PREDICTION OF HOT TEARS IN DC-CAST ALUMINUM BILLETS

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Abstract

The appearance of hot tears, a very severe defect in castings, is a major limitation to the production of foundry cast parts and to the productivity of continuous casting processes such as the direct chill casting of aluminum alloys. As an example, the casting speed of the direct chill casting of billets is limited for some aluminum alloys because of their high propensity to develop hot tears, which initiate at non-zero liquid fraction at the bottom of the sump.

In order to predict the occurrence of hot tears in solidifying parts, a hot tearing criterion based on the ability of the interdendritic flow of liquid to compensate for the thermally-induced deformation of the roots of the dendrites has been recently derived by Rappaz, Drezet and Gremaud [1]. Based upon a mass balance performed over the liquid and solid phases, this criterion accounts for the deformation of the solid skeleton and for feeding of the interdendritic liquid: it allows for the calculation of the pressure drop in the liquid at the roots of the dendrites. If the pressure falls below a given cavitation pressure, hot tears will initiate and propagate.

The present paper gives a summary of the main features and assumptions of the new hot tearing criterion. The equations defining the hot cracking sensitivity index in the particular case of a uniform thermally-induced deformation rate in the mushy zone are presented. The influence of the solidification path for the AA6063 alloy is studied.

This criterion has been implemented in a FEM thermo-mechanical model of the DC casting of round billets of aluminum alloys. It is shown that the bottom of the sump is more sensitive to hot tearing than the primary cooling zone and that the casting speed has a large influence on the appearance of hot tears, as observed in production. Finally, it is shown that the criterion developed by Clyne and Davies [2], when applied to the same conditions, yields the opposite trend.

1. Introduction

In the mushy zone, two major defects related to stresses can be encountered : porosity and hot tears. As pointed out clearly by Campbell [3], the first defect is associated with a hydrostatic depression into the mushy zone combined with segregation of gaseous solute elements (hydrogen, nitrogen, carbon monoxide). This depression is associated with the suction of the liquid in the porous dendritic region. The models developed for the prediction of microporosity formation are therefore based on the solution of the Darcy equation coupled with a mass balance and a microsegregation model of gaseous elements [4].

The formation of hot tears is also linked with a lack of feeding in the mushy zone, but for specific regions where the dendritic network is submitted to uniaxial tensile stresses [5-7]. These stresses are induced by differential thermal contraction upon cooling and might lead to the development of hot tears.

Different tests aimed at classifying the alloys with regard to their sensitivity to hot tearing were used in the past, such as the ring mould test [6], the cold finger test [7] and the dog bone test [8]. Recently, Instone et al. [9] have developed a novel apparatus which utilizes a modified tensile testing machine and customized mold to control solidification and mechanical parameters during solidification.

In industry, hot tearing represents a major limitation to casting productivity. As an example, central hot tears are often observed by means of acoustic detection at the center of DC cast aluminum billets. Figure 1 shows such a crack usually made out of three macro-cracks surrounded by micro-cracks [10,11].

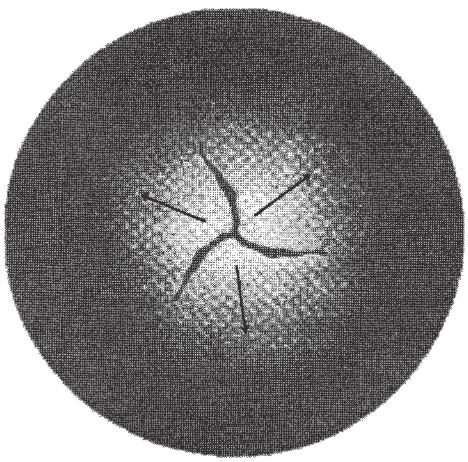

Figure 1: central hot tears observed in DC cast aluminum billets [11].

Due to the complexity of the mechanisms involved in hot tearing formation, the models developed so far are relatively simple, most of them being based upon the consideration of the solidification interval [3]: the larger the solidification interval of the alloy, the more sensitive it will be to hot tearing. The most sophisticated models use a back-diffusion model [3], for which the maximum hot cracking sensitivity is dictated by the Fourier coefficient in the solid phase. Clyne and Davies [2] have recognized that hot cracking was due to an opening of the mushy zone in a "vulnerable" region where the dendrite arms can be pulled apart easily. They introduced a Cracking Sensitivity Coefficient (CSC) which is given by the ratio of the vulnerability time to the relaxation time.

In the present contribution, the main features of the new hot tearing criterion derived by Rappaz et al. [1], so-called RDG criterion, are reported hereafter. The criterion has been implemented in a thermo-mechanical model of the DC casting of round billets of aluminum alloys and its predictions are reported together with those using the Clyne and Davies criterion [2].

2. The RDG hot tearing criterion

The present section gives an overview of the hot tearing criterion recently derived by Rappaz, Drezet and Gremaud. A detailed description of the model can be found in [1,6].

Figure 2 is a schematic diagram of the equiaxed dendritic growth as observed in inoculated aluminum alloys [12]. In this case, the dendrites are assumed to grow in a given thermal gradient, G, and with a velocity given by v_T. Above a certain volume fraction of grains, mass feeding can no longer compensate for shrinkage, the specific mass of the solid being larger than that of the liquid for most metallic alloys. Therefore, the liquid has to flow from right to left in a packed bed of solid grains.

If the dendritic network is submitted to a tensile deformation, ε, perpendicular to the thermal gradient, the flow should also compensate for that deformation if no hot tears form. The pressure in the interdendritic liquid is schematically represented at the bottom of Figure 2: it decreases from the metallostatic pressure, p_m, near the end of mass feeding.

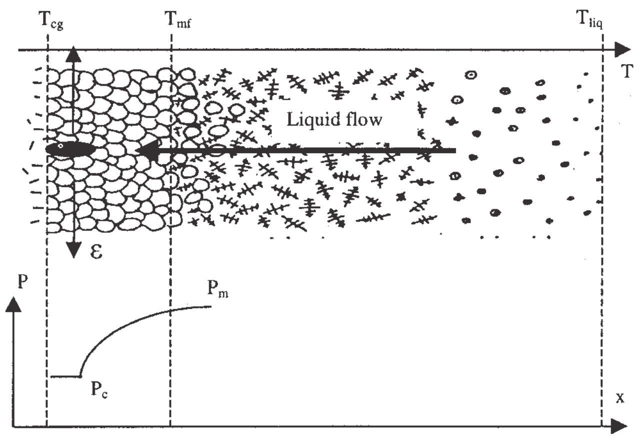

Figure 2: schematic of the formation of a hot tear between equiaxed grains as a result of a localized strain transmitted by the coherent dendrites below. The pressure drop in the interdendritic liquid is also indicated.

Above the mass feeding temperature, T_{mf}, the grains have not yet coalesced and are free to move within the liquid. On the other hand, below the temperature at which coalescence of the grains takes place, T_{cg}, all the grains form a coherent solid network which can transmit the thermal stresses induced by cooling. Note that the temperature at which coalescence between two grains occurs depends on their misorientation and is therefore not unique. Between T_{mf} and T_{cg}, the film of liquid can only resist up to a cavitation pressure at which a void is nucleated and can develop into a hot tear. Any opening of the continuous interdendritic liquid film present in the packed bed of grains can hardly be compensated for by feeding from the upper region of the mush because of the high volume fraction of solid (i.e., low permeability).

The RDG criterion is therefore based on the derivation of the two pressure drop contributions associated with deformation and shrinkage respectively. To do so, a mass balance is performed at the scale of a small volume element of the mushy zone in a reference frame attached to the isotherms [1].

Assuming no porosity formation, the volume fraction of liquid, f_l, is equal to $(1- f_s)$ and the specific masses of the two phases, ρ_s and ρ_l, are assumed to be constant, but not equal (solidification shrinkage factor β). The velocity of the liquid is related to the pressure gradient in the liquid via the Darcy equation and the permeability of the mushy zone is given by the Carman-Kozeny approximation [1].

Considering that the fluid moves along the thermal gradient only, whereas the solid deforms in the transverse direction, one can calculate the pressure within the mush:

$$p = p_a + \rho g h - \Delta p_{sh} - \Delta p_{mec} \qquad (1)$$

where p_a is the atmospheric pressure, $\rho g h$ the metallostatic contribution. Δp_{sh} and Δp_{mec} are the pressure drop contributions in the mush associated with the solidification shrinkage and the deformation induced fluid flow, respectively. In steady state conditions and assuming an uniform mechanical deformation rate throughout the mush, $\dot{\varepsilon}$, these two contributions are given by:

$$\Delta p_{sh}+\Delta p_{mec}=\frac{180\mu\Delta T}{G\lambda_2^2}\left[v_T\beta A+\frac{(1+\beta)B\dot{\varepsilon}\Delta T}{G}\right] \quad \text{with}$$

$$A=\frac{1}{\Delta T}\int_{T_{end}}^{T_{mf}}\frac{f_s^2 dT}{(1-f_s)^2},\quad B=\frac{1}{\Delta T}\int_{T_{end}}^{T_{mf}}\frac{f_s^2\cdot F_s(T)}{(1-f_s)^3}dT \quad \text{and}$$

$$F_s(T)=\frac{1}{\Delta T}\int_{T_{end}}^{T} f_s dT \qquad (2)$$

T_{end} is the temperature at which bridging of the dendrite arms between grains occurs, that is T_{cg} (see figure 2) or the eutectic temperature if more than a given amount of eutectic is formed. μ is the viscosity of the liquid (10^{-3} Pas for aluminum alloys). The two parameters A and B depend only on the nature of the alloy and on its solidification path, i.e. on the relationship between f_s and T. They can be calculated using a back diffusion model such as that of Clyne and Kurz [1,13] or a more sophisticated microsegregation model as presented in the next section.

The ratio of the integration interval $\Delta T = T_{mf} - T_{end}$ to the thermal gradient yields the length of the mushy zone over which most of the depression occurs, as shown in figure 2. Equation 2 reveals that the shrinkage contribution is proportional to this length and to the speed of the isotherms whereas the mechanical contribution is proportional to the square of this length and to the strain rate. Both contributions are inversely proportional to the square of the secondary dendrite arm spacing, λ_2, which is determined using a coarsening model [13].

Eventually, if the pressure, P, given by equations (1) and (2), falls below the cavitation pressure, P_c, a hot tear forms. This condition allows the calculation of the maximum strain rate sustainable by the mushy zone, $\dot{\varepsilon}^{max}$, and a hot cracking susceptibility, HCS, can be defined as $1/\dot{\varepsilon}^{max}$. The higher HCS, the more susceptible the alloy. Rappaz et al. [1] computed HCS as a function of the solute content for a binary Al-Cu alloy and compared the results with the measurements of Spittle and Cushway [14] and with the criterion of Clyne and Davies [2]. The "Λ curve", typical of hot tearing, was well reproduced by the present criterion.

On the other hand, equations (1) and (2) allow to calculate for a given alloy the depression over the mush:

$$\Delta p = p_a - p = \Delta p_{sh} + \Delta p_{mec} - \rho g h \qquad (3)$$

provided the thermal gradient and the strain rate near the solidus are known. In section (4), these two quantities are computed with the help of a thermo-mechanical model. If the depression in the mush, ΔP, is higher than the cavitation depression, $\Delta P_c = p_a - p_c$, a hot tear forms.

In the binary system Al-Cu, the coalescence temperature, T_{cg}, corresponds to either a solid fraction of 99% or the eutectic temperature if more than 1% of eutectic is formed [1]. In the next section, the determination of this temperature together with the solidification path for the industrial alloy AA6063 are presented.

3. Solidification path of an AA6063 alloy

The AA6063 aluminum alloy is a common alloy cast in shapes of billets and further on extruded. Its composition is Al Mg 0.7 wtpct Si 0.4 wtpct. For sake of simplicity, the iron content is ignored. In order to implement the new hot tearing criterion into the a thermomechanical model of the DC casting of AA6063 billets, the two parameters A and B appearing in equation (2) must be calculated. To do so, the solidification path of the alloy is first computed using the microsegregation model of Doré and Rappaz [15,16]. Figure 3 shows the computed solidification paths over the liquidus map for five different solidification times. Also represented are the monovariant eutectic lines and the ternary eutectic point in the Al-rich corner of the phase diagram. All five solidification paths reach the eutectic valley Al-Mg_2Si and end up at the ternary eutectic point, except for the solidification time of 1010 sec. This is explained by the back diffusion which becomes more important at longer solidification times.

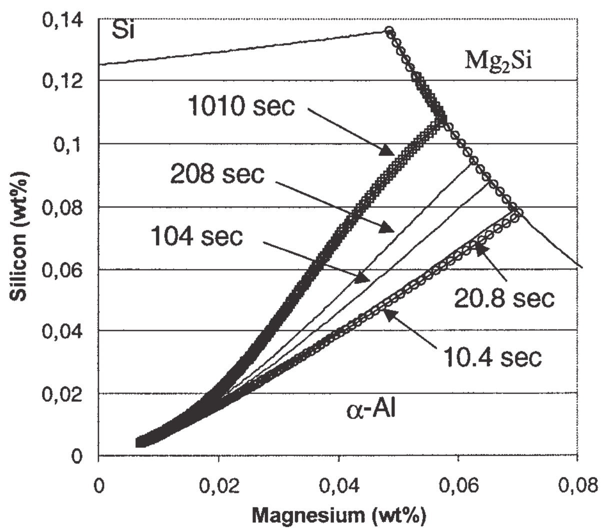

Figure 3: solidification paths for five solidification times for an AA6063 alloy.

Figure 4 shows the solid fraction as a function of the temperature near the end of solidification. This zone is of particular interest for hot tearing since it allows us to determine the coalescence temperature, T_{cg}, which corresponds to either a solid fraction of 99% or the eutectic temperature if a monovariant line is reached before. Except for a solidification time of 1010 sec, the coalescence temperature is given by the temperature at which the solidification path reaches the eutectic valley Al-Mg_2Si.

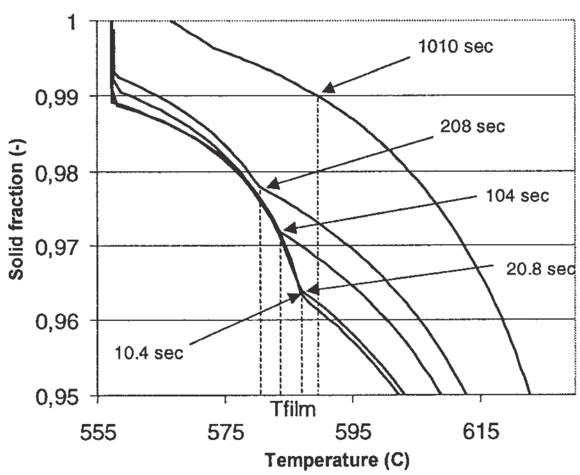

Figure 4: solid fraction versus temperature curves near the end of solidification for the cases of figure 3.

With a solidification time of 1010 sec, the solid fraction versus temperature curve approaches values very close to one. It is therefore not surprising that the two integrals A and B of equation (2) get very large values in that case, as shown in figure 5. Finally, one should not consider that these two integrals alone determine the hot cracking sensitivity as a function of the solidification time, since the cooling rate is linked to the thermal gradient and to the speed of the isotherms.

All these quantities plus the deformation rate combine together to yield the pressure drop derived in equations (1) and (2).

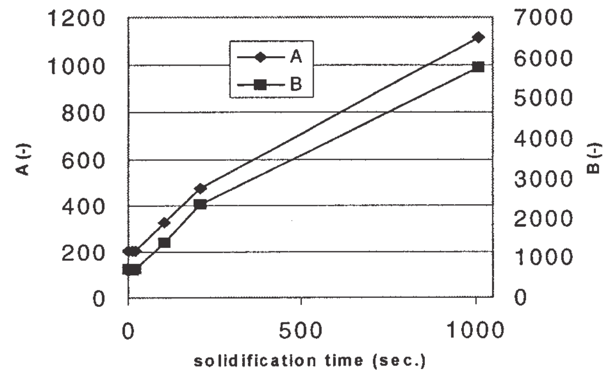

Figure 5: parameters A and B for different solidification times, for the AA6063 alloy.

4. Application to the DC casting of round billets

The present section deals with the implementation of the new hot tearing criterion into a FEM thermo-mechanical model of the billet DC casting process, which is schematically presented in figure 6. To do so, axisymmetric conditions are considered and the whole thermomechanical description of the AA6063 alloy from room temperature up to the coalescence temperature is included in the FEM model built in Abaqus [17]. The boundary conditions associated with the primary and secondary coolings [18] are moving along the computation domain, which increases with the continuous addition of layers at a rate equal to the casting speed. The inlet metal temperature is set to 660°C and the whole cast length is 1 meter to ensure that steady state conditions within the billet are reached.

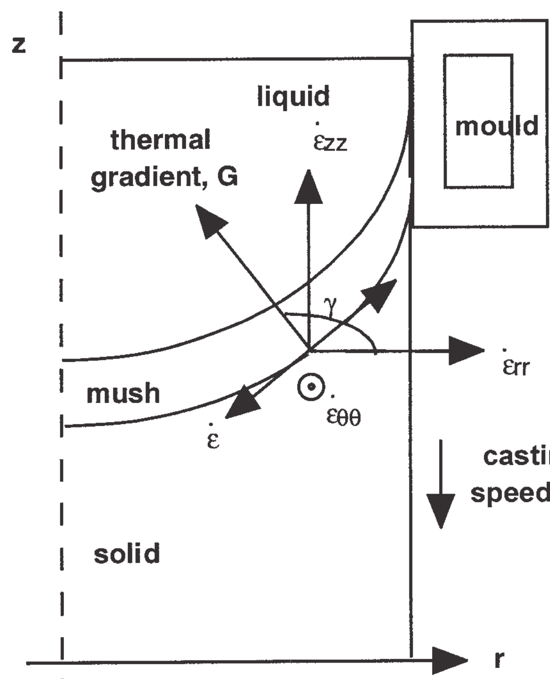

Figure 6: schematic representation of the DC casting of round billets and of the strain rate perpendicular to the thermal gradient.

Under axisymmteric conditions, the mechanical strain rate perpendicular to the thermal gradient is computed at the coalescence temperature T_{cg} as a function of the radial, hoop and axial components of the strain rate tensor:

$$\dot{\varepsilon} = \sin\gamma\, \dot{\varepsilon}_{rr} - \cos\gamma\, \dot{\varepsilon}_{zz} + \dot{\varepsilon}_{\theta\theta} \qquad (4)$$

where γ is the angle between the thermal gradient and the radial axis (see figure 6). Moreover, the speed of the isotherms, v_T, is a function of the casting speed, v_c. and the angle γ :

$$v_T = v_c \sin\gamma \qquad (5)$$

After a cast length corresponding to approximately the billet diameter, the temperature field becomes stationary in a frame attached to the mould. Figure 7 shows the temperature field in the steady state regime of casting with special focus on the mushy region.

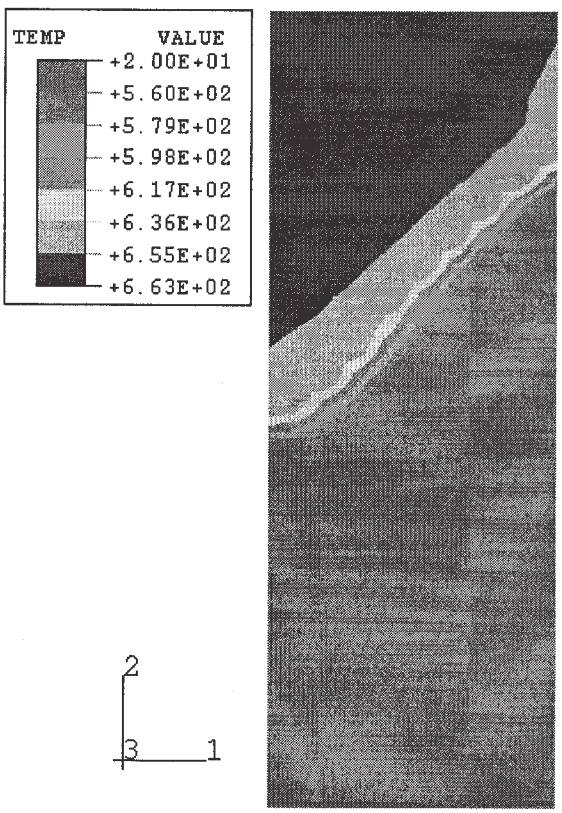

Figure 7: temperature distribution in the steady state regime of casting (200 diameter billet cast at 120 mm/min), calculations made with Abaqus.

The RDG criterion has been implemented in the FEM model of casting with the help of the user subroutine UVARM [19]. Once the temperature at a given integration point falls below the coalescence temperature, the liquid height, the thermal gradient, the angle γ and the deformation rate are used to compute the depression in the mush, ΔP , with the help of equations (1-3) and the solidification model presented in the previous section. Figure 8 shows the distribution of this depression for a DC billet 200 mm in diameter cast at a speed of 120 mm/min. The higher the depression, the more prone the alloy is to develop cracks. The two extremities of the billet correspond to the start-up and ending phases of the process. In the central part of the billet, the depression no longer changes with the cast length. Its value is about 2 kPa at the surface of the billet and it decreases slightly before reaching a maximum of 5.6 kPa at the center of the billet. This means that during run conditions, the center of the billet is more sensitive to hot tearing than the surface.

It is also interesting to note that the central zone sensitive to hot tearing shown in figure 8 expands in the start-up region of the casting. This is more visible when the depression at the billet center is represented as a function of the cast length (see figure 9). The depression reaches a maximum around 6.3 kPa during start-up before attaining a fixed value of 5.6 kPa in the stationary phase of the process.

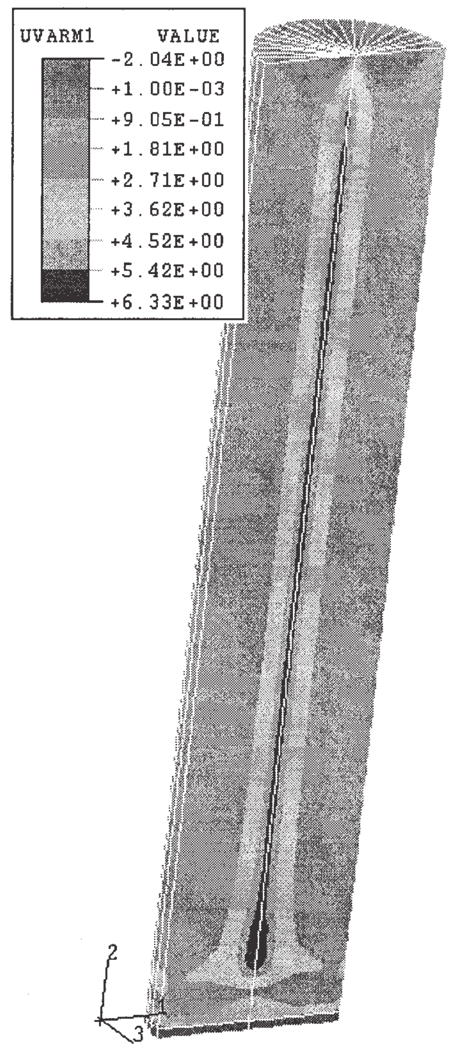

Figure 8: computed depression in kPa for a billet 200 mm in diameter cast at 120 mm/min.

If the cavitation depression, ΔP_c , is higher than 5.6 kPa, this means that hot tears might initiate during start-up but not propagate further on. By comparing observations of hot tears in

DC cast billets and the prediction of the criterion, one could determine the cavitation depression which is a key parameter of the RDG hot tearing criterion. Drezet and Rappaz [20] have found a cavitation depression around 2 kPa by using the maximum casting speed at which an Al-Cu 4.5 wt pct alloy can be cast without developing hot tears. The values found here are of the same order of magnitude, that is a few kPa.

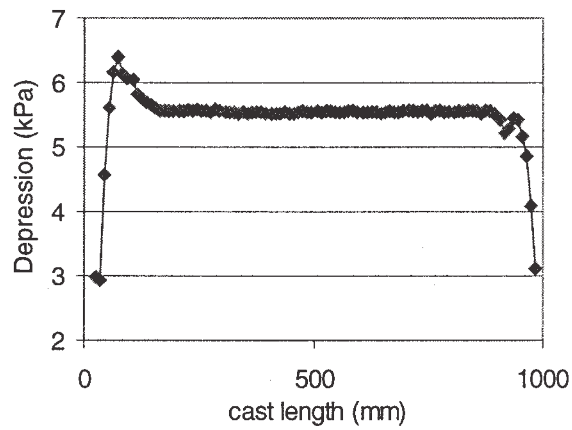

Figure 9 : depression at the center of the billet as a function of the cast length.

5. Sensitivity to the casting speed

Figure 10 shows the radial distribution of the depression computed with equation (2) in the steady state regime for 200 mm diameter billets cast at four different casting speeds: 60, 80, 100 and 120 mm/min. The higher the casting speed, the larger the depression at the billet center. Apart from the thermal conditions in which the alloy solidifies, this increase is mainly explained by the fact that the strain rate perpendicular to the thermal gradient is highly dependent on the casting speed, as shown in figure 11.

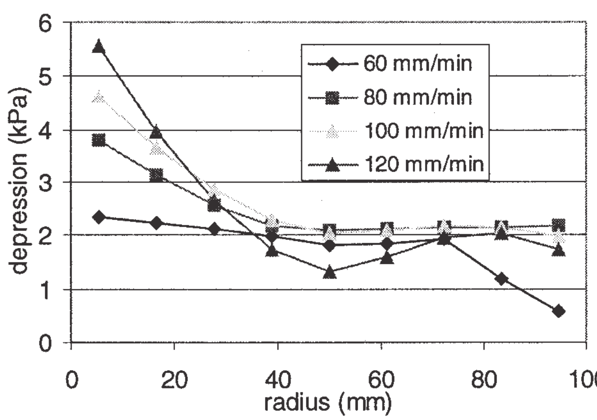

Figure 10: steady state depression as a function of the radius for billets 200 mm in diameter cast at various casting speeds.

With increasing casting speeds, the sump depth, thus the metallostatic pressure, increases. Nevertheless, the mechanical contribution to the total depression in equation (2) increases faster.

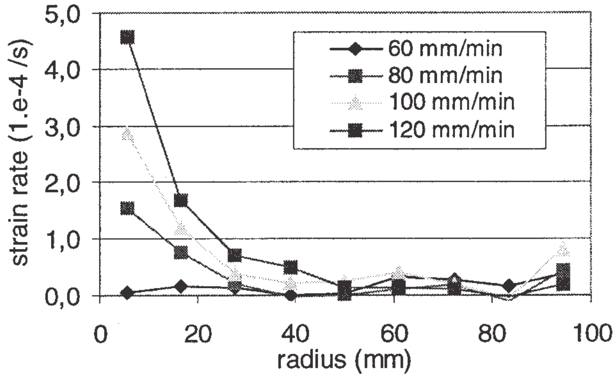

Figure 11: strain rate perpendicular to the thermal gradient at the coalescence temperature as a function of the radius for various casting speeds.

6. The Clyne and Davies criterion

The prediction of the RDG hot tearing criterion is compared in this section with that of Clyne and Davies [2]. These authors have defined a Cracking Sensitivity Coefficient as:

$$CSC=\frac{t_v}{t_r} \qquad (6)$$

where t_v is the time during which the mushy zone is vulnerable to hot tearing ($0.01 < f_l < 0.1$, where f_l is the fraction of liquid) and t_r is the time during which stresses can be relaxed ($0.1 < f_l < 0.6$). Figure 12 shows the radial distribution of the CSC parameter as computed with equation (6) for 200 mm diameter billets cast at various casting speeds. In this graph, the higher the casting speed, the lower the cracking sensitivity. Moreover, the CSC parameter is more uniform throughout the billet than the RDG criterion: the center does not seem to be particularly sensitive to hot tearing.

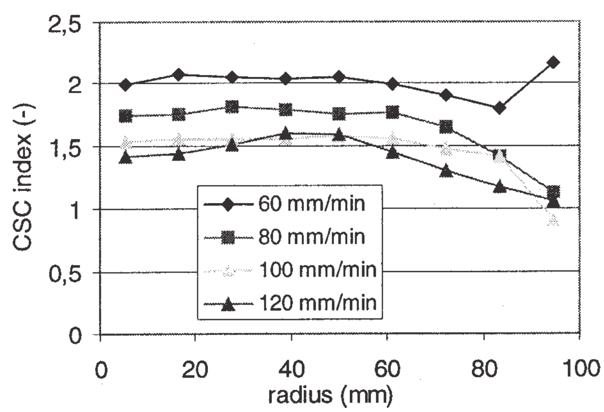

Figure 12: CSC index as a function of billet radius in the steady state regime of casting for various casting speeds.

Conclusion

The RDG hot tearing criterion is a simple two-phase model in which both deformation of the coherent solid and interdendritic fluid flow are considered. When applied to the DC casting of billets, the new criterion allows to determine the associated depression in the liquid. The higher this depression, the more prone the alloy to initiate cracks. Implemented in a FEM model of the DC casting process, this criterion demonstrates that the bottom of the sump is more sensitive to hot tearing than the region of the primary cooling. The conditions at start-up are even more critical. Contrary to the Clyne and Davies approach, the RDG criterion predicts that the sensitivity to hot tearing increases with the casting speed owing to larger thermally-induced deformation at the bottom of the sump. This corresponds to what is observed on real ingots.

Coupled with a microsegregation model and implemented in thermo-mechanical models of casting processes, the RDG criterion should be helpful in designing proper casting conditions, notably at start-up, to avoid central hot cracks.

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