A Hot Tearing Criterion for the Continuous Casting Process

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Abstract

The severity of hot tearing during the continuous casting process greatly influences the quality of the final product. Then again the demands on the product quality affect the allowable degree of hot tearing. Therefore a sound hot tearing criterion should account for both: the correct prediction of hot tearing and its harmfulness regarding the final requirements. The present paper introduces a hot tearing criterion fulfilling both demands by approaching the problem from the point of accumulated strain within a certain range in the mushy zone. On the basis of a hot tearing indicator, the strain accumulated during the process can be compared to an experimentally evaluated strain which yields the amount of hot tearing. The basis of the model and its effects are illustrated on the basis of a slab caster.

Key words: Continuous Casting, Hot Tearing, Hot Tearing Criterion, Critical Strain.

1. Introduction

The degree of damage by hot tearing in the continuous casting (CC) process depends on the property demands on the final product and sometimes on the further processing routes. Both open hot tears as well as segregated (healed or filled) hot tears can degrade the quality of the final product. In fact, depending on the final product, segregated hot tears might have an even more negative effect regarding the quality than open hot tears.
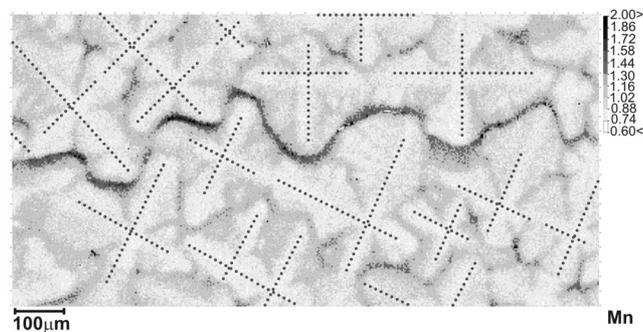
Figure 1: Manganese concentration mapping of a segregated hot tear at primary grain boundaries [4].

The reasons are extensively published in [1-3] and can be summarized as follows: Segregations within the hot tear may result in the formation of undesirable phases (e.g. martensite) or a banded structure in the final product. Enrichments of Mn and

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S within the hot tear result in the precipitation of interdendritic sulfides, which will be elongated in the rolling process, resulting in the formation of inclusion bands. **Figure 1** shows an example of a segregated hot tear in terms of a manganese concentration mapping. Additionally, the orientation of the dendrites is illustrated in order to visualize primary grains. It can be seen that the hot tear follows primary grain boundaries, a fact which is observed in most cases of hot tearing in CC.

Regarding the different definitions of hot tearing, which can be found in the literature [e.g. 5-7], the important outcome is that hot tears are understood to be generated within in the mushy zone due to tensile stresses. The extent of tensile straining during solidification results from the combination of material deformation behaviour and casting process related loads, which are characterized by a large quantity of possible degrading effects, such as bulging of the shell between guiding rolls or unbending of the partly solidified strand. The strain and strain rates due these effects can be described using sophisticated mechanical models.
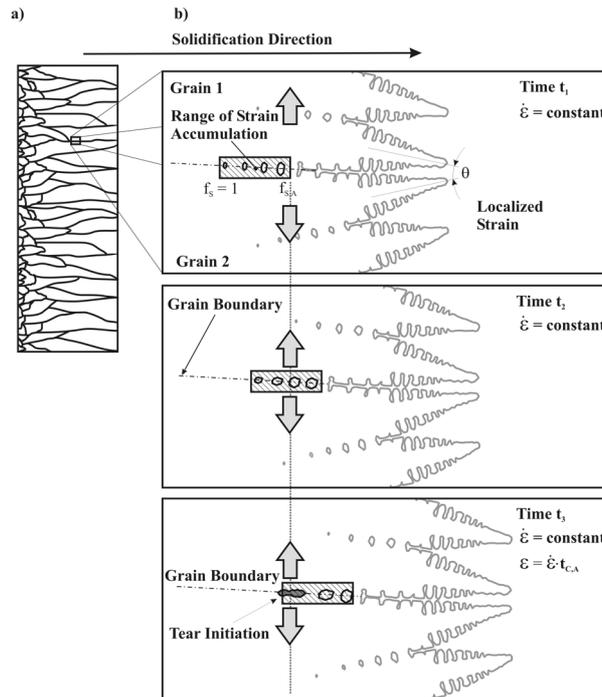
Figure 2: Schematic illustration of hot tear initiation due to strain accumulation within a certain range of the mushy zone of during columnar solidification [2].

Therefore an adequate hot tearing model for the CC process, which fulfils the demands of defining deformation limits, can be realized with a strain-based criterion. A strain-based hot tearing model based on the assumption of an accumulated strain within a certain critical temperature range of the mushy zone was published in previous papers [1,2]. This approach enables the quantification of deformation limits considering demands on the final product quality by coupling finite elements strand mechanics with the consideration of varying solidification and process conditions.

2. The Strain Based Hot Tearing Criterion

The principle of the hot tearing model is illustrated in **figure 2**, which schematically shows the columnar microstructure in a solidifying shell (a) and progress of the hot tear initiation considering the favoured crack formation along primary grain boundaries (b). Due to the longer diffusion paths at grain boundaries, a higher enrichment of segregating elements leads to a longer existence of liquid films between two primary grains. The model assumes that strain only acts in a preferable range of strain accumulation and additionally that solidification progress takes place. According to the fact that hot tears are generated within the mushy zone, a volume element corresponding to a solid fraction $f_{S,A}$ is able to accumulate strain until it is totally solidified, $\varepsilon_A = \dot{\varepsilon} \cdot t_A$. The probability of hot tearing hence increases with rising accumulated strain.

In order to investigate the influence of accumulated strain on the extent of hot tearing, an experimental apparatus was employed. A detailed description of the testing technique can be found in the literature [8]. Being very close to real CC conditions, the experiment is very suitable for a detailed investigation of hot tearing. The experimentally determined values for a given steel grade are displayed in **figure 3**. It can be seen that the values remains fairly low up to a certain limit. However upon exceeding a certain accumulated strain, the hot tearing tendency increases sharply. Depending on the amount of hot tearing, a hot tearing indicator (HTI) as a function of the accumulated strain was defined for a given steel grade:

$$HTI = a \cdot \exp\left(\frac{\varepsilon_A}{b}\right) = a \cdot \exp\left(\frac{\dot{\varepsilon} \cdot t_A}{b}\right) \tag{1}$$

Seeing that the definition of the HTI encompasses the amount of hot tearing (number of tears) and its severity (length), it is hence possible to define critical values of the total accumulated strain $\varepsilon_C\left(HTI\right)$ depending on the product quality demands.
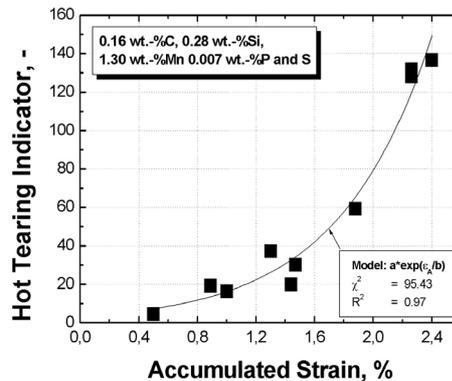
Figure 3: Hot Tearing Indicator (HTI) as a function of accumulated strain for a given steel grade.

Therefore, the totally accumulated strain in the process should not exceed the critical values:

$$\varepsilon_A^{process} < \varepsilon_C\left(HTI\right) \tag{2}$$

The determination of the left term in equation (2) will be illustrated in the following by determining the time of strain accumulation within a certain critical range of the mushy zone using a thermal model of a CC machine. Employing Fourier's law of thermal conductivity, the following generalized form of heat conservation can be derived:

$$\rho \cdot c_p \frac{\partial T}{\partial t} - \text{div}(\kappa \cdot \mathbf{grad}\, T) = \dot{Q}_T \tag{3}$$

In equation (3), ρ is the density in kg/m³, c_p the heat capacity in J/kg·K, T the temperature in K, t the time in s, κ the thermal conductivity in W/m·K and $\dot{Q}_T$ a source term in W/m³, which accounts for energy released during phase changes or for energy which is withdrawn due to outer cooling. On the basis of this equation a sophisticated thermal model for simulating continuous casting machines has been developed. Applying typical boundary conditions for the primary and secondary cooling zones, it is thus possible to calculate the enthalpy field over for the total length and the cross section of the strand in extremely fine time and length discretisation. The shell thicknesses corresponding to f_S of 1 and $f_{S,A,}$ are determined by means of a microsegregation model. In doing so the fraction of solid as a function of temperature is calculated using the direct finite difference method proposed by Ueshima *et al.* [9]. In this model the transverse cross section of dendrites is approximated by a regular hexagon. Further assumptions are the complete mixing of solute elements in the liquid phase, no axial diffusion and local equilibrium as well as the solute distribution in the three phases (δ-Fe γ-Fe and liquid). For a detailed description of this model the reader is referred to the literature.

Hence, using the thermal model together with the microsegregation analysis, the time during which each element i can accumulate strain within the preferable range of strain accumulation can be computed by

$$t_A^i = t_2^i - t_1^i \tag{4}$$

where the time step t_1^i resembles the time when the element i first reaches $f_{S,A}$ and t_2^i denotes the time when i is fully solidified (i.e. $f_S = 1$). Thus equation (5) is valid where $s_{fs}(t)$ is the strand shell thickness as a function of time for different fractions of solid f_S:

$$t_2^i : s_{f_{S,A}}^i\left(t_1^i\right) = s_{f_S=1}^i\left(t_2^i\right) \tag{5}$$

Consequently it is possible to evaluate the influence of casting parameters on hot tearing. This will be done in the following by varying the casting speed for a 0.16 wt.-% C steel and by applying strain at different positions in the caster.

3. Hot Tearing Indication in a Continuous Casting Machine

In order to predict the HTI during the solidification of a continuous casting machine, the described thermal model is used for calculating the shell growth as a function of solidification time or as a function of the strand length respectively for selected casting parameters. **Figure 4a** shows the normalized shell thickness (s/s_0) as a function of the normalized solidification time (t/t_S) for a 0.16 wt.-% C steel (chemical composition of other elements are listed in the diagram). The liquidus temperature corresponds to $f_S = 0$, solidus temperature to $f_S = 1$. The preferable range of strain accumulation lies between $f_s = f_{s,A}$ and $fs = 1$. In the present model it is assumed that $f_{s,A}$ lies between 0.8 and 0.99, a range which should be derived from experiments in conjunction with the used microsegregation model. Thereof the time of strain accumulation, t_A, within this certain range can be determined as graphically illustrated in **figure 4a**.
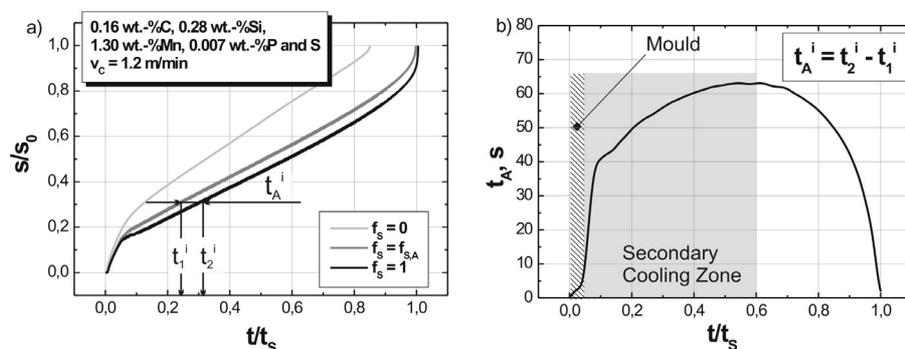
Figure 4: a) Calculated shell thickness as a function of normalized solidification time for a 0.16 wt.-%C steel and b) the determined time of strain accumulation t_A, versus normalized solidification time.

The resultant time of strain accumulation t_A is illustrated in **figure 4b**. It can be seen that immediately below the mould, the time of strain accumulation increases sharply. A maximum of t_A is reached approximately at the end of the secondary cooling zone. After this maximum, t_A decreases to very small values towards the end of solidification due to the accelerated final solidification. Obviously elements which solidify at the end of the secondary cooling zone can therefore accumulate substantially more strain than elements before or after. This means that it is more likely for these elements to exceed a given critical strain than elsewhere (cf. equation (2)). Consequently the occurrence of hot tears is also more likely in this region – *ergo* at higher values of t_A.
Vaterlaus and Wolf [10] found a very similar distribution of the number of internal cracks over the normalized solidification time, as shown in **figure 5**. It should be noted that the values in **figure 5** result from both, solidification conditions and the mechanic loads. Additionally this figure shows the differences in crack formation for

fixed and loose side of the slab which result from the different directions of strain application.

In order to illustrate the consequences of considering the time of strain accumulation, it is assumed that the selected steel grade is cast at four different casting velocities v_c. The thermal model hence yields the solidification progress as shown in **figure 6a**, where t_S is the time of total solidification for $v_c = 1.8$ m min^{-1}. It is interesting to note that it is not the maximum value of t_A but only its position that changes with casting speed.
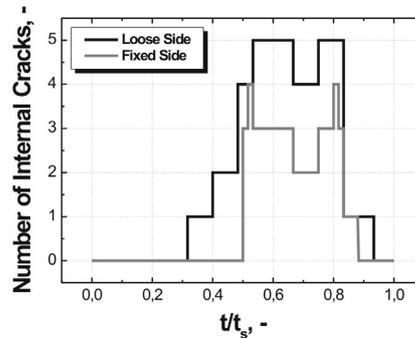
Figure 5: Number of internal cracks vs. normalized solidification time of a slab of 220 x 2000 mm² with 0.20 wt.-%C from data according to [10].

Given that the strand is exposed to strain at three different regions of the strand, the respective values of t_A for the first element in each region can be calculated. Thereby region 1 lies shortly below the mould (corresponding to bending the strand), region 2 inside the secondary cooling zone and region 3 at the straightening zone. The values of t_A are illustrated in **figure 6b** which shows that t_A decreases considerably in region 1 for rising casting speeds, whilst increasing severely in region 3. In region 2 no noticeable changes of t_A can be observed. Considering solely t_A would hence allow the conclusion that rising casting speed has a harmful effect in region 3 and vice versa in region 1.
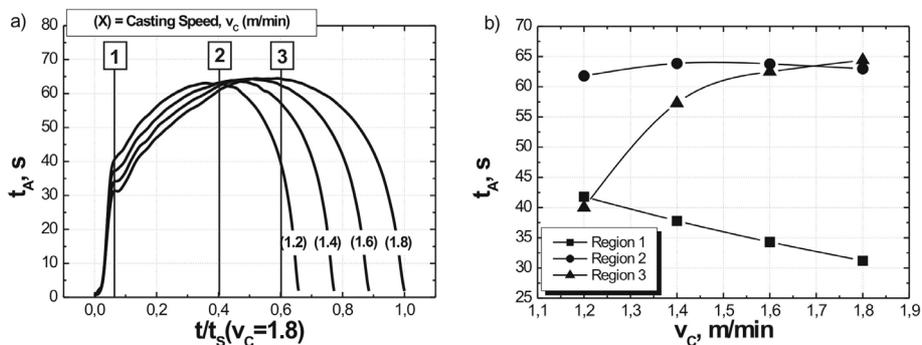
Figure 6: a) Time of strain accumulation t_A as a function of normalized solidification time for different casting velocities and b) t_A as a function of casting velocity in the different regions.

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Furthermore it is assumed that a constant strain of 2.4 % (total strain) acts in all three regions. Whilst seeming excessively high, this value has been chosen for a clear illustration of the effects regarding the strain accumulation during solidification.

However the treatment of t_A is not sufficient for assessing the hot tearing probability since the strain rate $\dot{\varepsilon}$ changes for different casting speeds according to equation (6):

$$\dot{\varepsilon}(v_C) = \frac{\varepsilon \cdot v_C}{l_R} \tag{6}$$

In equation (6), ε denotes the strain and l_R the length of the region where strain can be accumulated. Using the equation and assuming $l_R = 2$ m, leads to strain rates between $2.4 \cdot 10^{-4}$ ($v_C = 1.2$ m min^{-1}) and $3.6 \cdot 10^{-4}$ s^{-1} ($v_C = 1.8$ m min^{-1}), which corresponds to typical strain rates during the CC process. Finally the Hot Tearing Indicator can be calculated using equation (1) together with the calculated t_A (Figure 6b). The resulting HTI is shown in **figure 7** for different casting velocities and regions.
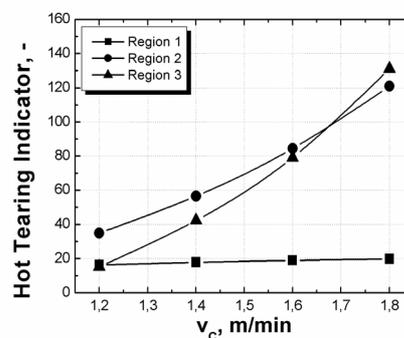
Figure 7: Resulting Hot Tearing Indicator as a function of casting speed for the three different regions along the strand length.

With regard to region 1 in **figure 7**, it can be seen that a total strain of 2.4 % has only little effect on the hot tearing probability, independent of casting speed. However it should be pointed out that these values result from a rather moderate strain rate (app. $2 \cdot 10^{-4}$ s^{-1}) and if a substantially higher strain rate of $1 \cdot 10^{-3}$ s^{-1} occurred (e.g. misaligned roll), the HTI would increase significantly. Changing casting velocities in region 2 increase the hot tearing possibility considerably, although the time of strain accumulation remains nearly constant. The increase of hot tearing probability with rising casting speed can also be observed in region 3.

The major advantage of this model is the specification of the critical Hot Tearing Indicator according to the final product demands, which will be part of plant trials. When casting a very sensitive steel grade (e.g. sour gas steel), the critical HTI would lie at comparatively lower values than a non-sensitive steel grade would. Given that a sophisticated mechanical strand model yields a detailed analysis of

the strain inside the solidifying strand, the maximum possible casting speed with regard to hot tearing probability can hence be chosen. Additionally an improved CC machine configuration and design can be achieved – an important feature for the plant builder. Moreover the basic idea of an accumulation of strain within a critical temperature interval also accounts for the influence of steel composition on the risk of hot tearing: a broader critical temperature range caused for example by the segregation of alloying elements increases t_A and hence the HTI. Thus the tendency towards increased hot tearing with rising alloying contents is also included in this model.

4. Summary

A hot tearing criterion for the continuous casting process considering the process itself and product quality issues has been presented. Through the basic idea of an accumulation of strain within a critical temperature range, it was thus possible to consider the influence of process parameters and alloying elements on hot tearing. By applying a constant total strain at various positions of a slab caster, it could be shown that the probability of hot tearing varies greatly over the solidification time.

5. Acknowledgement

6. References

[1]   Pierer, R., Bernhard, C. and Chimani, C.: A contribution to hot tearing in the continuous casting process, Revue de Metallurgie, No. 2, 2007, P. 72–83.

[2]   Pierer, R., Bernhard, C. and Chimani, C.: A new hot tearing criterion for the continuous casting of steel, SP07, Sheffield, UK, 23–25 July 2007.

[3]   Bernhard, C., Demands on Process Related Hot Tearing Criteria, BHM, Vol. 149, 2004, P. 90–95.

[4]   Reiter, J. and Pierer, R.: Internal Report, CD Laboratory for Metallurgical Fundamentals of Continuous Casting Processes, March, 2007.

[5]   Eskin D., Suyitno G. and Katgerman L.: Mechanical properties in the semi-solid state and hot tearing of aluminium alloys, Progress in Material Science, Vol. 49, 2004, P. 629–711.

[6]   Campbell J.: Castings, Oxford, Butterworth-Heinemann, 1991.

[7]   Verein Deutscher Eisenhüttenleute: Stahl-Eisen-Prüfblätter, Verlag Stahleisen GmbH, Düsseldorf, 1992.

[8]   Bernhard, C., Hiebler H. and Wolf M.: Experimental Simulation of Subsurface Crack Formation in Continuous Casting, Revue de Metallurgie, No. 3 2000, P. 333–344.

[9]   Ueshima, Y., Mizoguchi, S., Matsumiya, T. and Kajioka, H.: Analysis of Solute Distribution of Carbon Steel with δ/γ Transformation during Solidification, Metallurgical transactions B, Vol. 17, 1986, P. 845–589.

[10]   Vaterlaus, A. and Wolf, M., 7th Concast Technology Convention, Zürich, 20–21 June, 1984.