CHARACTERIZATION OF HOT TEAR SEGREGATIONS IN CONTINUOUS CASTING OF SLABS

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ABSTRACT

The formation of hot tears (also columnar cracks, internal cracks) in continuous casting of steel may - despite of the achieved improvement of the machinery and maintenance - still be a limitation for a further increase of casting speed and a threat for the quality of certain steel grades. The present paper deals with the results of analytical investigations into the enrichment of alloying elements and trace elements within hot tear segregations (HTS) in cast slabs and also in probes from a laboratory experiment. Depending on the steel composition and the demands on the final product properties, these segregations may result in the formation of undesirable phases and coarse precipitates as well as the formation of a banded structure, associated with an anisotropy of the mechanical properties.

The results show, that the enrichment of certain elements equals or even exceeds the enrichment in center segregations. The enrichment of Mn depends on the carbon content. The simulation of HTS formation in a laboratory experiment is possible, as the comparison of the segregation factors in the HTS will show.

KEYWORDS

continuous casting; slabs; cast structure; hot tears; hot tear segregation; manganese distribution; carbonitrides

INTRODUCTION

Hot tearing (or columnar cracking, internal cracking) is still an existing problem in all technical casting processes. Today, the mechanism of hot tearing seems - at least for non-ferrous metallic alloys - well understood [1,2]. Different hot tearing criteria exist, commonly based on the assumption that intergranular pores act as nuclei for the subsequent formation of open hot tears. A preliminary stage of the hot tear initiation is the liquid feeding of the stretched primary grain boundaries, sometimes falsely termed as "healing" of the hot tears. In the continuous casting of steel this earliest stage of hot tearing results in the formation of segregations at the "mesoscopic scale". To emphasize the important difference between hot tearing and this type of defect, the term "hot tear segregation" (HTS) was proposed [3]. Hot tears are formed due to tensile stresses in the slab shell, caused by bending, straightening or roller offset, and through bulging, roller jerks, and similar. Figure 1 shows the position of typical hot tear types within the slab.

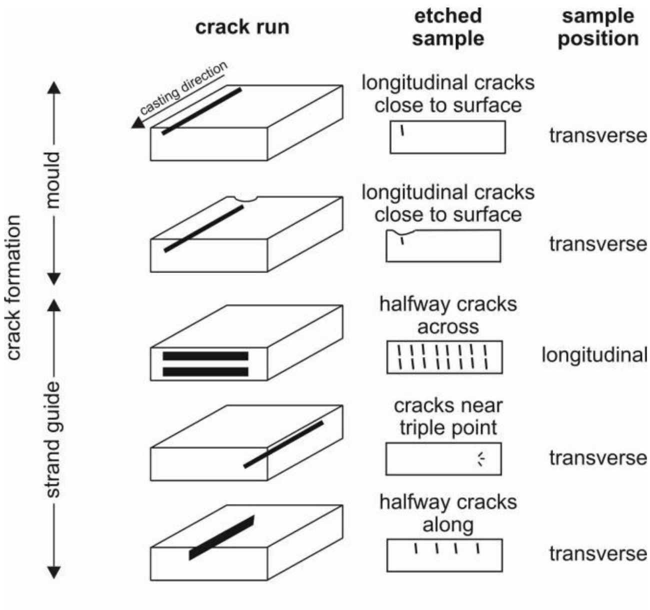

Fig. 1: Sketch of types of cracks examined in slab samples.

1. MICROANALYTICAL INVESTIGATIONS INTO HOT TEAR SEGREGATIONS IN SLABS

Under certain conditions, HTS may result in a serious deterioration of the final product properties: they are often associated with the precipitation of coarse sulfides and carbo-nitrides and the formation of hardening phases in banded structures in the final product.
Within the scope of the actual work, two methods for investigations of the formation of HTS were applied:

- The characterization of hot tears in cast slabs using a electron microprobe analyzer (EPMA) and the comparison between the segregation levels in the HTS, crystal segregation (microsegregation) and the center segregation of the slabs (macrosegregation).
- The initiation of HTS in experiments and the subsequent characterization of the segregations by EPMA.

In order to assess the quality of the slabs, the kind of centre segregation, the deviations from the slab geometry (channels, bulges), and the formation of cracks, etching plates (samples) are produced, which are then employed for further microanalytical investigations (Fig. 1). Depending on the goal of the test, samples are cut from the etching plates according to a sampling plan, prepared, subjected to a preliminary light optical analysis and subsequently analyzed with a microprobe analyzer (EPMA). The concentration mapping worked out with the microprobe analyser and their interpretation are not described in detail, as this would go far beyond the scope of this paper. The reader is referred to the appropriate Literature [4,5,6].
The chemical compositions of the steel grades under consideration are listed in table 1.

Table 1: Chemical composition of steel melts under analysis

Element / Melt	C mass-%	Si mass-%	Mn mass-%	Nb mass-%
Steel A	0.03	0.02	0.22	0.002
Steel B	0.18	0.36	1.18	0.022
Steel C	0.04	0.35	1.68	0.045
Steel D	0.36	0.22	0.62	<0.001
Steel E	0.17	0.44	1.51	0.021
Steel F	0.16	0.45	1.53	0.025
Steel G	0.46	0.19	0.72	<0.001
Steel H	0.18	0.38	1.17	0.024

Figures 2 and 3 provide optical impressions of the element distribution (example concentration mapping of manganese) over the half thickness of a slab for steels H and C, respectively. The dendrites (poor in Mn) are bright, the enriched interdendritic region is dark. The coarsening of the primary structure between the surface and the center of the slab, as well as the enrichment of Mn at the macroscopic scale within the center segregation are clearly visible. The enrichment of Mn in the higher carbon steel is more pronounced than in the low carbon steel.

The enrichment of elements is quantified by a segregation factor, denoted as c_{max}/c_{min}. It should be mentioned, that this procedure demands a careful handling of the microprobe raw data: artifacts have to be identified by filters and subsequently disregarded in the analysis. This procedure is described in detail elsewhere [7]. Figure 4 shows the segregation factor of Mn in the quarter (microsegregation) und half slab position (center segregation) versus carbon content for more than 50 samples from different steel grades [5]. What emerges from the graph in figure 4 is that there are two clearly distinguished collectives of the manganese segregation factors. (Please note the different concentration scales for figure 2 and 3.) As figure 4 shows, a carbon content of 0.18 mass-% results in a mean segregation factor for the crystal segregation of manganese of 1.7, while for the centre segregation a factor of 2.4 is recorded.

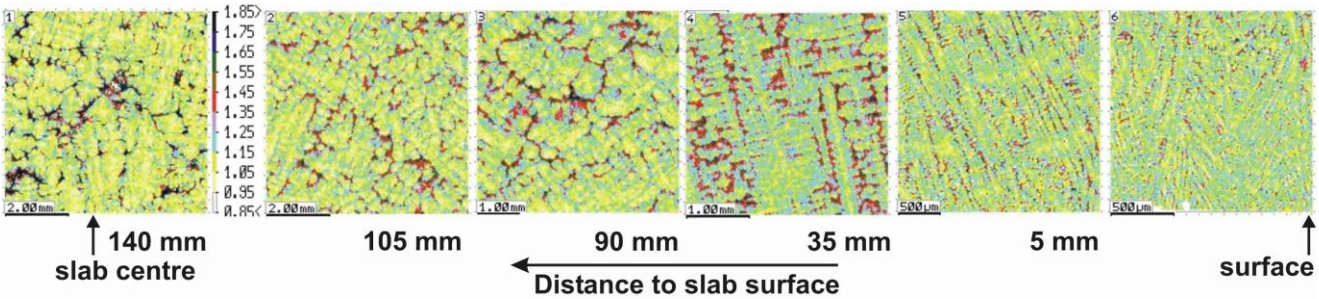

Fig. 2: Concentration mapping of manganese over the slab thickness; Steel H.

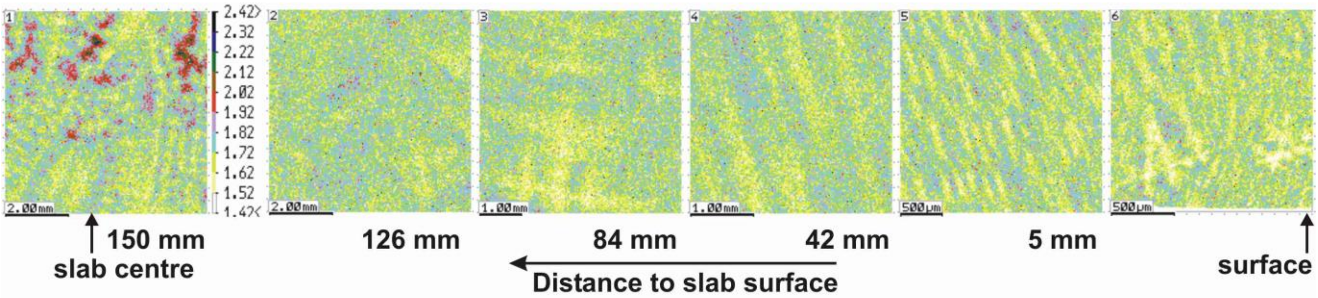

Fig. 3: Concentration mapping of manganese over the half slab thickness; Steel C.

The same analysis procedure was used to characterize the segregation of elements in the hot tear segregations. In addition the type and shape of non-metallic inclusions are investigated with respect to the micro-alloyed steel grades, which will be shown later on.

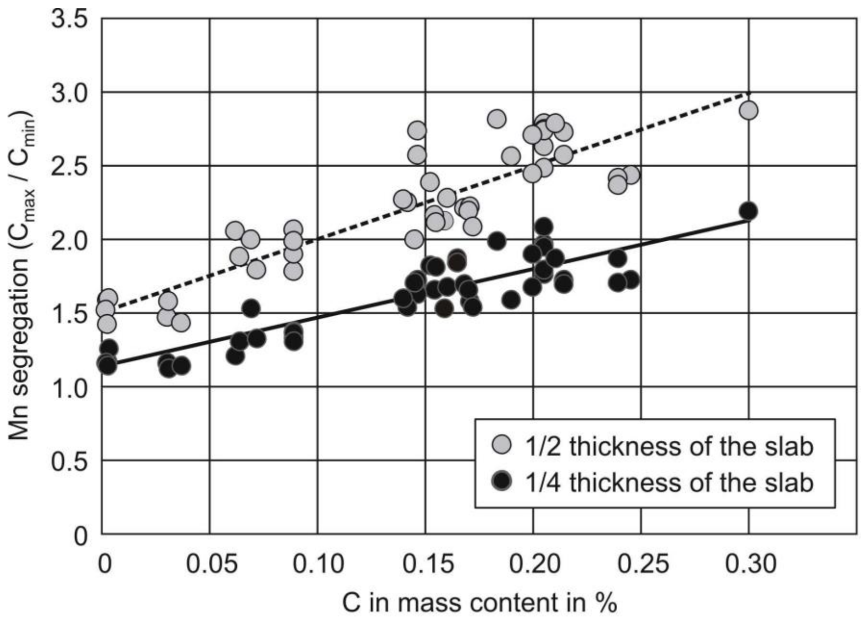

Fig. 4: Segregation factors for crystal and centre segregation of manganese in dependence on the carbon content of various steel grades [5].

1.1 Results of microanalytical investigation of hot tear segregations in a steel melt with 0.18 mass-% carbon

The segregation behavior of manganese during solidification of a steel melt containing 0.18 mass-% carbon is seen in figure 2. Figure 5 represents the enrichment of Mn and Nb in a hot tear segregation. Apart from manganese concentrations that results in the precipitation of sulfides, the central area of the lastly solidified residual melt shows line-like precipitations of niobium-titanium-carbonitrides. The number of niobium-titanium-carbonitrides increases towards the slab centre, where networks of niobium-titanium-carbonitrides can be observed in the dendritic interstices (Fig. 6).

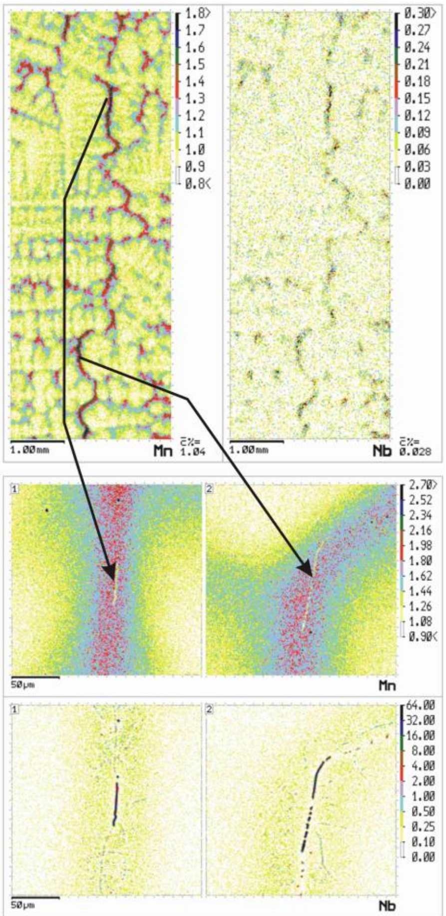

Fig. 5: Concentration mapping of manganese and niobium in a hot tear crack (halfway crack); Steel H.

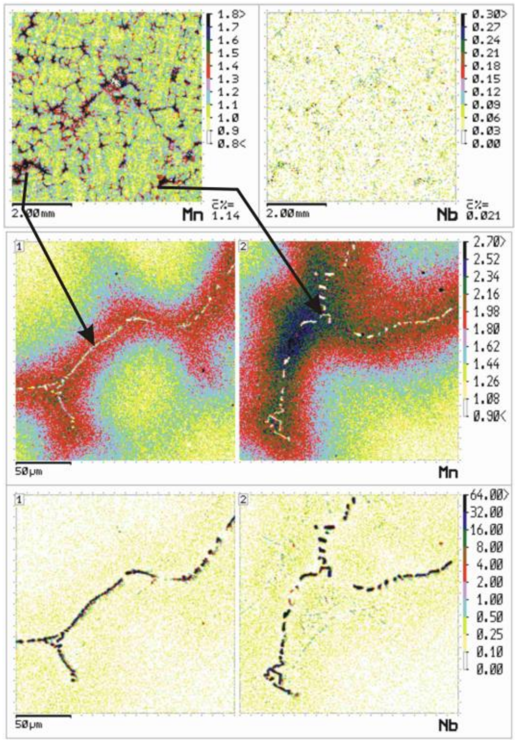

Fig. 6: Concentration mapping of manganese and niobium in the slab centre; formation of niobium-titanium-carbonitrides (Nb_{1-x}, Ti_x)(C_{1-y}, N_y) networks; Steel H.

Compiling the segregation analyses of steel H, one will obtain the segregation factors c_{max}/c_{min} for manganese in dependence on the slab thickness as shown in figure 7. In the case of microsegregation, the Mn segregation factor is 1.7, whereas in the case of the center segregation it is 2.2. In the halfway cracks manganese shows a segregation factor of 2.1. The enrichment of Mn is thus marginally lower compared with the enrichment in the center segregation for the steel grade H.

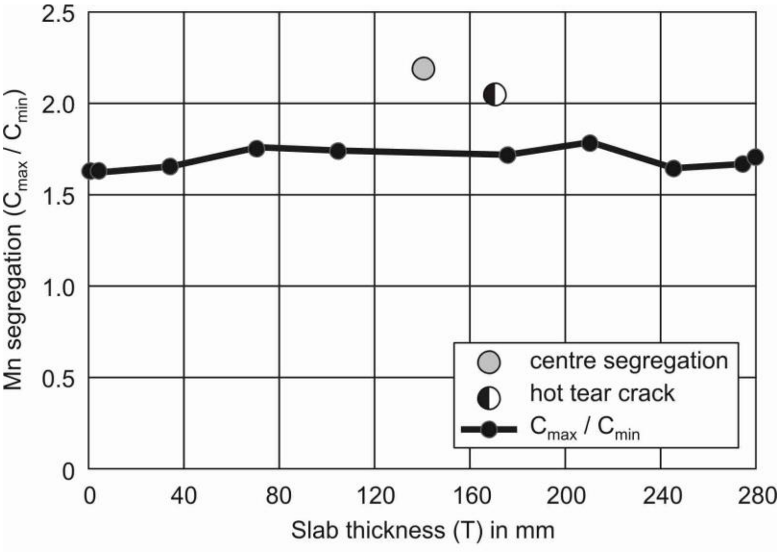

Fig. 7: Distribution of manganese segregation factors over the slab thickness (T); Steel H.

1.2 Results of microanalytical investigation of hot tear segregations in a steel melt with 0.04 mass-% carbon

The microsegregation of manganese in the steel grade with 0.04 mass-% is substantially less pronounced than in the steel grade having 0.18 mass-% (Fig. 3). The segregation behavior of manganese in hot tears is depicted by figure 8. Again, in the centre of the segregated residual melt last to solidify, precipitations of niobium-titanium-carbonitrides can be observed in the hot tear segregations.

An overview of the segregation analyses on the slab from steel C is illustrated in figure 9. In the case of microsegregation, the segregation factor calculated for manganese is 1.3, and 1.45 in the case of centre segregation. What deserves particular attention here is the segregation behavior of manganese in the hot tear segregation, where the manganese segregation factor reaches a value of 1.43.

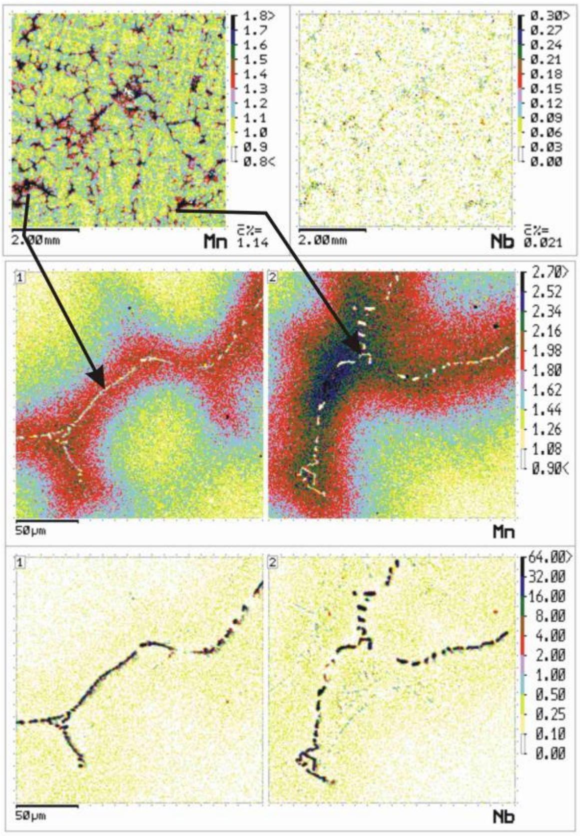

Fig. 8: Concentration mapping of manganese and niobium in a hot tear (halfway crack); Steel C.

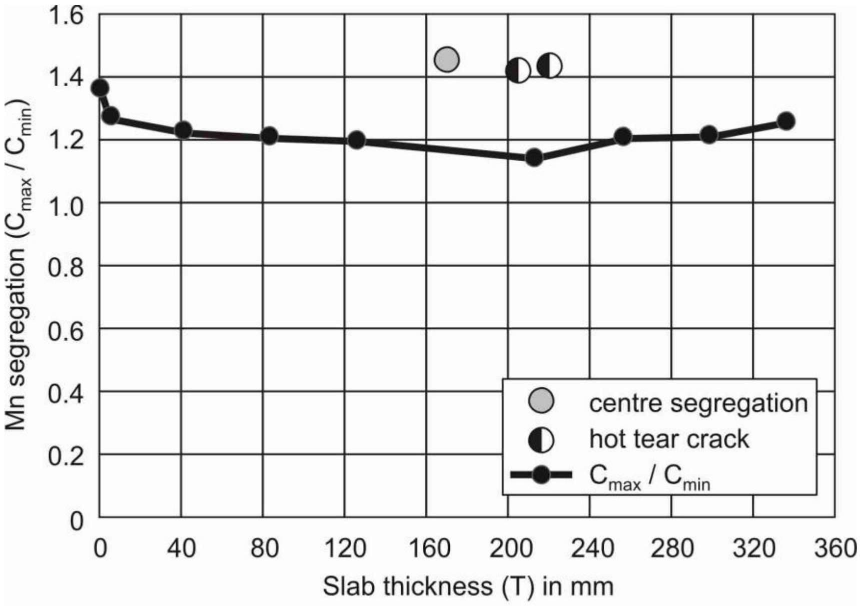

Fig. 9: Distribution of manganese segregation factors over the slab thickness (T); Steel C.

1.3 Assessment of test results

Under the effect of tensile stresses, hot tears are initiated at the solidus front of the strand shell to spread out along the dendritic interstices into the solidified material. The hot tears are situated outside the primary dendrites (i.e. primary grain boundaries) in the dendritic interstices, longitudinally or transversally to the direction of casting (transverse and longitudinal cracks) - see figure 1. As illustrated in the previous sections, these cracks are mainly hot tear segregations. In the literature, no description about the mechanism of these types of defects can be found. However, it seems that hot tear segregations are a preliminary stage of the initiation of open hot tears. Since the hot tear segregations are continuous regions of high solute enrichments, it is usually not possible to observe any material separation in the slab samples. Only in few cases cavities can be observed in these regions indicating the initiation of open cracks.

The segregation of the various elements is mainly influenced by the carbon content and the modification of the solidified Fe-crystal, respectively. Besides, there exist influences of carbon on the structure parameters, e.g. the secondary dendrite arm spacing that influences the back diffusion. According to the present analysis results, the level of manganese segregation in the hot tears increases with increasing C-content and is usually between the values for crystal segregation and the values for centre segregation, figure 10 and table 2.

Table 2: Overview of segregation factors determined

Segregation factors / Melt	Crystal segregation	Longit. cr. near surface	Diagonal cracks	Cracks near triple point	Halfway cracks, long.	Halfway cracks, transv.	Macro segregation
Steel A	1.55	1.49	1.48			1.52	1.66
Steel B	1.67					2.01	2.33
Steel C	1.23					1.43	1.45
Steel D	2.27	2.50			2.52		2.81
Steel E	1.61	1.82	1.79	1.88			2.25
Steel F	1.67	1.69		1.86	1.72		2.18
Steel G	1.95	2.12			2.80		3.10
Steel H	1.69					2.05	2.21

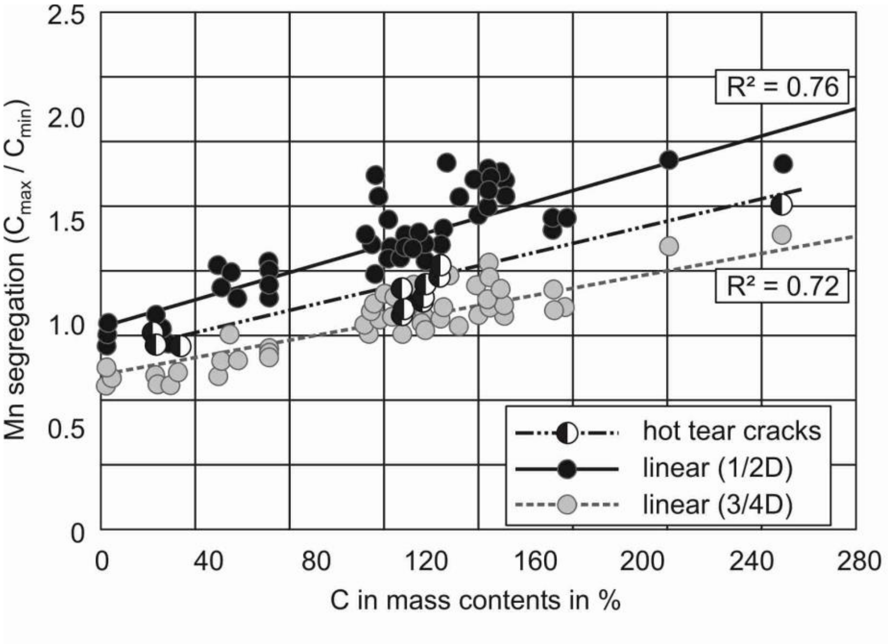

Fig. 10: Dependence of manganese segregation factors in hot tears on the carbon content of the respective melt as well as their position with respect to the mean values of crystal and centre segregation.

2. MICROANALYTICAL INVESTIGATIONS ON SPECIMEN FROM EXPERIMENTS

To investigate the influence of various elements on hot tearing at the laboratory scale, the so called Submerged Split Chill Tensile (SSCT)-test was used [8,9,10]. The characteristics of the SSCT-experiment are the existence of a deformable mushy zone together with a columnar grain structure, the conformity of the microstructure with that of a continuous casting shell and a main load direction perpendicular to the main dendrite growth axis. The method allows the initiation of HTS under controlled conditions.

Figure 11 depicts the enrichment of Mn and Nb in a hot tear segregation from an SSCT-experiment on steel containing 0.037 mass-% C; 0.32 mass-% Si; 1.56 mass-% Mn; and 0.037 mass-% Nb. A total strain of 1.6 % results in the formation of HTS. The segregation factor of P in the HTS amounts to 15 – 20. The segregation factor of Mn ranges from 1.35 – 1.75 with an average value of 1.5. This is similar to the enrichment of Mn in the halfway cracks in slabs. The segregation factor of Cr and Ni ranges also between 1.65 and 2. Within the HTS, coarse manganese-sulfides and

Nb(C,N) can be found as well a pores, indicating the incipient nucleation of open hot tears. The HTS are solely formed along primary grain boundaries.

A further critical element with respect to hot tearing is Cu. As the equilibrium partition coefficient of Cu is rather high – values of 0.7 and 0.8 for the solidification to ferrite and 0.85 for the transition to austenite can be found in literature [11,12] – the resultant microsegregation of Cu is moderate. As an increasing Cu-content in the order of magnitude of some tenth of a percent does also not dramatically lower the solidus temperature, Cu will only marginally influence the critical limits of crack formation [13]. Nevertheless, the enrichment of Cu in the HTS is remarkable: the segregation factor amounts to between 1.6 and 2.0, with the average value of 1.7. As will be demonstrated in the next example, the formation of Cu-rich phases in context with the precipitation of coarse sulfides is possible.

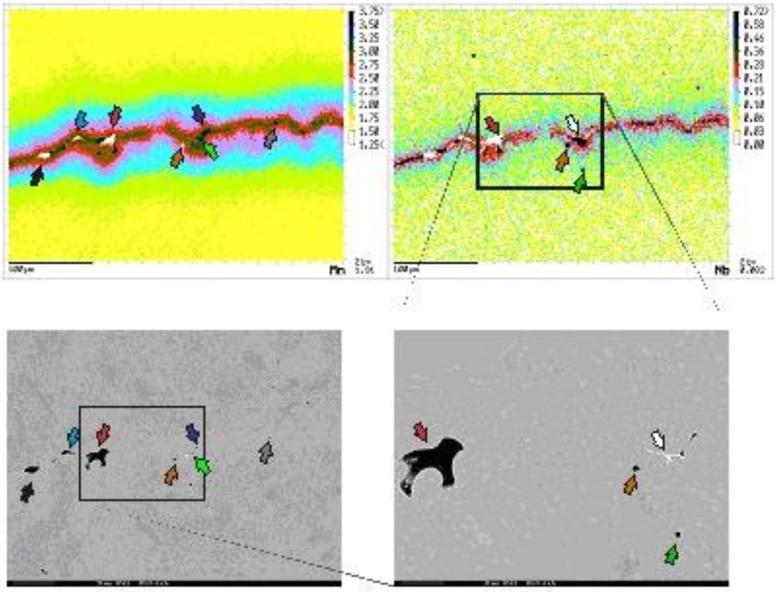

Fig. 11: Concentration mapping of Mn and Nb in a HTS and BSE (Back Scattering Electrons) of the same area, light blue and red arrows mark voids, dark blue and light green arrows mark sulfides and orange and white arrows mark carbo-nitrides; SSCT-Test.

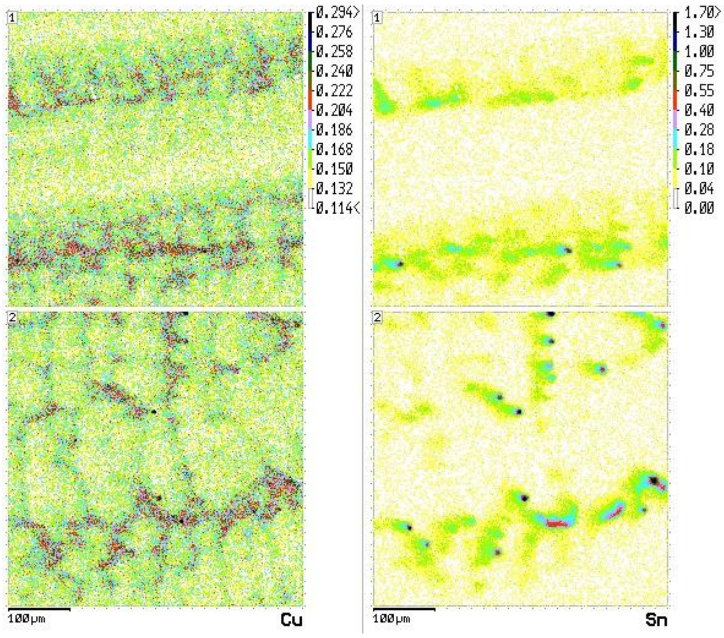

Fig. 12: Concentration mapping of Cu and Sn in HTS of a steel with 0.15 mass-% C, 0.15 mass-% Cu and 0.035 mass-% Sn; SSCT-Test.

A further SSCT-series has been performed on steels with 0.15 mass-% C, 0.15 mass-% Cu and in addition 0.015 – 0.035 mass-% Sn and 0.034 – 0.08 mass-% Ni respectively [13]. Figure 12 shows an example for the enrichment of Cu and Sn in HTS. The highest concentration for both elements can be found in a spot-like shape around coarse sulfides. The context with the formation of sulfides during solidification is apparent, although, due to the lack of thermodynamic data, not yet fully understood. The maximum concentration of Cu and Sn around the sulfides amounts to several mass-%. Although, Cu and Sn show no remarkable influence on the crack susceptibility, they contribute to the harmfulness of HTS during the further processing.

The metallographical and analytical investigations of HTS emphasize the importance of this kind of defects for the final product quality. The enrichment remains in the material even after reheating and hot rolling at highest deformation degrees and – depending on the cast steel grade – may result in the formation of hardening phases and banded structures (Fig. 13). Coarse precipitates, like manganese-sulfides or carbo-nitrides might also influence the behavior of the material during the further processing steps as well as the properties of the final product. The presented results will serve as an important basis for the better understanding of the relevance of HTS on the final product properties.

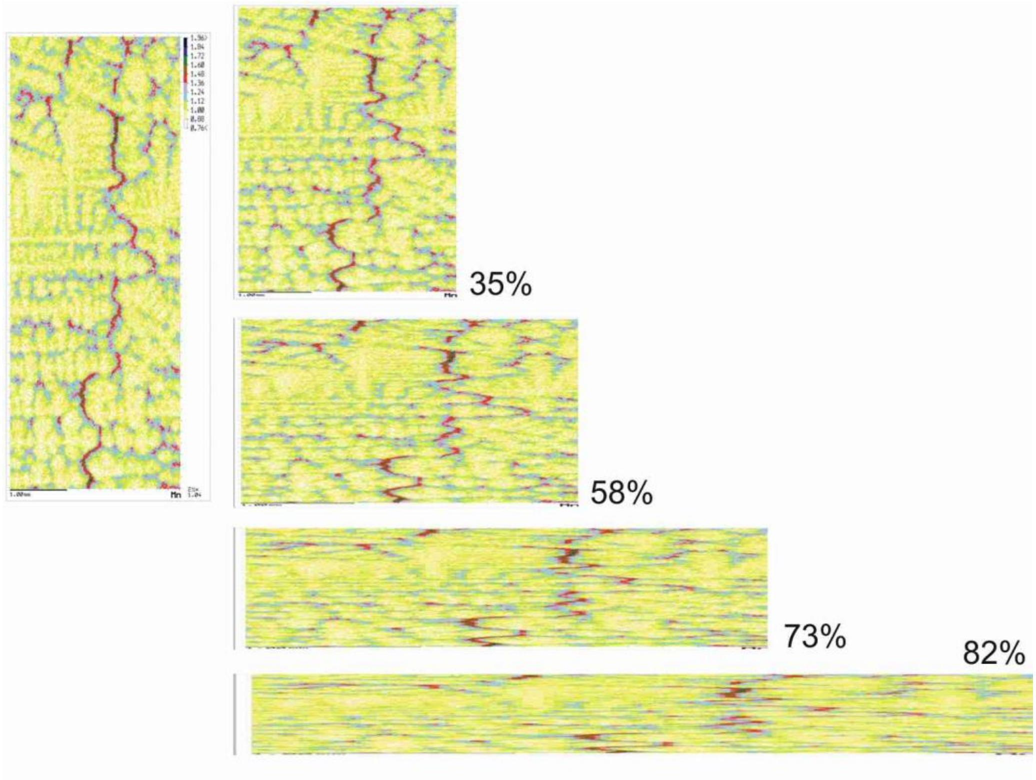

Fig. 13: Simulation [4] of the behavior of a hot tear crack following a thickness reduction of 82 %; Steel H.

3. SUMMARY

The results of the presented investigations may be summarized as follows:

- The enrichment of alloying elements in hot tear segregations (HTS) equals or even exceeds the enrichment in centre segregations. HTS may therefore result in the formation of a banded structure and the formation of brittle phases during and after further processing.
- The remarkable enrichment may also be the reason for the precipitation of coarse sulfides or carbo-nitrides in the HTS. Depending on the further processing and the demands on the final product, these precipitations may deteriorate the product quality.
- Even elements, which do not significantly influence the hot tearing susceptibility, such as Cu or Sn, within the afore described concentration ranges, may form extremely enriched phases, with Cu or Sn contents in the range of several percents in weight. This enrichment might negatively affect the behavior of the steel during the further processing and – in any way - remain in the product even after reheating and hot rolling with high deformation degrees.

- The enrichment of Mn in the HTS depends on the carbon content: the higher the carbon content, the higher the enrichment of Mn.
- The determined segregation factor for Mn in typical types of HTS in slabs corresponds very well with the segregation factor in HTS from probes of the SSCT-experiment. This is an important basis for the planning of further research activities on the role of hot tear segregations for the quality of steel grades at the highest quality levels.

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