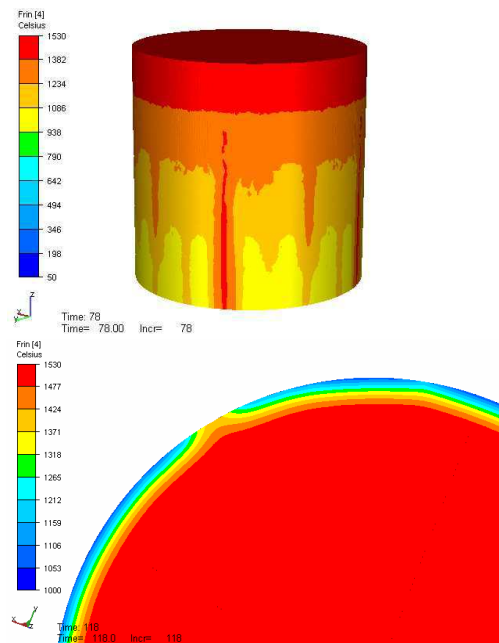Figure 4. Won et al. criterion [3] computed on the round bloom surface

Figure 3. Temperature field [°C] computed on the round bloom surface (up: side view – down: section view at the mould exit)

This model can also be used in order to estimate the optimal mould taper. Heat transfer and metal shrinkage were modelled considering that no air gap can form. Within this condition, the solid skin uniformly shrinks. Within these conditions, the metal shrinkage can be computed (figure 5). One can consider that the optimal mould taper should follow perfectly the metal shrinkage. This calculation is in good agreement with some literature results about design of mould tapers [20].
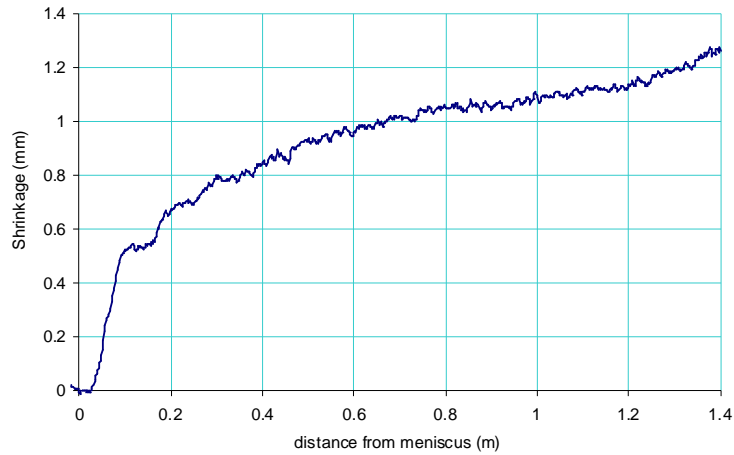
Figure 5. Calculation of metal shrinkage without formation of air gap

Square Section Casting. The study of the solidification of a square bloom shows that the air gap is localised in the corner (figure 6 a). The metallostatic pressure is responsible for the surface bending. Saraswat at al. obtained the same conclusion using a 2D thermal-mechanical model [4]. Besides, some computations showed, as reported by Park et al. [1], that if the mould is too long and/or if the taper is not adapted to the grade or to the casting speed, the corner of the bloom might be undersolidified. Here, some computations were done with a non-tapered and a tapered square section mould. We of course observe different air gaps in these two conditions. One can see on figure 6 b that the hot tearing criterion defined by Yamanaka et al. [18] is significantly higher in the bloom corner for the non-tapered mould. The reason is that the corner is undersolidified for the non-tapered mould due to air gap forming in that case (figure 7). Hence, the corner remains a longer time in the brittle temperature range and under tensile stresses.
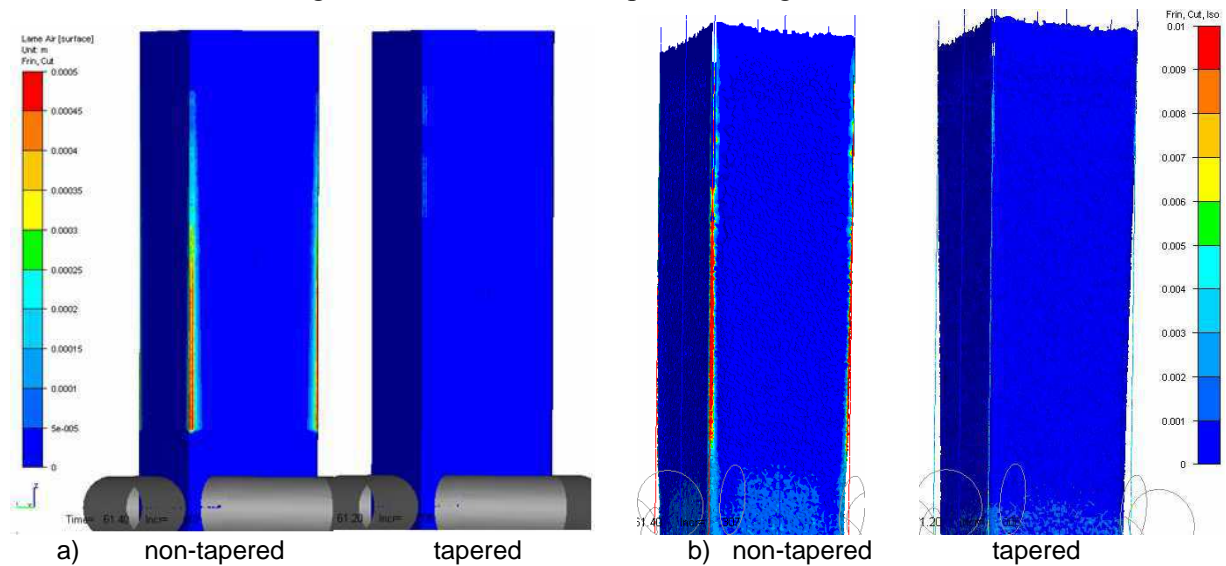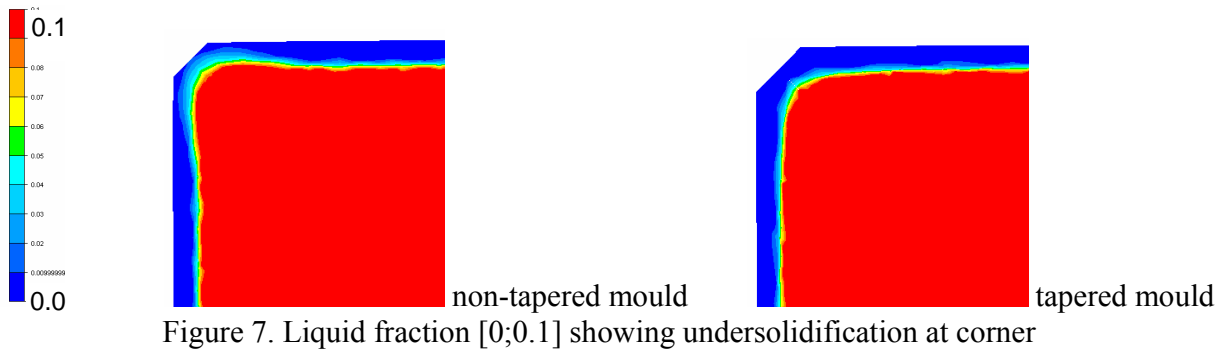

a)   non-tapered   tapered   b) non-tapered   tapered

Figure 6. a) Influence of mould tapering on air gap [m] formation.
b) Yamanaka et al. [18] criterion projected onto the solidus surface

non-tapered mould   tapered mould

Figure 7. Liquid fraction [0;0.1] showing undersolidification at corner

Hot Tearing in Secondary Cooling

Thermal-mechanical modelling permits to estimate the strains generated in the brittle temperature range. Yet, in the top region of the continuous caster, the metal in the mushy state (and a fortiori, in the brittle temperature range) occupies a thin vertical layer (figure 8). Then, a fine mesh (2 mm) must be used.

Hot tears often appear in subsurface of billets, close to the corner [21]. Since these defects form at the very beginning of the secondary cooling, the influence of both primary and secondary cooling conditions was studied.

Figure 8. Refined mesh used in solid shell to compute the hot tearing criteria (liquid fraction represented on the picture)
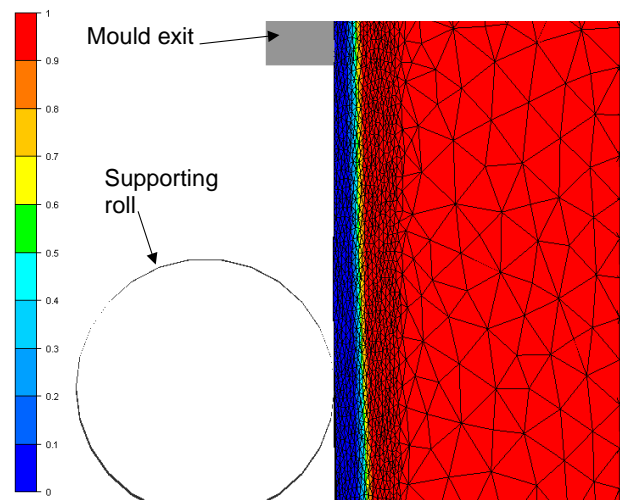
Figure 9 shows the place of maximum hot tear probability. However, the Yamanaka et al. [18] criterion reaches a value lower than 1%: this relatively low value indicates that hot tears may not appear under classical production conditions.

Some simulations were then performed for different casting speeds, showing that hot tearing risk increases with the casting speed (figure 10). The model behaviour is hence in good agreement with the actual behaviour of a continuous caster. It permits to study the impact of parameters such as corner radius, shape and intensity of sprays, casting speed, etc. on the product quality.

Figure 9. Yamanaka et al. [18] criterion cumulated in the primary and in the secondary cooling
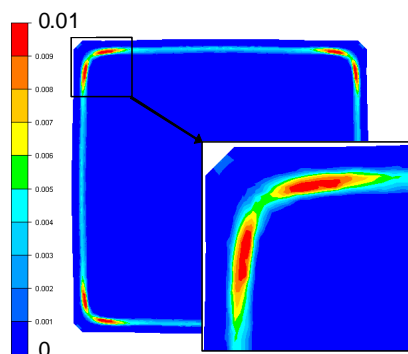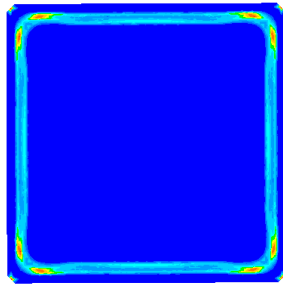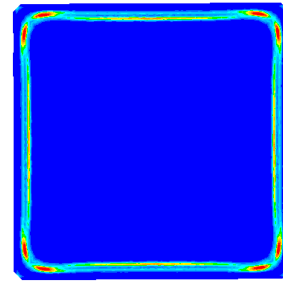
<div align="center">Casting speed : V   Casting speed : V+20%</div>

Figure 10. Influence of the casting speed on hot tearing risk, according to the criterion of Yamanaka et al. [18].

<u>Simulation of Bending Strains</u>

THERCAST has also been used to simulate a curved billet continuous caster. The pressure field obtained on the surface of the billet (figure 11) is typical of a bended structure, with compressive stresses along the intrados (inner surface of the bended billet) and tensile stresses along the extrados (outer surface). The Yamanaka et al. [18] criterion increases at the first extractor's level. The hot tearing criteria permit to detect when the inner cracks may form.
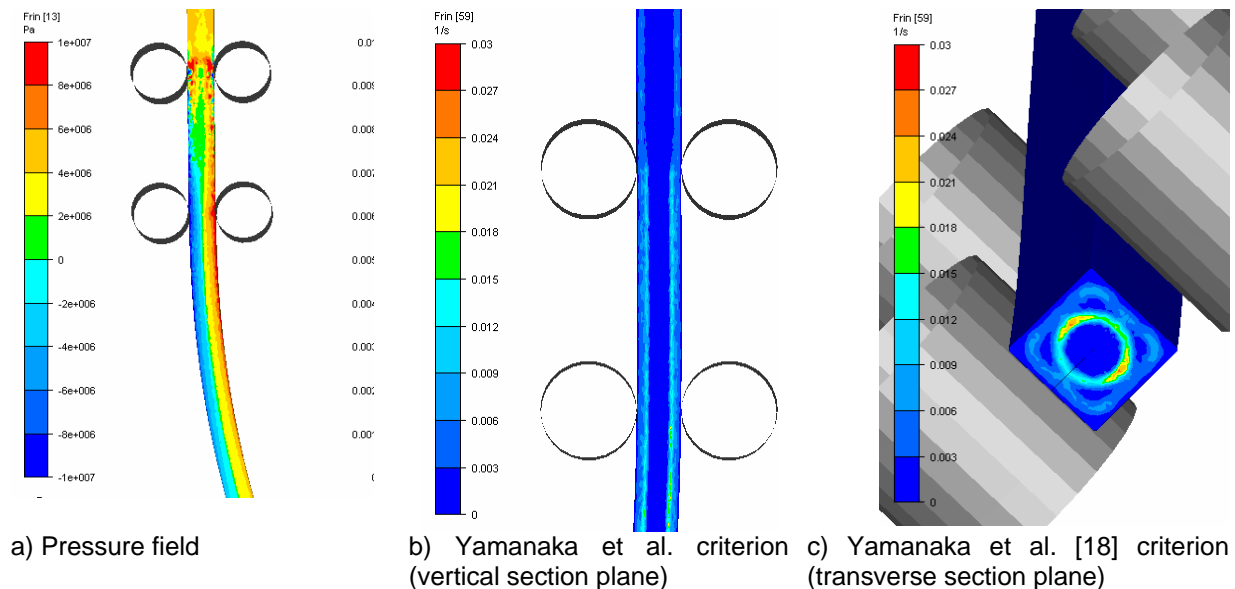
a) Pressure field   b) Yamanaka et al. criterion (vertical section plane)   c) Yamanaka et al. [18] criterion (transverse section plane)

Figure 11. Pressure field and Yamanaka et al. criterion after bending

Conclusions

Using the software THERCAST, the analysis of the deformation of round and square blooms, inside and below the mould, has been done. It has been shown that a 3D finite element modelling of the thermal-mechanical behaviour of the solidified shell permits to better understand the impact of process parameters on the formation of defects. In this study, the use of appropriate strain based hot tearing criteria coupled with a thermal mechanical finite element analysis permit to determine the most critical areas with respect to hot tearing. The results of the computations are in good agreement with in-situ observations. It is shown that numerical simulation can be used to estimate the impact of process modification on the quality of the continuously cast metal. These examples illustrate how nowadays numerical models are used in the steel industry to optimise the quality of the production and the productivity of industrial machines.

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