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Experimental und numerical investigations on hot tearing during continuous casting of steel

Abstract

This paper focuses on hot tearing during continuous casting of steel and the experimental and numerical prediction of the hot tearing susceptibility. The first part of this publication explains the requirements for hot tear formation and the different hot tear appearances in three stages. The so called SSCT-test (submerged split chill tensile - test) is used at the Chair of Ferrous Metallurgy (CoFM), Montanuniversitaet Leoben (MUL), to determine the critical strain for hot tear formation, and is explained in the second part of this paper. An in-house developed software calculates the accumulated strain and the position of the generated hot tear segregations during the SSCT test. This software is also used to estimate accumulated strain for different steel grades on a typical casting machine. The determined critical strain (SSCT-test) and the estimated accumulated strain are combined to predict hot tear formation during continuous casting, as will be shown in the end of this publication.

Keywords

Continuous Casting, Hot Tearing, Hot Tear Segregations, Prediction, Internal Quality

1. Introduction

Surface defects in continuous casting (CC) typically originate in the meniscus region of the mould during initial solidification of the steel shell. While the shell is kept in form inside the mould mainly by the mould walls, no continuous stabilization support is present after the mould exit, ferrostatic pressure causes bulging, leading to induced strain inside the solidifying shell. Depending on the casting machine, also bending and un-bending operations, as well as friction on or reheating of the strand can cause strain to the solid-liquid phase during solidification, leading to defect formation, namely hot tearing.

Hot tears (HT) or hot tear segregations (HTS) are typically found in the half way region of flat and long products during continuous casting. The following criteria have to be fulfilled to create HTS:

- HTS originate only in the solid-liquid region during solidification.

- Tensile stresses are applied perpendicular to the solidification front by
    - mechanical forces (bulging, bending/unbending, …), or
    - thermal forces (reheating of the strand surface).
- HTS are situated at primary grain boundaries,
- originate at a definite fraction of solid, and
- only during columnar dendrite growth.

Only if all of prior mentioned criteria are fulfilled, HTS will form inside the solidifying strand and cause problems, more or less critical depending on the steel alloy and product quality demands. More than 20 years of research on field of hot tearing was carried out at the CoFM at the MUL, using experimental test assemblies like the SSCT test, but also self-developed software tools ("Sol-A-Sys") to predict HTS formation, as will be shown later on in this paper.

2. Hot tearing – appearance of HTS

The appearance of HTS can be classified in three stages, as is shown in **Figure 1**.

1. The area between the primary grains is filled with residual liquid during the end of solidification, containing heavy segregating elements like Mn, S and P. The strain is applied perpendicular to the HTS orientation, according to chapter 1, but the residual liquid is able to compensate the shrinkage and no pore formation occurs. This is called *Stage I*.
2. If the strain is further applied and the solidification front is moving too slow towards fs=1, the residual liquid film cannot compensate the shrinkage anymore and first pores will form, leading to *Stage II*.
3. *Stage III* typically contains precipitations due to the enrichment of different elements in the residual liquid like Mn or Nb [1]. With increasing strain a coalescence of pores can occur and – in worst case – lead to so call "open hot tears".

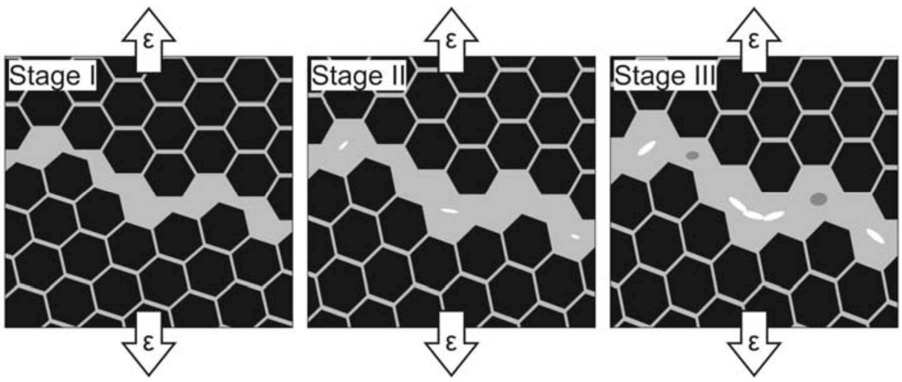

Figure 1: Stages I-III of HTS formation during CC of steel.

Examples of HTS appearances of stages I – III, regarding element distribution of Mn, P and Nb, in as cast slabs as well as for SSCT samples, have already been published by Pierer et al. [1] Ilie et al. [2] compared center- and microsegregation of as cast slabs with HTS, formed during CCC and obtained by SSCT tests. The quantification in **Figure 2** clearly displays the comparability of HTS (by CCC or SSCT) with the index for center segregation of slabs, leading to problems during further rolling and/or forging processes.

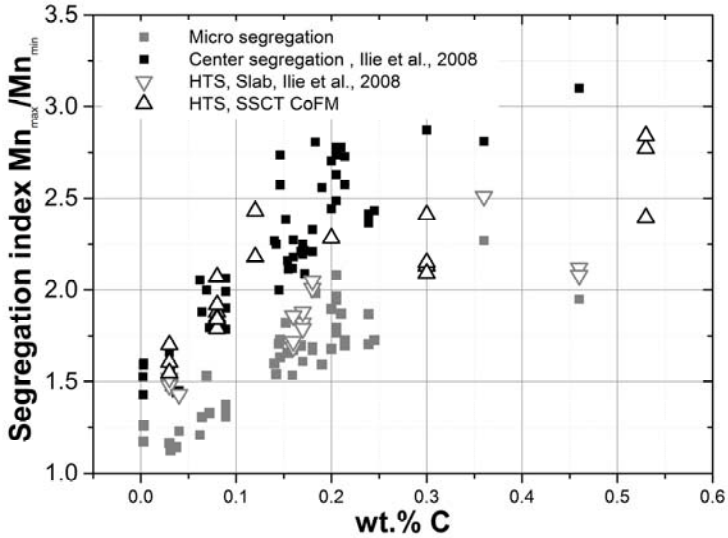

Figure 2: Segregation index of Mn; Micro- and centersegregation of slabs vs. SSCT-test samples. [2]

3. Hot tearing - Experimental

An appropriate tool to determine the hot tearing susceptibility of steels has to fulfil certain demands, although the “as-near-to-process” criteria may be the most important one. All criteria for HTS formation, previous mentioned in **chapter 1**, can be achieved by use of the SSCT test at the Chair of Ferrous Metallurgy, Montanuniversitaet Leoben. The laboratory experiment itself was originally adopted from EPF Lausanne [3,4], mainly carrying out investigations on Al-alloys, and was applied on steel alloys at the Chair of Metallurgy in Leoben. [5,6]

The cylindrical SSCT test sample consists of an upper and a lower part, both made of typical structural steel, schematically drawn in top left of **Figure 3**. The SSCT test itself can be described by 4 main steps:

1. The test sample is placed above the liquid steel melt in *step 1*. The alloy is prepared in a typical induction furnace (~25kg). Lollypop samples are used for chemical analysis, temperature is measured by conventional type S thermocouples.
2. During *step 2* the test sample is submerged into the liquid alloy and a steel shell starts to solidify. A temperature measurement by two type K thermocouples inside the lower part of the test sample determines the heat flux during the shell growth.
3. A certain amount of strain is induced to the solidifying shell at a definite strain rate during *step 3*, by moving the lower part of the test sample towards the bottom of the crucible. If the strain exceeds a critical value, HTS are formed.
4. The test sample is lifted out of the liquid melt in *step 4*, after the total amount of strain was induced in *step 3*. During the uplifting the steel shell still continues to solidify until the sample it is fully raised out of the melt.

The test sample is then removed from the assembly to cool down to room temperature and further tests are carried out new test samples and varying parameters, as will be shown later on in this paper. The steel shell is then cut in 16 pieces, the half is metallographically prepared (embedded, grinded, polished). Details were already published by Pierer et al. [2] Etching by Bechet-Beaujard [7] – parameters depending on steel composition – is done prior to HTS encountment by light-optical-microscopy (LOM). Examples will be shown contemporary with simulation results in the next chapter.

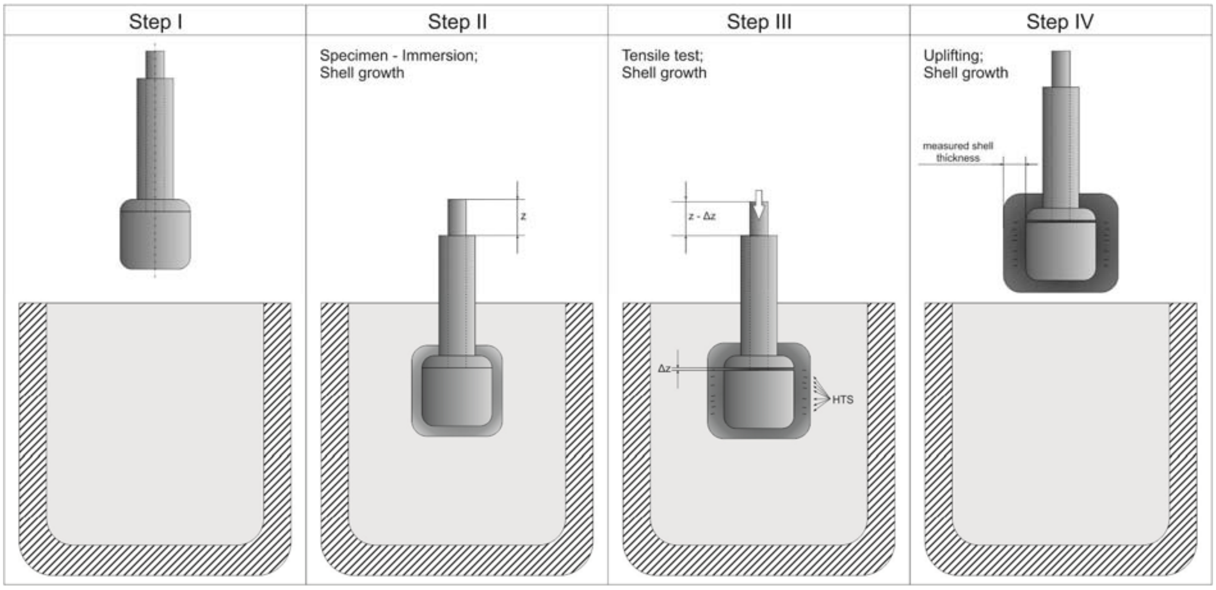

Figure 3: Stages I-IV of the SSCT-test at the CoFM.

4. Hot tearing – Simulation and prediction

The in-house developed software named "Sol-A-Sys" (Solidification-Analysis-System) uses a one-dimensional solidification model to calculate shell growth during steps I – IV. Heat flux was already determined using two type K thermocouples inside the lower part of the test sample. Material data like density, thermal conductivity and specific heat capacity are predicted by commercial tools (IDS) or Sol-A-Sys itself, having the ability to vary models respective microsegregation.

Three steel grades (LC, MC and UHC) are presented in **Figure 4** regarding shell growth (left) and strain accumulation (middle) during a typical SSCT test, calculated by Sol-A-Sys. The shell growth is plotted for different fractions of solid (f_s=1, 0.96, 0.2, 0), the time for Stage I and II ($t_{shellgrowth}$, 20s) and Stage III ($t_{tensile}$, 10s) are especially pointed out in the plot for the LC steel. The total applied strain ε_{total} was kept equal at 2% for all 3 simulations

The black dashed area between f_s=1 and f_s=0.96 marks the region of strain accumulation during Stage III for all investigated steels. Based on experimental experience of the last 20 years, this solid fraction of 96% was found to fit best on most of the investigated steel grades for strain accumulation. The concept of strain accumulation itself is based on the assumption of induced and accumulated strain on a volume-element, moving through the 2-phase-region during solidification between f_s=0.96 and f_s=1. The longer $t_{solidification}$ the more strain can be induced to this element.

The trend of the accumulated strain is explained in detail for the MC steel in the center of **Figure 4**. The lower part of the test sample starts to move in stage III, first strain is induced to the solidifying shell ("a"), leading to a constant increase of strain until "b". Point "b" marks a bend in the strain progress, representing the total induced strain especially for that volume-element having fs=0.96 at the start of the tensile test. The maximum of accumulated strain can be found in point "c" for precisely that volume-element, reaching f_s=1 at the end of stage III. More strain can be induced in "c" than in "b" due to the longer solidification time, exemplarily depicted for the UHC steel at the bottom left in **Figure 4**. After point "c", all remaining elements start with f_s=0.96 but reach the end of stage III with f_s<1, leading to a decrease in induced strain down to zero at point "d".

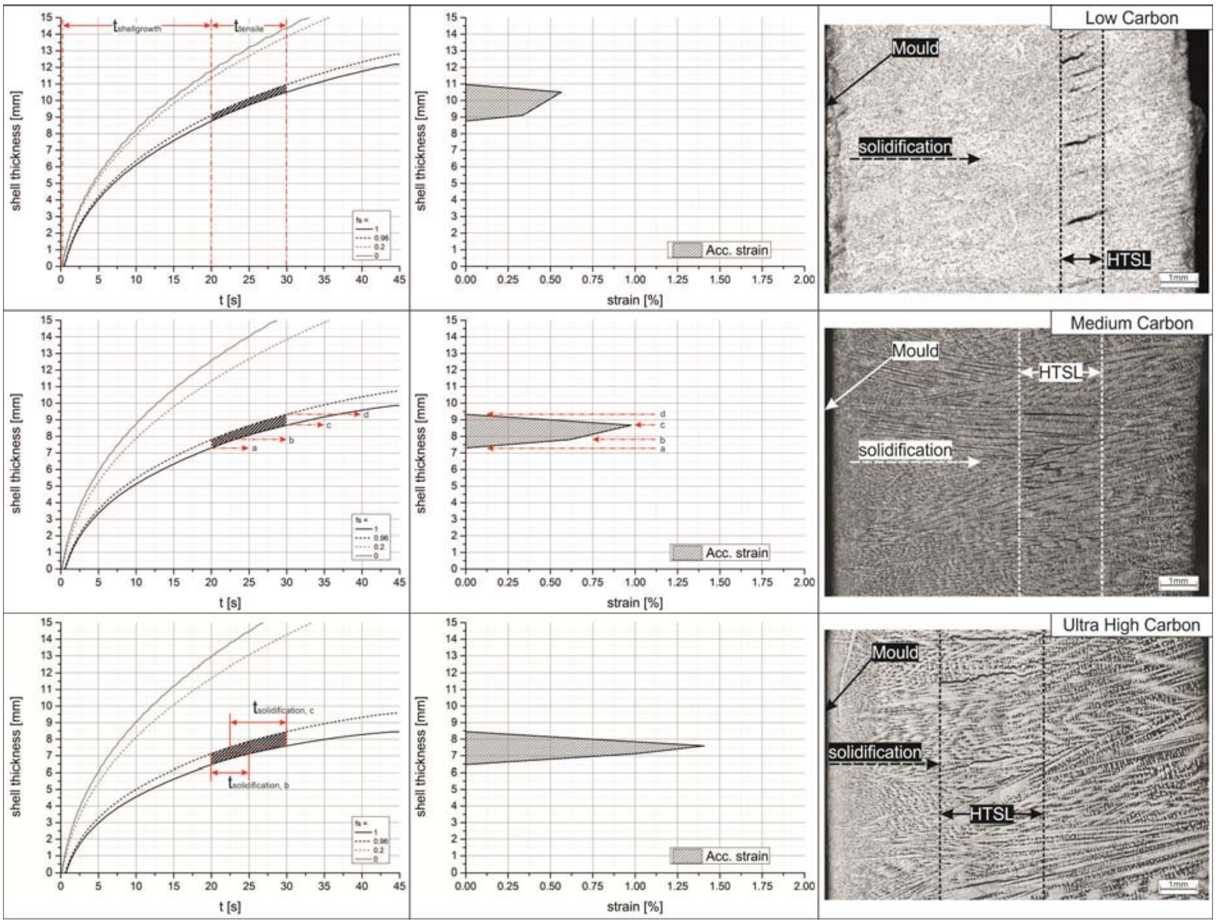

Figure 4: SSCT test: Predicted shell growth (left) and accumulated strain (middle) for LC, MC and UHC steel grades. HTS position and mean hot tear segregation length (HTSL, right).

Images of several HTS in these steel grades, obtained by SSCT tests, are plotted on the right of **Figure 4**. The simulation results (left and middle in **Figure 4**) are not in definite accordance to the images of the SSCT samples (HTS start/end) due to different test parameters (total induced strain ε_{total}, strain rate …) but representatively mirror the general tendency:

- The lower T_s the nearer HTS_{start} to the surface (mould).
- The larger $t_{solidification}$ ($0.96 < f_s < 1$) the higher ε_{acc}.
- The higher ε_{total} the higher ε_{acc}.
- The higher the strain rate the higher ε_{acc}.

The latter is explained in detail for the UHC steel grade in **Figure 5** by applying the total strain of 2% in half of the time, thus doubling the strain rate. Only in this special case the total applied strain ε_{total} is induced to the solidifying shell during the SSCT test:

$$\varepsilon_{total} = \varepsilon_{acc} = 2\%$$

Sol-A-Sys is not only limited to SSCT-test calculations only, but can also be used to predict shell growth and strain accumulation for any continuous casting assembly, if the following machine parameters are available:

- Mould length and heat flux distribution.

- Casting radius and speed.
- Bending/unbending position and radii.
- Roller carpet; optional position of Liquid Core Reduction (LCR) or Softreduction and relating roll parameters.
- Heat flux in Secondary Cooling Zone (SCZ).

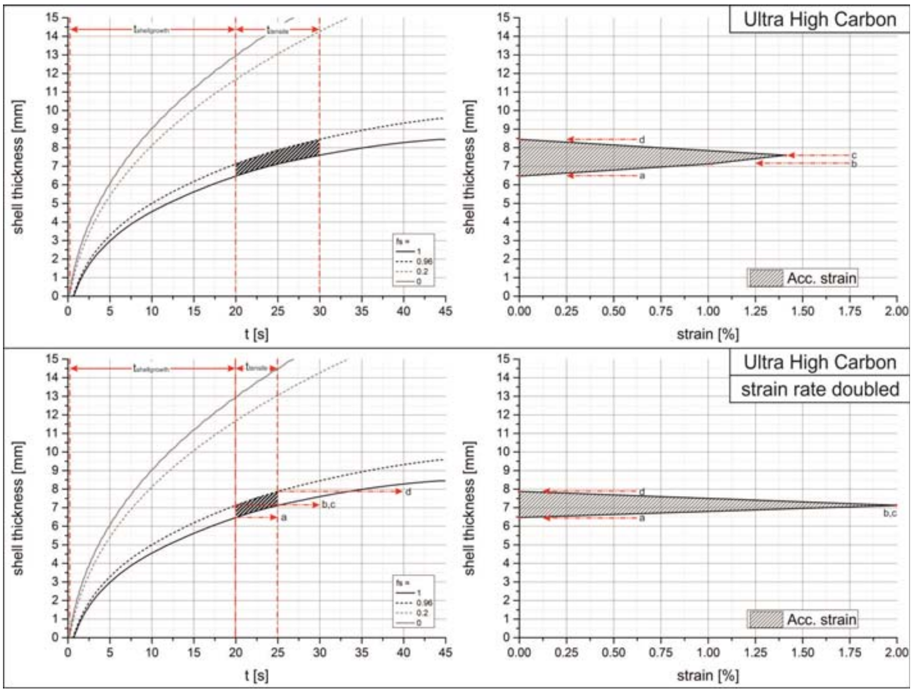

Figure 5: Shell growth and accumulated strain, UHC steel (top); doubled strain rate (bottom).

Two steel grades with differing proneness to hot tearing (composition given in **Table 1**) were used to estimate the trend of the accumulated strain for slab (225mm thickness) on a conventional continuous casting machine. The strain was calculated for different cooling strategies for both steels, results are presented in **Figure 6**. Cooling characteristics of the so called “Softcooling” and “Hardcooling” strategies can be found elsewhere. [8]

Table 1: Chemical analysis of steel A and B.

[wt.-%]	C	Si	Mn	P	S	Nb
Steel A	0.170	0.430	1.540	0.015	0.007	0.015
Steel B	0.150	0.017	1.109	0.008	0.007	0

Both plots at the top of **Figure 6** present the development of the accumulated strain for steel A (left) and steel B (right) under hard- (full line) or softcooling (dashed line) conditions. The accumulated strain on the X-axis is plotted against the shell thickness of the slab (Y-axis), comparable to the depiction of the SSCT-tests (**Figure 4**).

Hardcooling always leads to less accumulated strain than softcooling, due to the increased solidification time ($t_{solidification}$) during slower cooling conditions. The grey dashed area illustrates the critical strain, determined for these steel grades by the SSCT-test. This area is only hit by steel A under softcooling conditions due to the higher content of Phosphorus. Latter results in a higher segregation degree, thus reduced T_s and consequent longer $t_{solidification}$, owing to the widened 2-phase region solid-liquid. These accumulated strain developments are estimated by Sol-A-Sys if the casting machine maintenance is assumed to be 100%.

With increasing number of casted heats the maintenance will drop, represented in these calculations by a misalignment of 3 different rolls at a degree of 1mm each. The accumulated strain drastically increases if the strand hits these roll positions, as can be seen best for steel B in the bottom right plot of **Figure 6**. In all cases the accumulated strain now exceeds the determined critical strain, independent on steel composition or cooling strategy, and the probability of HTS formation is elevated.

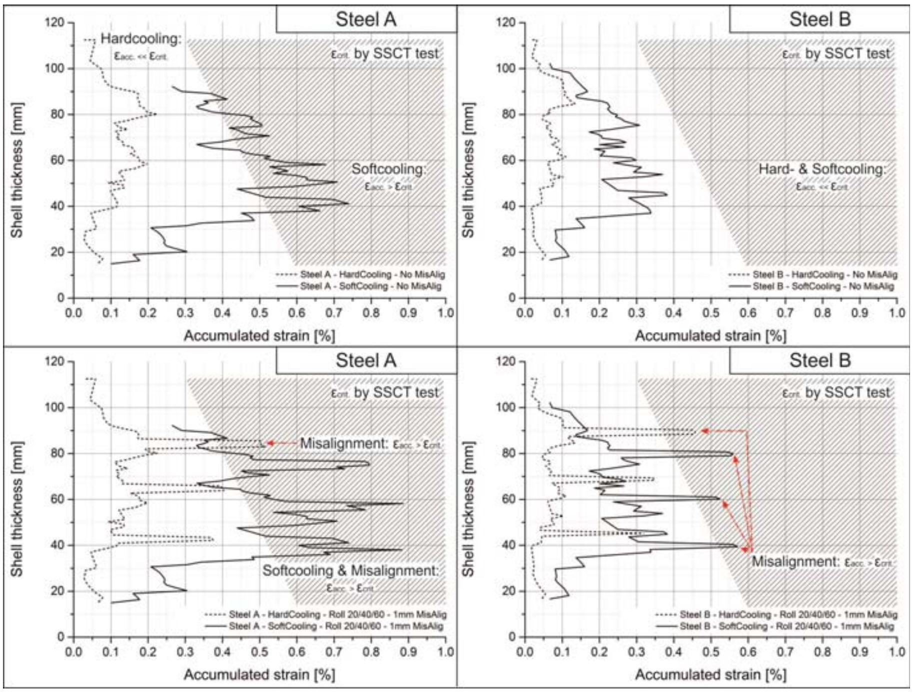

Figure 6: Predicted accumulated strain (steel A vs. B) for 2 different cooling strategies with 100% maintenance of the casting assembly (top); strain development for roll misalignment of 1 mm (bottom).

5. Summary

The SSCT test is a suitable method to investigate HTS formation during the solidification of steel with conditions equal to continuous casting processes. Varying several testing parameters makes it possible to determine a critical strain ε_{crit} for a specific alloy. An estimation of the accumulated strain ε_{acc} during CC can be done by simulation, for this specific alloy on any conceived continuous machine, if all boundary conditions (thermal and mechanical) are provided and the maintenance is assumed as 100%. HTS formation is elevated if the calculated accumulated strain exceeds the determined critical strain.

Machine maintenance has to be considered as an important parameter to prevent HTS formation for any steel grade as well as the content of heavy segregating elements. The degree of segregation can reach even values comparable to center segregation, possibly leading to hard and brittle phases during reheating and rolling and product losses in worst case.

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