A contribution to hot tearing in the continuous casting process

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1. INTRODUCTION

Hot tears (or hot cracks) are separations, which might form during casting, welding or hot forming when the temperatures of sub-areas of the material are between solidus (T_S) and liquidus (T_L) temperature, together with simultaneously acting tensile stresses [1]. In contrast to the casting of eutectic alloys, both open and healed cracks have to be seen as potential defects, depending on further processing and the demands on the final product.
The formation of hot tears is generally related to the interaction between a reduced ductility of the solidifying steel in the mushy zone and tensile stresses, which are caused by different mechanisms, like bulging and unbending. The continual tendency towards enhanced casting productivity and increasing quality demands, as well as the development of new steel grades, makes the prediction of hot tearing still a vital and challenging topic.
This paper gives an overview of existing hot tearing models from literature. Moreover, results of a laboratory testing method serve as a benchmark for a comparison of the different models and their significance for the continuous casting (cc) process.

2. HOT TEARING CRITERIA

Models of hot tearing can be classified in stress-based, strain-based and strain rate-based criteria. Models that cannot be allocated to this classification are termed as criteria-based on other principles. In the following, four models will be presented as examples.
The stress-based criteria are based on the assumption that a semisolid body will fracture if the applied or induced stress exceeds a critical stress, σ_C. The critical stress results either from the strength of the already solidified material or from the strength (surface tension) of the liquid film between dendrites or grains. The latter assumption was, for example, proposed by Rogberg [2], taking into account the surface energy and the thickness of the liquid film.
The strain-based criteria are similar to the stress-based criteria, which are based on the definition of a critical strain ε_C of hot tearing. In order to determine ε_C much work was done in the past using different experiments. Won et al. [3] correlated experimental determined values of ε_C with the brittle temperature range ΔT_B and the strain rate $\dot{\varepsilon}$. This enables the calculation of ε_C as a function of chemical composition and strain rate.
A hot tearing criterion based on the strain rate was developed by Rappaz et al. [4], defining a hot cracking susceptibility coefficient (HCS), which can be calculated using the reciprocal value of the maximum strain rate $\dot{\varepsilon}_{max}$.
An example for a hot tearing model, which is based on other principles, was published by Clyne and Davies [5]. They define HCS as the ratio between the vulnerable time period (t_V) and the time available for a stress-relief process (t_R).
Table 1 summarizes the briefly described criteria from literature using the classification described above.

Model based on	Criteria	Literature
Stress	$\sigma_{process} > \sigma_C$	Rogberg [2]
Strain	$\varepsilon_{process} > \varepsilon_C$	Won et al. [3]
Strain rate	$HCS = 1/\dot{\varepsilon}_{max}$	Rappaz et al. [4]
Others	$HCS = t_V / t_R$	Clyne and Davies [5]

Table 1: Four different criteria for hot tearing

3. EXPERIMENT

A proper laboratory simulation of hot tearing in the cc process has to fulfill the following demands:

- the existence of a deformable mushy zone together with a columnar grain structure;
- the conformity of the microstructure with that of a cc shell;
- the fact that the main load directions are perpendicular to the main dendrite growth axis;

These demands have been realized in the submerged split chill tensile-test (SSCT), a proven laboratory method. Details of this laboratory experiment were already published [see references in 6].

4. RESULTS AND CONCLUSION

Figure 1 shows the average number of hot tears (NHT) in the SSCT-specimen after hot tensile tests with two different applied strains (1% and 2%) as a function of carbon content. The carbon content varies between 0.05 wt-% and 0.70 wt-% (0.28 wt-%Si, 1.30 wt-%Mn, 0.007 wt-%S and wt-%P).
For both total strains, the NHT shows the same characteristic: Between 0.05 wt-% C and 0.30 wt-% C the NHT increases to a maximum with a local minimum at 0.12 wt-% C. After reaching the maximum at 0.30 wt-% C, the NHT tends to decrease.

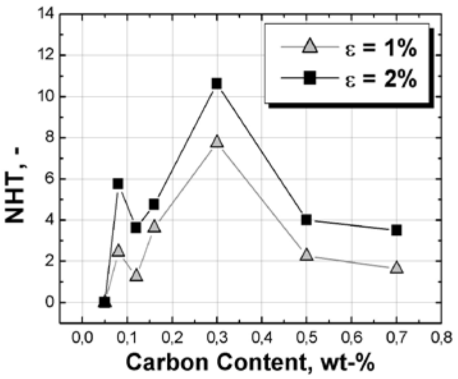

Fig. 1: Number of hot tears as a function of carbon content

The initially described four hot tearing criteria were applied to the benchmark experiment. The results are compared in figure 2 with the NHT as a measure of hot tearing susceptibility. Assuming the ratio between the measured tensile strength σ_{max} and the calculated critical stress σ_C for HCS yields a good correlation with the general tendency of the experimental results, but overestimates the crack susceptibility for high C- and high Mn-steels. Generally, this behavior applies also to the other three criteria. However, it should be mentioned that the reproduction of the local maximum of HCS at 0.1 wt.-% C and the minimum at 0.12 wt.-% C depends on the microsegregation model used .

Although the applied models are very different, their results show a similar characteristic. However, the results could be improved, especially for the high C high Mn steels. A further demand, which has not been discussed so far, is the quantification of limits in order to prevent hot tearing.

A key factor regarding the improvement of the coherence of hot tearing criteria might be their combination. Apparently, all criteria describe relevant parameters, but only the critical stress and strain criterion fulfill the demands defining a deformation limit. The latter being more easily implemented into common mechanical strand models.

Assuming the critical strain criterion as a basic model [6], the universal validity can be improved by the following extensions:

- the accumulation of strain within a critical temperature range, resulting in a solidification growth rate dependency of ε_C, similar to the Clyne-Davis criterion;
- the strength and the thermal contraction near solidus temperature;
- and the important influence of microstructure (columnar or equiaxed, coarse or fine).

In doing so, the local critical limits of shell deformation depend on the actual conditions at each position in the caster. As a result, the criterion can easily be implemented in a thermal-mechanical strand model. This and the continuation of the experimental work is the purpose of ongoing research work.

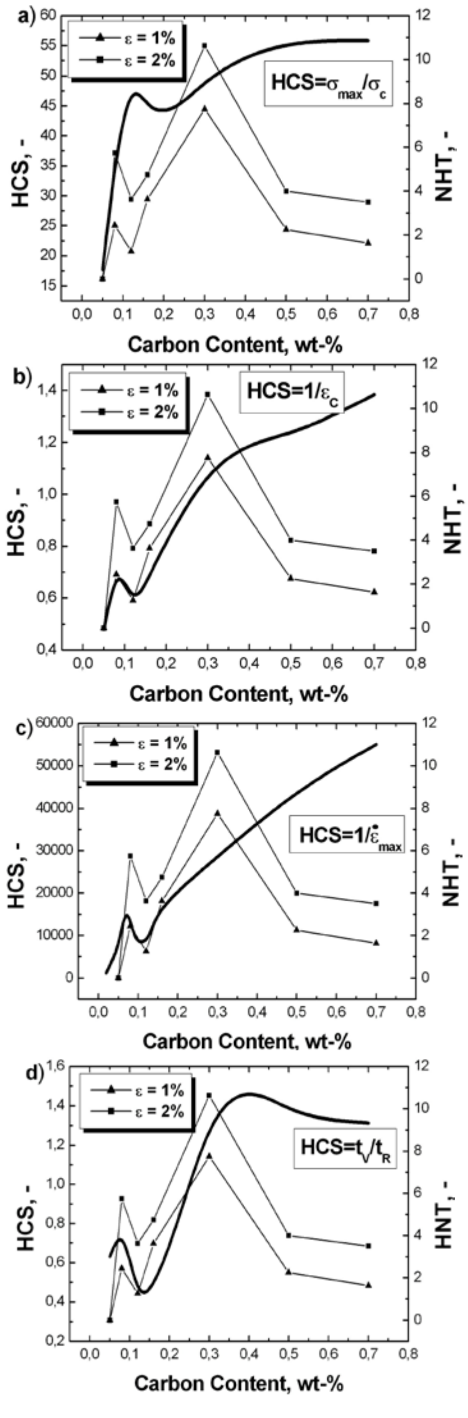

Fig. 2: Calculated HCS in comparison with experimentally determined hot tearing susceptibility

5. REFERENCES

[1] Verein Deutscher Eisenhüttenleute: Stahl-Eisen-Prüfblätter, Verlag Stahleisen GmbH, Düsseldorf (1992)

[2] Rogberg, B.: Scand. J. Metall. Vol. 12, (1983), 2, pp. 51-66.

[3] Won, Y. M., T. J. Yeo, D. J. Seol and K. H. Oh: Metallurgical and Materials Transactions B, Vol. 31, (2000), pp. 779-794.

[4] Rappaz, M., J.- M. Drezet and M. Gremaud: Metallurgical and Materials Transactions A, Vol.30A, (1999), pp. 449-455.

[5] Clyne, T. W. and G. J. Davies: Br. Foundryman 74 (1981), 4, pp. 65-73.

[6] Bernhard, C., R. Pierer, A. Tubikanec and C. Chimani: Proceedings of the CCR'04, June 14-15 2004, Paper No. 6.3.