A transversal crack in a steel slab and its analysis

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ABSTRACT. *This contribution tries to verify the hypothesis on the initiation and propagation of the cross crack by means of behaviour in tensile tests with the con-cast slab of the same basic chemical composition in the range of temperature moving from 25°C to 1450°C. The tensile tests were made on 18 test bars at suitably chosen temperature differences and gradually led to the tension ruptures of the bars under exactly defined conditions. Simultaneously, the roughness of the resultant rupture surface depending upon the temperature was studied in detail. Thus relations between the roughness of the rupture surface, tension force, work to rupture and contraction with the test bars at the given range of temperature were determined. On the basis of the comparison of the rupture surfaces of cross cracks found in the study and the rupture surfaces obtained at the given interval of test temperatures in the course of this study, properties of material of the slab affected by the cross crack and its most probable behaviour during solidification and cooling were then evaluated by analogy. In this way it was possible to specify and verify the mechanism of cross crack initiation and propagation and to assess the temperature interval, within which the initiation was the most probable.*

INTRODUCTION

This paper deals with the causes of a transversal crack in a steel slab with an 1300×145 mm cross-section by means of results from two models. Samples were taken from and around the crack in order to analyze the concentration (chemical heterogeneity) of the selected elements. Simultaneously, the concentration of elements at the surface of the crack was measured after the crack was opened. The chemical heterogeneity of elements was analyzed by means of the JEOL JXA 8600/KEVEX analytical equipment. The measurement results were processed using mathematical statistics procedures. The results proved that there was an internal crack initiating immediately below the curve of the solid-state temperature and consecutively propagating.

Two original models have been developed and used in the investigation of a continuously cast low-carbon-steel slab [1]. The first numerical 3D model of the temperature field of a concasting is capable of simulating the temperature field of a caster. Experimental research and data acquisition have to be conducted simultaneously with the numerical computation.

The second model—of dendritic segregation of elements—assesses critical points of slabs from the viewpoint of their increased susceptibility to crack and fissure [1,2]. In order to apply this model, it is necessary to analyse the heterogeneity of selected elements in characteristic places of the solidifying slab. The model, based on measurement results obtained by an electron micro-probe, generates distribution curves showing the dendritic segregation of the analyzed element, together with the partition coefficients of the elements between the liquid and solid states.

The combination of both models enables the prediction of cracks and fissures in critical points of the continuously cast carbon-steel slab.

FRACTURE BEHAVIOUR OF ANALYSED SLABS

Fracture behaviour of continuously cast slab A in the temperature interval from 25°C to 1450°C

Test specimens for tensile tests were taken from cross section of the slab (marked as slab A) with dimensions of 250×1530 mm^2. Chemical composition of this slab is the following (in wt%): 0.12 C, 0.38 Mn, 0.26 Si, 0.010 P, 0.012 S, 0.06 Cr, 0.064 Cu, 0.033 Al(sum), 0.03 Ni. It is close to chemical composition of the slab with cross crack (marked as slab B). Test specimens were taken from the slab after its solidification and cooling down to a room temperature. Mechanical tensile tests were made on test bars with thread of total length of 245mm. Nominal diameter of test bars was 6mm and their measured length was 100mm. The tests as such were completed in the laboratory of the Faculty of Metallurgy and Materials Engineering at the Technical University of Ostrava on special tensile machine. The equipment used for tests and conditions of tests are in detail described in the work [3].

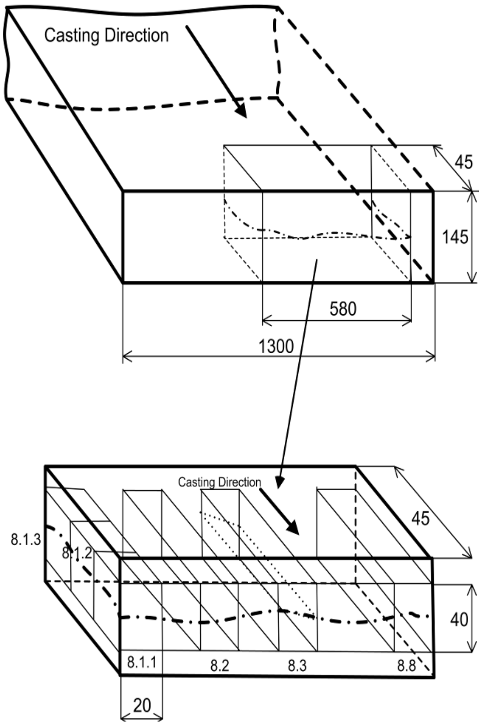
Electronic scanning microscope JEOL JSM 840 has been used for fractographic analysis of rupture. Complete fractographic analysis of the selected set of torn test bars is contained in the work [4].

Influence of temperature on morphology of rupture of the slab A

The following behaviour has been ascertained by tests: at temperatures 25, 312, 536, 632 and 732°C ruptures of test bars are trans-crystalline and ductile and they are realised by cavity mechanism. Ruptures are free of defective signs. Ruptures at temperatures 798 and 841°C show on test bars significant drop of contraction (down to 11 %). At the temperature of 988°C there prevails an interdendritic fracture.

Zone of temperatures, in which there occurs almost complete contraction of test bars (Fig. 2), lies in the temperature interval from 1134 to 1420°C. It is possible to observe formation of cavities in the central part of almost complete narrowing (Fig. 2).

At temperature of testing of 1423°C, which is close to a solidus temperature proportion of interdendritic fracture increases. Next increase of testing temperature to 1450°C is accompanied by overall attenuation of boundaries and dendrites and their prevailing melting in. Before rupture of test bar there occurs an interdendritic fracture with almost zero contraction (Fig. 3). It follows from result of fractographic analyses that rupture behaviour of continuously cast slab is in the investigated temperature interval characterised by two extremes of contraction values: complete, total contraction under the solidus temperature (Fig. 2) and zero contraction, which occurs right before rupture of test bar in the area of co-existence of solid and liquid phases (Fig. 3).



- The distances between the samples 8.1, 8.2 and 8.3 are 200 mm
- Samples 8.3 – 8.8 were extracted consecutively
- The size of the samples represented by double numbers (i.e. number-point-number) were 41x20x45 mm
- The size of the samples represented by triple numbers (i.e. number-point-number-point-number) were 41x20x13 mm

Figure 1. A cracking corpus extraction schema and the sampling

Morphology of ruptures of steel with low carbon contents had already been investigated in dependence on their plastic characteristics up to temperatures of solidus by authors Longauerová et al. [5]. They mention three temperature areas of embrittlement in carbon steels. If we, however, proceed in direction of descending temperatures, we find the following areas: the first area of embrittlement of steel is in proximity of temperature of solidus, the second area of embrittlement is in high-temperature area of stable austenite (1200 to 900°C), the third area of embrittlement is in the interval of transformation of gamma to alpha, or alpha to gamma (900 to 600°C).

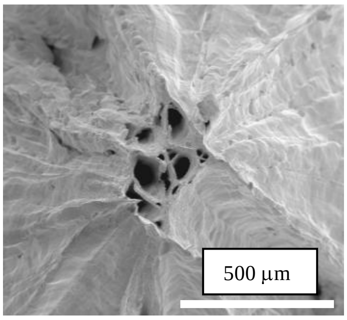


Figure 2. (slab A) Rupture at 1420°C, contraction 100 %.

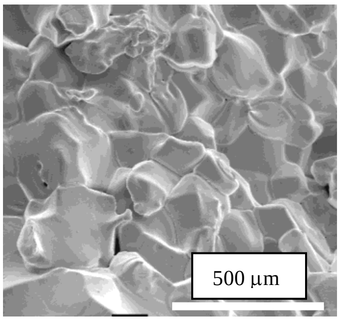


Figure 3. (slab A) Rupture at 1450 °C, contraction 0 %.

Presence of liquid films at interdendritic interfaces or at grains boundaries is given as cause of embrittlement in the first area. Embrittlement in the second area is caused mainly by precipitation of fine particles of sulfitic type, or other phases at grain boundaries. The following reasons are given as causes of embrittlement in the third area: formation of pro-eutectoid ferrite at boundaries of austenitic grains, shifting of grain boundaries, precipitation of secondary phase particles, etc.

Progress of rupture of continuously cast slab B with cross crack

Results of analyses of cross crack made after laboratory opening of the crack on its surface have proved that crack is propagated preferentially at dendrite boundaries [2]. It was ascertained that it nucleates in areas with increased zonal segregation of segregated elements, which are at the same time connected with presence of micro-shrinkages (Fig. 4). Legibility of fractographic photos taken from the surface of transverse crack is deteriorated due to oxidation of the rupture surface. It is, nevertheless, possible to find in relief signs of rupture along dendrite boundaries (Fig. 5), as well as signs of trans-crystalline ductile failure (Fig. 6). Interface of surface of original transverse crack and final rupture in laboratory made under liquid nitrogen (i.e. at temperature of approx. -196^{o}C) by brittle fracture, is shown in Fig.7.

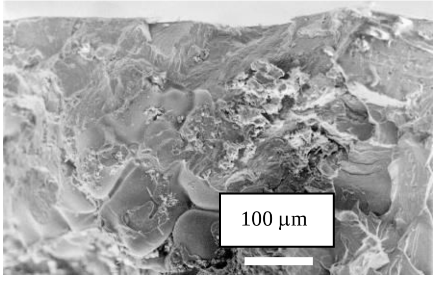


Figure 4. (B) Surface of cross crack with distinct micro-shrinkages.

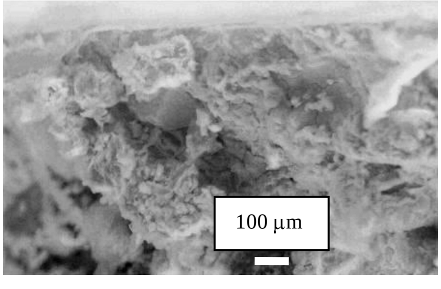


Figure 5. (B) Oxidised surface of cross crack with signs of development between dendrites.

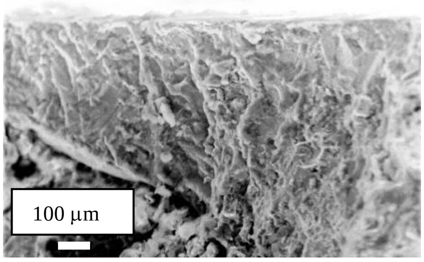


Figure 6. (B) Partly oxidised, ductile trans-crystalline fracture of cross crack.

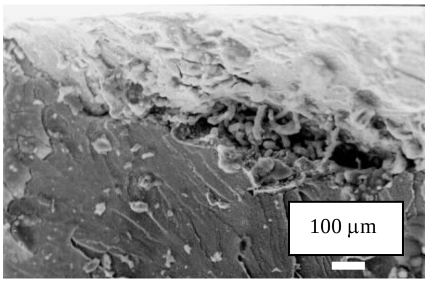


Figure 7. (B) Interface of trans-crystalline fracture of cross crack with brittle final fracture.

Afterwards on the basis of model of non-stationary temperature field for the slab B with transverse crack there were calculated durations of dwell of selected areas of slab between the temperature of liquidus and solidus, i.e. values of local time of solidification Θ. Calculation described e.g. in the work [6] was made for the top edge of the mold (10 mm from the top edge of the slab B with dimensions 1300x145 mm^2) and for the area of central part of the slab (72.5 mm also from the top edge of the same slab), in nodal points given in the Table 2. Due to the fact that dendrite arms spacing is a function of the local time of solidification [2], it is possible to establish that the coarsest dendritic structure of slabs is at the distance about 170 mm from the right edge.

Table 2. Values of local time of solidification Θ [s] calculated in nodal points of the slab B with cross crack.

Distance from the top edge [mm]		Distance from the right edge of the slab [mm]						
		650	530	410	290	170	50	10
10	Θ [s]	25.4	25.4	25.4	25.4	25.4	22.7	9.03
72.5	Θ [s]	341.8	347.2	354.8	355.0	372.9	217.7	12.3

DISCUSSION OF OBTAINED RESULTS – COMPARISON OF FRACTURES OF ANALYSED CAST SLABS

Seven characteristic surfaces were available for mutual comparison of morphology of fractures taken from surface of cross crack (slab B) after its opening in liquid nitrogen. These surfaces were afterwards compared with ruptures of the slab A obtained within the temperature range from 25 to 1450°C. Total set of 72 characteristic pictures of rupture relief were available. It was possible to draw the following conclusions on the basis of mutual comparison of micro-relief of rupture surface of cross crack on the slab B with micro-reliefs of rupture of the slab A:

a) On the rupture of cross crack of the slab B there have not been established any morphological signs, which characterise total contraction occurring on the bars from the slab A at the temperature from 1134°C to 1420°C (see Fig. 2). On the rupture of cross crack there have also been found no signs that are typical for a sharp drop of contraction of test bars taken from the slab A at temperature of 1423°C or also signs characteristic for a zero contraction, which accompanies ruptures of tensile test bars taken from the slab A at temperature of 1450°C (see Fig. 3). It is possible to exclude with high probability a possibility of initiation of cross crack within the given temperature range.

b) Identical signs of micro-reliefs of the cross crack surface of the slab B with micro-relief of ruptures of tensile test bars from the slab A were found on slab ruptures, which were torn at the temperature from 732°C to 988°C (see relief of ruptures in Figs. 4, 5, 6 and 7 from the surface of cross crack and relief of ruptures in Figs. 8 and 9 from tensile test specimen taken from the slab A). It is therefore possible to presume that initiation and subsequent propagation of transverse crack occurs with high probability within the temperature interval from 990 to 730°C. At temperatures below 730°C no identical signs of micro-relief and cross crack were fully reliably found.

c) During cooling of tensile test bars in the temperature interval from 990 to 730°C there occur the following values: work to rupture A from magnitude of approx. 5 J to 14 J, tensile force F from magnitude 1179 N to 2086 N, and also contraction Z from magnitude 11 % to the magnitude of 76 %. This means that there increases not only strength of slab material, but also its plasticity.

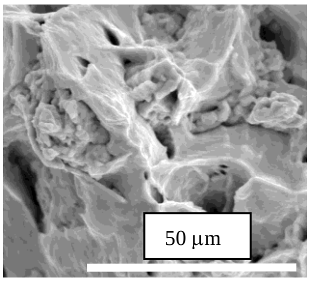


Figure 8: (A) Rupture at 732°C, contraction 76 %.

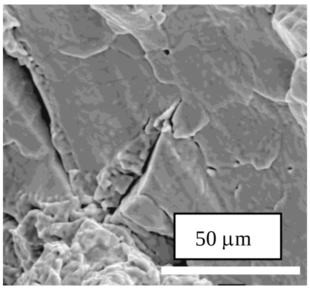


Figure 9: (A) Rupture at 988°C, contraction 11 %.

The preceding facts ensuing from comparison of ruptures demonstrate that initiation of cross crack can be expected in high-temperature area of stable austenite, i.e. in the second area of embrittlement, which is usually characterised by the temperature range from 1200 to 900°C. In our case it is possible to presume initiation of partial transverse crack rather at the temperature of 990°C, which is in case of test bars from the slab A characterised as absolutely the lowest work to rupture (A = 5 J, see tab. 1). With respect to discrete progress of cross crack (consisting of individual partial cracks), it is possible to assume that its initiation occurs in such points of the slab, which solidify as the last ones, have comparatively the most coarse dendritic structure and at the same time it is possible to expect in them higher frequency of shrinkage porosities and micro-shrinkages. Shrinkage porosities really do occur on the transverse crack surface (Fig. 4).

On the basis of analyses of ruptures and fractured surface of transverse crack it is possible to presume that progressive propagation of individual partial cracks and their mutual local inter-connection occurs in the second and third area of embrittlement. The third area of embrittlement is in the interval of transformation of iron gamma to alpha, i.e. in the interval from 900 to 600°C and it can comprise also eutectoid transformation. In our case it is possible to assume propagation of cross crack, connected with gradual inter-connection of individual partial cracks up to temperature of approx. 730°C. Below this temperature propagation of partial cracks and thus also their mutual inter-connection already stops. That’s why the second transverse crack is characterised even after complete cooling down of the slab to temperature of surrounding temperature by partial discontinuity. In spite of the fact that crack covers comparatively large surface of the central part of the slab, it is continuous only on larger parts of this surface (in other words – on smaller parts of surface it is discontinuous (discrete)).

CONCLUSION

On the basis of preceding considerations it is possible to reconstruct initiation and propagation of cross crack in continuously cast slab B in the following way:

1) Initiation of partial cracks occurred below temperature of 990°C, which is – according to analogy with fracture behaviour of the compared slab A – characterised by minimum work to rupture and at the same time by low plasticity.

2) Initiation of the first partial cracks has occurred with high probability in centre of the slab, in its right half (if we consider it from position against direction of movement of the slab in continuous casting machine = CCM) at the distance of 170 mm from its right edge. This area of the slab B is characterised by the coarsest dendritic structure, the longest interval of solidification between temperature of liquidus and solidus, and also the top of the solidification cone in this half of the slab (Tab. 2 in this study and Fig. 1 in [2]).

3) Initiation of next partial cracks occurred in direction towards the central part of the slab, and also in direction towards its right edge. Dendritic structure coarsening decreases in both directions. Coarsening of dendrites in direction towards the central part of the slab decreases slowly (tab. 2), that’s why initiation and other propagation of partial cracks occurred here more easily than in the opposite direction.

4) Refining of dendritic structure in direction to the right edge of the slab (Table 1) has lead to substantial decrease of probability of initiation of partial cracks and their further propagation subsequently also stopped approx. 60 mm from the slab edge.

5) Initiation of partial cracks was supported by existence of micro-shrinkages and internal state of stress, when direction of main stresses was perpendicular to the cross (transverse) crack, the extent of which kept growing, which was, however, only partly inter-connected.

6) Progressive propagation of partial cracks, connected with their partial interconnection occurred during cooling of the slab down to the temperature of approx. 730°C, when there occurred a complete braking of their further propagation, and the size and position of cracks were stabilised up to ambient temperature.

7) It also follow from this study that with use of the model of non-stationary temperature field it is possible in connection with the model of chemical heterogeneity to determine size (coarsening) of dendritic structure.

8) In the given case it is possible to assume that segregation together with high local concentration manganese gradient (the concentration of which on surface of transverse crack was measured at the same time as the highest – 3.31wt% [2]), was the factor that had influenced growth of dendrites.

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