OLIVIER JAOUEN, FREDERIC COSTES AND ALI SAAD [1]

IMPROVING THE INGOT QUALITY BY UNDERSTANDING THE BEHAVIOR OF THE MOLD FLUX DURING CASTING PROCESS USING A 3D FLUID/STRUCTURE NUMERICAL SIMULATION MODEL

Abstract

It is well known now that the ingot defects like hot tears or cracks are rooted at the first beginning of the solid shell birth. Damages result from the competition between hydrostatic pressure within the turbulent flow of the liquid zone and the solidifying skin under tensile stresses and strains state. In addition, the thermal energy extracted from the cast product by the mold has huge impact of the thickness of the shell. It depends on the air gap growth issued from the shrinkage of the solidifying metal together with the deformation of the mold components. In addition, within the pouring phase, the mold flux can be inserted between mold and ingot shell that is also impacting the heat exchanges. Numerically speaking, the method able at taking all that phenomena into account through an accurate way is a fluid/structure model. Indeed, a standard CFD method does not represent the solid behavior, so that the stresses, strains, air gap evolution due to the shrinkage of the shell are not reachable. In this paper, a new 3D fluid/structure model involving the turbulent fluid flow and the solid constitutive equation is described. The management of the dedicated “liquid time step” allowing high velocity motion into the liquid phase of the alloy coupled with the “solid time step” dealing with the solid phase and the corresponding slow motion, is presented. The model considers as well added bags of mold flux on top of ingot surface impacting not only the heat exchanges with ambient but also with mold during casting process. An application on an ingot casting process taking into account the coupling with the deformation of the mold is presented. Moreover, based on that model, it is shown that the segregation within the ingot is tracked. In addition, the top powder is accounted as deformable body following the shrinkage of the top surface of the ingot. The exothermic reaction is considered as well in order to estimate its impact on the cooling time and the final quality of the cast product

Keywords

Finite Element, Casting Simulation, 3D Numerical Software, Turbulence, CFD Computation, Fluid/Structure model, CAFE Method ach paper must include keywords in order indicating the main topics discussed in the paper.

1. Introduction

The microstructure and grain sizes of a cast ingot are generally not compatible with the characteristics of the final part. In addition, internal porosities may be created within the solidification. The microstructure and the closure of porosities are in first approximation related to local deformation in the forged part. So that, the final quality of a forged product is strongly dependent of the original cast ingot. Hence, controlling the health of the initial ingot,

[1] Transvalor S.A.

or at least, knowing the location of the defects like porosities, cracks, etc. is essential for the caster. In the process of ingot casting, the first solidified zones occurs must before the end of the pouring and the liquid areas remain present even well after the end of the filling. Obviously, behaviour of the different metal phases is fully coupled during the process. Strains, stresses and distortions occurring at the first instants of solidification are at the origins of potential defects like porosities, cracks or hot tears that take place in the brittle temperature range (BTR) of the alloy. In addition, it appears that, depending on the tonnage, solidified areas at the end of the pouring of ingots can represent up to 30% to 40% (figure 1) of the total mass. Hence, there is no doubt about the presence of defects at that stage in such amount of transformed shell. Within this framework, thermo-mechanical modelling is of interest for steel makers. It can be helpful in the adjustment of the multiple process parameters in order to improve casting productivity while maintaining a satisfying product quality. However, optimization of the parameters requires a quite complex model that delivers very precise responses. From this point of view, the use of a CFD model sequenced with a structure model is not well suited to simulate respectively the liquid and the solid phases. Indeed, it is necessary to take into account together liquid, mushy and solid areas through an accurate fluid/structure model. Moreover, at each instant and locally, the air gap growth should be considered for its influence on the heat transfers between metal shell and moulds that dramatically change throughout the solidification.

Figure 1: Solid skin of a small ingot (~300kg) just after the pouring [1**]**

2. A Thermo-mechanical fluid/structure model

In order to consider the cast product, a 3D finite element thermo-mechanical solver based on an Arbitrary Lagrangian Eulerian (ALE) formulation is used in the casting model. Whereas Lagrangian formulation is considered concerning the components of the cooling system, cast iron molds, insulators, frames, running system, powder, etc. One of the special features of the casting model is that a specific contact analysis is carried out in order to define the face to face correspondence between the different meshes at respective interfaces between domains. This point will also be a boarded later.

The first step of the model is to solve the thermal aspect of the casting process. This is possible thanks to the following scheme:

The treatment of thermal problem is based on the solution of the heat transfer equation, which is the general energy conservation equation:

$$\frac{dH(T)}{dt} = \nabla.(\lambda(T)\nabla T) \tag{1}$$

where T is the temperature, λ (W/m/°C) denotes the thermal conductivity that depends on turbulent velocity coming from (1) and H (J) the specific enthalpy which can be defined as:

$$H(T) = \int_{T_0}^{T} \rho(\tau)C_p(\tau)d\tau + g_l(T)L\rho(T_s) \tag{2}$$

T_0 (°C) being an arbitrary reference temperature, ρ (kg/m^3) the density, T_s (°C) the solidus temperature, C_p (J/kg/°C) the specific heat, g_l the volume fraction of liquid, and L (J/kg) the specific latent heat of fusion. In the one-phase modelling, $g_s(T)$ is previously calculated using the micro-segregation model [9], [10]. In (1), turbulent velocity coming from mechanical solution of (5) is considered in convection terms.

In order to ensure the thermal coupling between the different components and also exchanges with ambient, boundary conditions are applied on the surface of each domain respectively. Theses boundary conditions could be of classical different types such average convection:

$$-\lambda\nabla T.\mathrm{n} = h(T - T_{ext}) \text{ at external surface or } -\lambda\nabla T.\mathrm{n} = \frac{1}{R_{eq}}(T - T_{mold}) \text{ at interface} \tag{4}$$

where h (W/m²/°C) is the heat transfer coefficient (HTC), and T_{ext} is the external temperature. Other conditions, such radiation, imposed temperature or heat flux can also be applied at external surface [3]. T_{mold} is the interface temperature of the mold and R_{eq} (W/m²/°C)$^{-1}$, the heat transfer resistance that can depend on the air gap and/or the local normal stress, as presented below:

$$R_{eq} = 1\Big/\min\left(\frac{1}{R_0}, \frac{1}{R_{air}} + \frac{1}{R_{rad}}\right) + R_s \text{ if } e_{air} > 0 \text{ or } R_{eq} = 1\Big/\left(\frac{1}{R_\sigma} + \frac{1}{R_0}\right) + R_s \text{ if } e_{air} = 0 \tag{5}$$

where $R_{air} = \frac{e_{air}}{\lambda_{air}}$ and $R_s = \frac{e_s}{\lambda_s}$ with e_{air} and e_s respectively the air gap and an eventual other body (typically slag or coating or mold flux) thickness and λ_{air} and λ_s the air and the eventual other body thermal conductivity. R_0 is a nominal heat resistance depending on the surface roughness, $R_{rad} = \frac{1}{\varepsilon} + \frac{1}{\varepsilon_{mold}} - 1\Big/\sigma_{stef}(T^2 + T_{mold}^2)(T + T_{mold})$ with ε_{mold} the emissivity of the mold, $R_\sigma = 1/A\sigma_n^m$ a heat resistance taking into account the normal stress σ_n, A and m being the parameters of the law.

As it can be seen, all aspects of solidification are considered in this thermal phase of the model scheme in terms of cooling of the part together with the behavior of the molds and the interactions with ambient of the cooling system.

Then the second phase of the model is to consider mechanical aspect. Hence, at any time, the mechanical equilibrium is governed by the momentum equation:

$$\nabla.\boldsymbol{\sigma} + \rho\mathbf{g} - \rho\boldsymbol{\gamma} = 0$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\mathbf{g}$ is the gravity vector, and $\boldsymbol{\gamma}$ is the acceleration vector. The very different behaviors of molten and solid metal are considered by a clear distinction between constitutive equations associated to the liquid, the mushy and the solid states respectively. In order to fit the complex behavior of solidifying alloys, a hybrid constitutive model is accounted. It consists in solving the full behavior in two steps. In the one-phase modeling, the liquid (respectively, mushy) alloy is considered as a thermo-Newtonian (respectively thermo-viscoplastic, VP) fluid; while, in the solid state, the metal is assumed to be thermo-elastic-viscoplastic (EVP) (figure 2). In particular, when considered as deformable, molds are treated through an EVP model that can derive to elastic-plastic (EP) behavior depending on yield stress values at different temperatures,. Solid regions are treated in a Lagrangian formulation, while liquid regions are treated using ALE [2], [3]. More precisely, a so called, transient (or coherency) temperature, is used to distinguish the two different behaviors. It is typically defined between liquidus and solidus, and usually set close to solidus. For more information, the interested reader can refer to [4], [5], [6], [9]

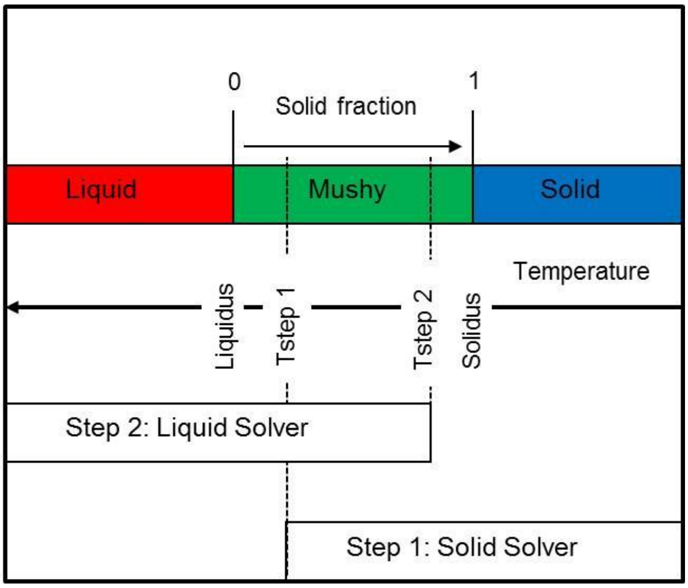

Figure 2. Schematic representation of the option 2 for the 2 steps algorithm. The high level of temperature for the step 1 (Tstep1) is within the mushy zone range. Same, the low level of temperature for the step 2 (Tstep2) is within the mushy zone, Tstep 1> Tstep2. In case of Tstep1 = Tstep2, it is similar to the option 1. The choice of the two temperatures Tstep1 and Tstep2 is depending on the structure of the alloy within the mushy zone. Typically, it can depend on the viscosity and/or the solid fraction and the composition.

With respect to the figure 2 scheme, the Cauchy stress tensor $\boldsymbol{\sigma}$ is that way, respectively locally expressed as the corresponding behavior to the cooling metal state. However, this scheme has a drawback. Indeed, the resolution is performed in one shot, taking account the total range of temperature. Due to the limits of actual algorithms and hardware precision, the corresponding total range of concerned viscosity cannot be considered. That is why, in order to override this limit and to account the very large variation of viscosity, from liquid to solid metal, a two steps scheme is applied aiming at solving mechanical equations (1) in a global point of view. Consequently, one step is dedicated to the liquid and mushy zones, the "liquid solver", and the second one is dedicated to the mushy and solid ones, the "solid solver". The liquid solver is dealing with true value of liquid viscosity, whereas solid solver uses an artificially increased value of viscosity, but such that the liquid behavior is remaining realistic in terms of hydro-static pressure. Under that context, two cases are possible. On the one hand, option 1, with the transient temperature that bounds the two steps. The full coupling liquid/solid is ensured by the control of liquid velocities and pressure with the solid corresponding data at "transient temperature volume interface" [7]. On the other hand, option 2, an overlap within the mushy zone is also available like a biphasic scheme. Another advantage of such a scheme is that any model can be associated to each solver. In particular, turbulent fluid flow related to the liquid zone of the metal is managed by the Navier-Stokes equations completed by terms coming from LES method [8]. As a matter of fact, any other model can be called, but LES method has been considered to get the best quality/cost ratio compared to RAN or DNS method [8].

Also, as mentioned above, the transfers, thermal and mechanical, between components of the cooling system are performed via connections established through a dedicated contact analysis. Yield, at each Gauss point of the surface mesh and at each time step, the distance to the faces in front is computed. Hence, the air gap growth is permanently updated and so the heat transfers following (5). That way, the full thermo-mechanic coupling between cast product and molds is ensured.

3. Criteria for Casting defect prediction

Precise prediction of defects like macro-porosities and/or hot tears is quite appreciated by steel makers. Several hot tear criteria are present throughout literature. Some are based on thermal considerations, others are fed with stresses, strain and/or strain rate. In [11] the conclusion of the authors tends to prove that the criterion of Yamanaka et al [12] is pertinent to forecast location of hot tears in solidification conditions. The expression of this criterion is the following:

$$\varepsilon_c = \int_{BTR} \hat{\dot{\varepsilon}} dt \tag{6}$$

where BTR is defined when $g_l \to 0$, typically $0 < g_l < 0.1$, introduced by Won et al [13] and $\hat{\dot{\varepsilon}}$ represents a norm value associated to the damaging components of the strain rate tensor, expressed in tensile stress axis orthogonally to the crystal growth direction [13]. The critical value ε_c depends on steel composition. However, Yamanaka introduced, by experimental observations, a threshold value 2% of the criterion above which, the odds of hot tears creation are high. Modeling experience tends to show that the same criterion applied with a lower threshold, 0.5%, gives distribution that fits quite well the macro-porosities evolution in solidification conditions [14].

4. Application to ingot casting process

In this paper, the model is applied to the casting of a 3t3 bottom poured ingot which geometry is presented figure 3. For more information, the interested reader can refer to [10].

The model considers the thermo-mechanical scheme described above. In order to account the exothermic powder that is laid out on the top surface of the ingot at the end of the pouring phase, the beginning of the burning reaction is activated once the mould is fulfilled. Its behaviour is set as deformable so that it is able to follow top surface shrinkage while ingot solidifies. Several simulation options are available. Indeed, the moulds can be considered either deformable or not deformable.

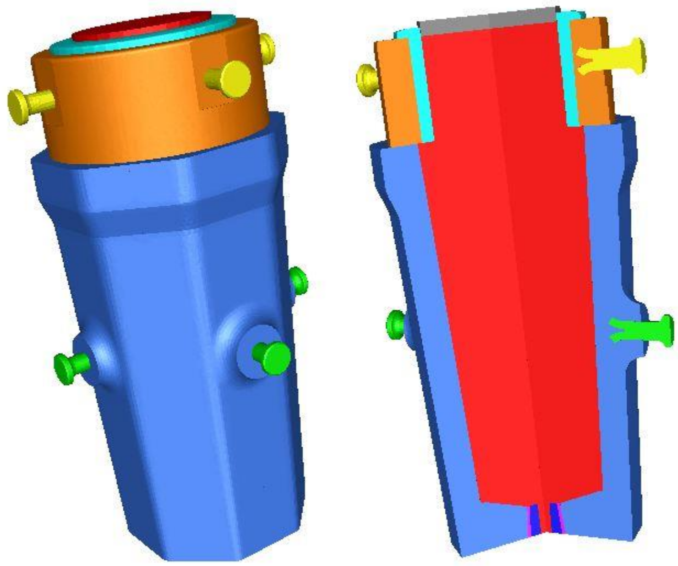

Figure 3. Illustration of the study case.

Through temperature distribution at ingot/mould interface during filling phase, one can see air gap thickness impacting heat transfers (HT) via (5) even during pouring phase. This is thanks to the fact that the model is dealing with local state of the alloy depending on the temperature and the local strain (figure 4). So that, the shrink is considered as soon as solidification is beginning within the casting process, independently to the process phase, pouring or cooling as mentioned in introduction (figure 1). On the other hand, the full coupling between liquid and solid alloy during casting, resulting from scheme figure 2, is demonstrated figure 5. It shows the full range of pressure in solid zones, that is coming from the solid solver in the step 1, and at the same time, the hydro-static pressure within the liquid, coming from the liquid solver in the step 2, at skin and in a cut plane. Hence, the changing from compressive at extern skin to tensile state at mushy zone, characteristic within casting process, is well illustrating. In case of the mould is considering as deformable, the stresses, at mould skin, are impacted by HT (figure 5, d). This information allows leading to the estimation of wearing and optimization of the life time of the mould that is resulting from the thermo-mechanical stresses cycles.

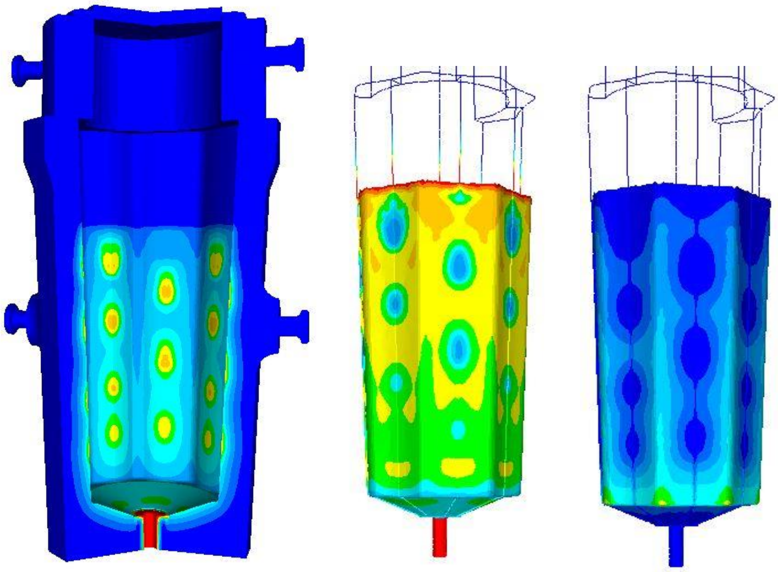

Figure 4. Temperature (blue 200°C, red 1200°C) at 60% filling in casting system (left). Temperature field at ingot skin (blue 750°C, blue 1550°C) (center). Air gap thickness at ingot skin (blue 0mm, red 5mm) (right).

In addition the impact of HT on pressure is visible through the orange/red surfaces corresponding to the air gap zones of figure 4. The full coupling between liquid and solid is for sure present as long as the two phases are coexisting together in time and space. Hence, it is necessary to deal with this not only during the pouring phase, but also all over the casting process time. Figure 6 shows the streamlines resulting from the turbulent part of the VP model within the liquid phase and the thickness of the steel solid skin at a given time during casting. It can be seen too, the local air gap at bottom of the ingot and on top closed to the riser insulator that is coming from the shrinkage of the solidified areas of the ingot. This is possible thanks to the EVP part of the algorithm. Yet, this figure is so demonstrating the power of the thermo-mechanical scheme figure 2 in representing the high velocity and low pressure in the liquid phase of the metal together with the high stresses and low displacements in the solid area. Figure 7 shows final shape after complete solidification.

The deformation of the top powder has been conducted by the open shrinkage of the ingot which is fully contained within the riser ensuring the quality of the cast product. Despite a small secondary shrinkage, this proofs the efficiency of the exothermic reaction that can drive the cooling. It's also confirmed by Niyama criterion that shows porosity risk within the riser and small zone at central axis. Another possibility of the thermo-mechanical scheme is to consider the segregation within liquid phase, even though shrinkage and stresses are taken into account in the solidifying area of the ingot. This is illustrated with the forth part of figure 7 (d). C segregation prediction indicates standard results with positive segregation on top and negative at bottom of the ingot.

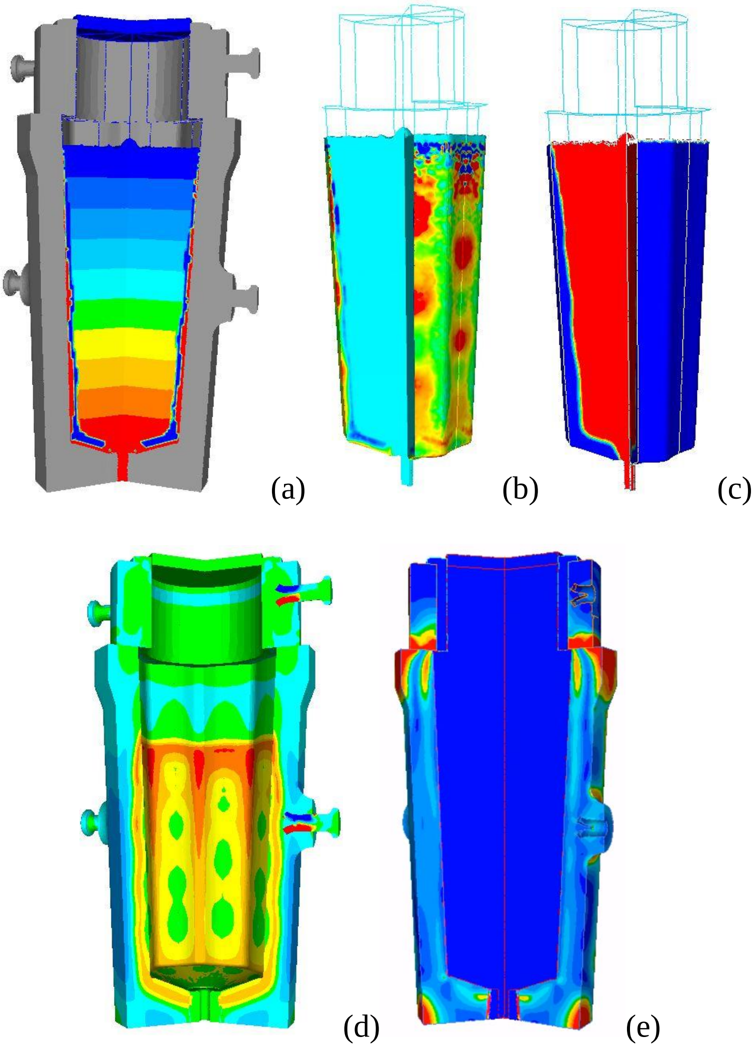

Figure 5. Hydro-static pressure within the liquid alloy (blue 0Pa, red 0.08MPa) at 60% filling in casting system (a). Pressure at skin and volume (blue -5MPa, red 10Mpa) (b). Solid fraction at skin and volume (blue solid, red liquid) (c). Stresses within the mould during the filling phase in case of deformable mould option (blue -30MPa, red 30Mpa) (d). vonMises stresses in the mould during casting after pouring phase (blue -0MPa, red 35Mpa) (e).

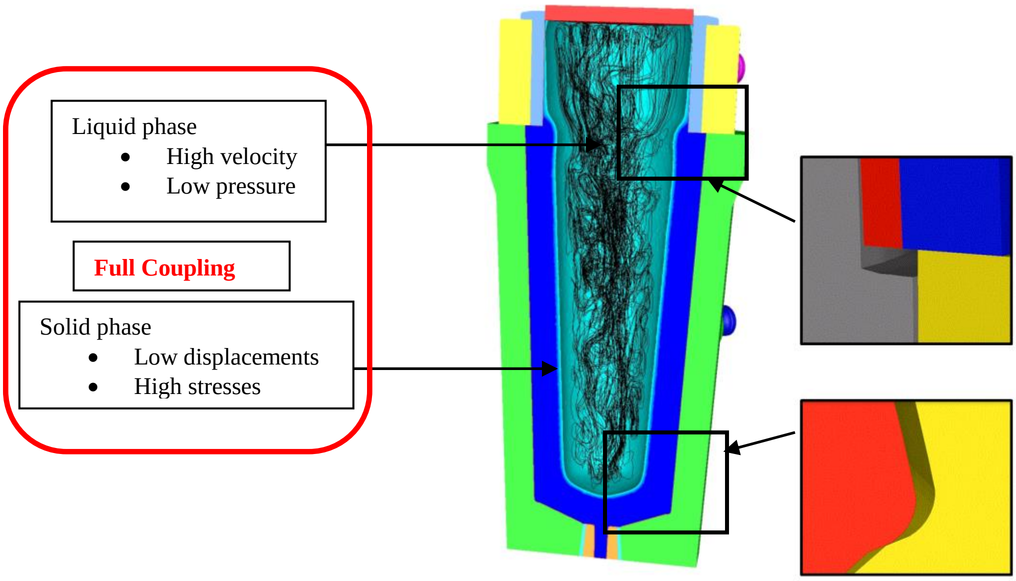

Figure 6. Illustration of the coupling between liquid and solid phases computed using the scheme figure 2. At centre, streamlines resulting from natural convection within the liquid metal and the solidified thickness in blue. On the right, air gap thickness at bottom and top of ingot during casting.

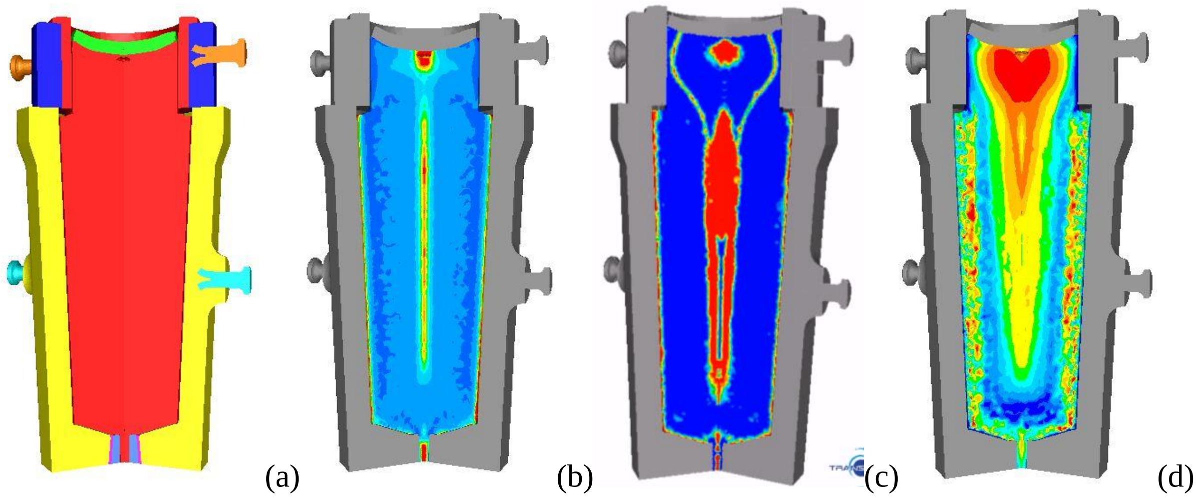

Figure 7. Final shape at complete solidification (a). Porosity risk by Niyama criterion (blue 0, red 0.001) (b). Hot tears and porosity risk with Yamanaka criterion (c). C segregation (blue - 0.3, red 0.3) (d).

5. Conclusion

This powerful model is introduced into the software THERCAST® that is industrially used. Thanks to the original model that couples liquid behaviour together with solid deformation, considering the whole range of data variations, it allows determining the thermo-mechanical comportment of the solidifying metal in ingot casting processes. In addition, associated to specific boundary conditions, it leads to forecast accurately the defects of ingot together with the behaviour of the mould. This powerful model gives access at the same time, to phenomena occurring at different scales. Fluid flow with turbulent behaviour in the liquid zone of the alloy is shown, together with stresses and strains within the solid metal. It allows to better understanding the impact of phases on each other through a two steps full coupling algorithm. In particular, the root of defects occurring at the very beginning of solidification is now much easier to catch. With such a tool, steel makers are able to foresee and so, to control and optimize their process. The presented example illustrates how nowadays numerical models could be used in the steel industry to improve the quality of production and the productivity.

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