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A NOVEL APPROACH FOR THE SIMULATION OF SURFACE CRACKS FORMATION IN CONTINUOUS CASTING

Abstract

The present study describes the possibilities of new experimental and numerical methods to predict the crack susceptibility under continuous casting (CC) conditions. The first method – the In-Situ Material Characterization by Bending (IMC-B) Experiment allows measuring of the critical strain values for surface defects upon all the most important process and material parameters. The IMC-B experiment uses solidified samples obtained directly from the melt and it is based on the 3-point bending test. Hence the material and process parameters are similar to CC. Strains are calculated directly after the experiment uses a simulation in Abaqus. The risk of surface cracks is provided using the new numerical tool, so-called defect indices implemented in IDS. In the framework of practical series a crack susceptibility of the commercial Nb-microalloyed steel is investigated after the subsequent cooling to the test temperature. The test temperature corresponds to the temperature at the beginning of straightening zone in cc. Samples cast at two different cooling conditions show another distribution of surface defects and critical strain value.

Keywords

IMC-B, continuous casting, surface cracks, surface defects, bending test, second ductility trough, IDS, defect indices

1. Introduction

Surface cracks are one of the most common surface defects in the CC of steel. This kind of cracks can form in the all of the cast steel grades. However, some of them like high alloyed or micro-alloyed steels are very sensitive to crack formation. Surface defects such as transverse cracks form initially in the early stage of solidification in the mould, often at the bottom of oscillation marks and propagate during slab bending and/or unbending in the critical temperature range, when the tensile strains on the slab surface reach the critical limit. The tensile strain at the slab surface during bending/unbending is approximately 1-2% [1] and are even higher at the bottom of the oscillations marks. This value is high enough for surface crack formation, if the bending/unbending process takes place in the critical temperature range. The reason for the building of surface cracks is a drop in the steel ductility due to the precipitation of carbon-nitrides and the formation of ferrite film along the austenite grain size. The risk of the surface cracks increase dramatically as a result of these phenomena.

Beside the knowledge about the mechanism of surface cracks, the prediction of the risk of cracking is still a challenge. Over the last 40 years many researchers have worked on different experimental methods to investigate crack susceptibility under CC conditions. Most of them are based upon hot compression [2], hot bending [3-5] or hot tensile tests [6]. However none of them allow investigating the critical strains on surface crack formation using all of the parameters typical for the CC process. These methods are only useful to predict the critical temperature range. This information is however still limited due to differences between the execution of these methods and real CC process. The prediction of the risk of surface cracks is especially difficult at high temperatures even using the most popular hot tensile test. Recrystalization in high temperatures increases the ductility of hot tensile samples and therefore the steel in this temperature range seems not to be sensitive to the crack formation. These results are in contrast to results from practical observation: cracks can be formed on the slab surface at a temperature above 1000 °C; even the ductility of hot tensile samples is very high. Moreover recrystalization is unusual in the CC process. Critical strains measured by the hot tensile test are also several times higher than at the slab surface by bending/unbending operations. The information regarding critical strains can be crucial for planning new CC machines. Therefore it is necessary to develop new experimental and numerical methods to predict the risk of surface cracks under cc conditions based on the critical strain values. This paper describes possibilities and first results of the In-Situ Material Characterization by Bending Experiment (IMC-B) and defect indices implemented in IDS – two powerful tools to investigate the crack susceptibility under cc conditions.

2. Motivation and characteristic features of the IMC-B experiment

The IMC-B experiment has been developed since 2009 at the Chair of Ferrous Metallurgy with the cooperation of industrial partners Siemens VAI and voestalpine Stahl. Since 2013 this experiment has further been used in the 2nd phase of COMET Program: “Application of computational thermodynamics and defect models to establish quality criteria for continuously cast steels”. The basic motivation for the development of the IMC-B experiment is the determination of critical strain values to the surface crack formation under conditions close to the CC process. It is also important to obtain more reliable information about the sensibility of slabs for crack formation. The IMC-B method is characterized according to the following features:

- Controlled solidification of the sample.
- Grain growth according to simulated continuous casting process.
- Sample includes solidification defects e.g. micropores.
- Controlled cooling to testing temperature, similar to cc conditions.
- Bending test at strain rate equivalent to the continuous casting process.
- Range of the applied tensile strain to values below few percent.
- Prevention of recrystallization during the test.
- Determination of critical strain values.

3. Performance o the IMC-B experiment

The IMC-B experiment consists of three steps (Fig.1):

- Steel melting in an induction furnace and production of a sample in the dimensions 180x60x23 mm by casting in the special mold.
- Mold opening, samples cooled in air and subsequent cooling or holding in the heat treatment furnace.
- Further cooling in the second heat treatment furnace, bending test in this furnace with subsequent immediate sample's quenching into the water. The experiment is performed with the defined stamp way and a constant strain rate. The tensile strains are calculated from a FE-simulation of the bending experiment in Abaqus.

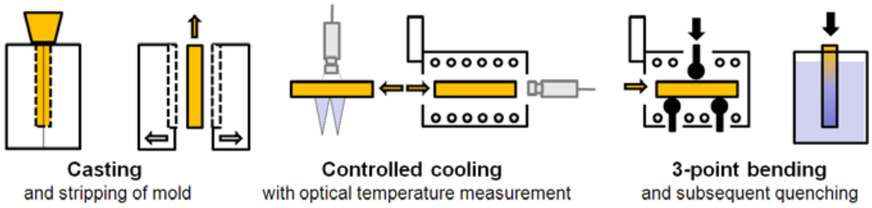

Fig. 1 Performing of the IMC-B experiment [7]

4. Numerical simulations

A simple 2D Model (coupled temperature-displacement) in Abaqus is used to calculate the tensile strain during the process. The maximum plastic strain in the x-direction is taken as a reference value for each experiment. The distance between stamps, sample thickness and temperature are according to the simulated hot bending test. Fig.2 presents an example of the simulation with the materials properties of the sample used for this calculation. Materials properties are calculated using JMat Pro and IDS. The stamps for the hot bending apparatus were made from a heat resistant steel – Böhler H525. The input parameters for stamps are taken from the same steel grade.

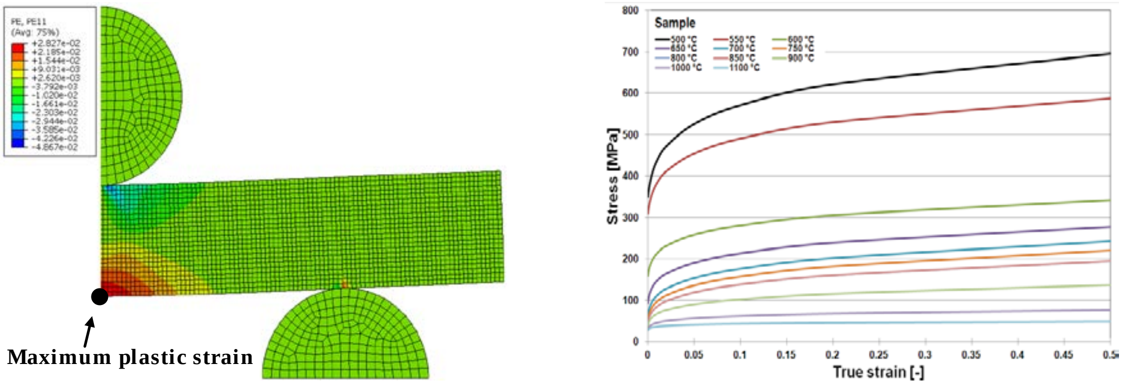

Fig. 2 (a) – An example of the simulated hot bending, stamp way occurs 1 mm; (b) – stress-strain curves for the sample

5. Defect indices

Defect indices are implemented in IDS to predict the risk of surface cracking. This numerical tool has been developed at the Aalto University. Defect indices reach values between 0 and 1. With increasing value, the possibility of surface cracks rises. Defect indices consider the influence of parameters at the cracks formation in similar equations. Defect indices having the major influence at the surface cracks are introduced below [8]:

- QI_{GRA} - considers the influence of composition, deformation by bending and straightening on austenite grains:

$$QI_{GRA} = 1 - \exp\left[-(C \cdot \frac{D^{\gamma}_{GRA}}{3300})^2\right] \tag{1}$$

$$C = \exp(\nu^{0.2}) \tag{2}$$

- QI_{COM} - considers the influence of precipitations:

$$QI_{COM} = 1 - \exp\left[-1000 \cdot (\sum f_k^C - \sum f_k^{C,S}) \cdot \frac{dT}{dt}\right] \tag{3}$$

- QI_{DIP} - considers the influence of deformation induced ferrite:

$$QI_{DIP} = 1 - \exp\left[-A \cdot (f^{ROD})^2 / (f^{ADC})^{1.5}\right] \tag{4}$$

where:

D^{γ}_{GRA} - is the as-cast austenite grain size (μm) calculated with IDS model; ν - is the rate of strains caused by the bending or unbending processes; Σf^{C}_{k} - is the sum of the fractions of all precipitates at temperature T; $\Sigma f^{C,S}_{k}$ - is the corresponding sum of those fractions at the solidus; f^{ADC} - is the fraction of decomposed austenite at temperature T; f^{ROD} - is the fraction of austenite decomposition above which one can assume recovered ductility; A - is a coefficient defined as $A=10 \cdot (f^{DIP}/f^{ROD})^{0.5}$

An example of the possibility of defect indices is shown in the Fig.3. The example shows the results of calculation on commercial continuous casting process with Nb – micro-alloyed steel. The bending strain in the straightening zone occurred 2 %. Results show that the risk of cracks due to deformation inducted ferrite increase significantly in the straightening zone. Steel are not sensitive on the surface defects due to precipitations and austenite grains in these case. NbC and MnS precipitations increase the risk of cracks only up to 0.3. The defect indices are still under the developing.

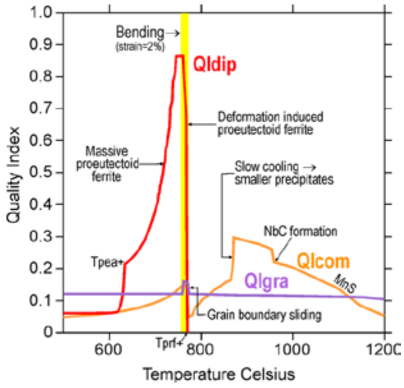

Fig. 3 Influence of parameters on the defect indices

6. Experimental procedure

The aim of the experiments was the investigation of critical limits to the surface crack formation of commercial Nb-microalloyed steel cast by voestalpnie Stahl. The basic steel composition is shown in the Table 1. Samples were produced in the mold and cooled in two different cooling strategies (hard and soft cooling strategy) and subsequent bend in the hot bending test in the temperature of the beginning of straightening zone. The difference between two of these strategies was another cooling intensively. Samples cooled in the hard cooling strategies were cooled harder in comparable to those cooled in the second strategy (Fig. 4). The crack susceptibility was investigated by simulating the cooling conditions on the slab wide side as well as at the corner range in both cooling strategies. Additionally a risk of crack was tested between both of these temperatures. The test temperature varied between 760 °C and 960 °C.

C	Si	Mn	P	Al	Nb	N	Fe
0.17	0.43	1.54	0.015	0.03	0.017	0.004	Rest

Table 1 Chemical composition of investigated steel grades, in mass-%

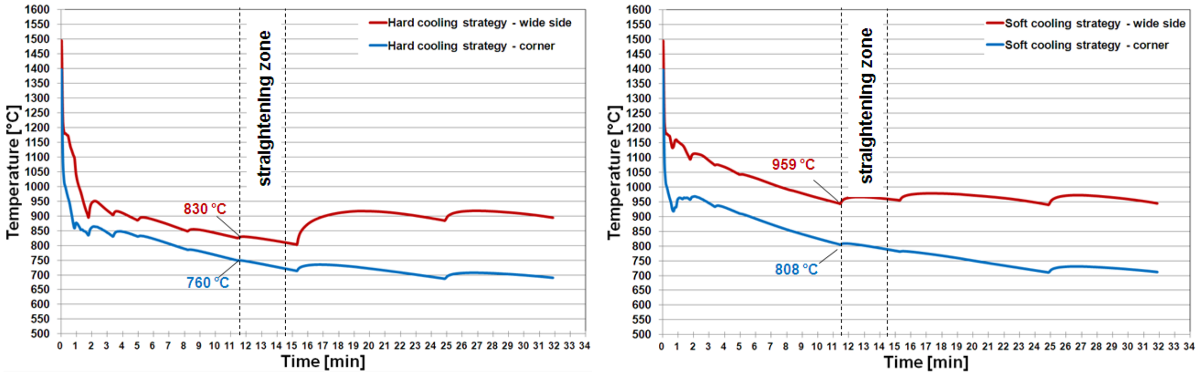

Fig. 4 Two calculated secondary cooling strategies, bending test at the beginning of straightening temperature, slab 225 mm, casting speed 1.2 m/min

A total number of fifteen experiments were performed: seven – for the simulation of crack formation under hard cooling strategy and eight – for soft cooling strategy. For each experiment the casting temperature was adjusted to 1620 °C. After a definite solidification time corresponding to the temperature of the mold exit in CC, samples were taken from the mold and cooled down in the air to a temperature between 860 °C and 1100 °C (depending on the cooling strategy). Then the samples were placed in a first heat treatment furnace and kept at constant temperature for 2 minutes. The samples were subsequently placed in a second furnace and cooled down to bending temperature. Afterwards samples were placed in the bending apparatus. The bending tests were performed with a different stamp way yet constant strain rate of $7.25*10^{-4}$ s^{-1}. The stamp way was between 0 and 3 mm. The corresponding strains were calculated with the model in Abaqus.

7. Results and discussion

Fig.5 shows one calculated cooling curve and two examples of experimental cooling curves from the test series with corresponding steps of performing of experiments. The experimental results are closely to the calculated data. This dependency is also similar in all another experiments.

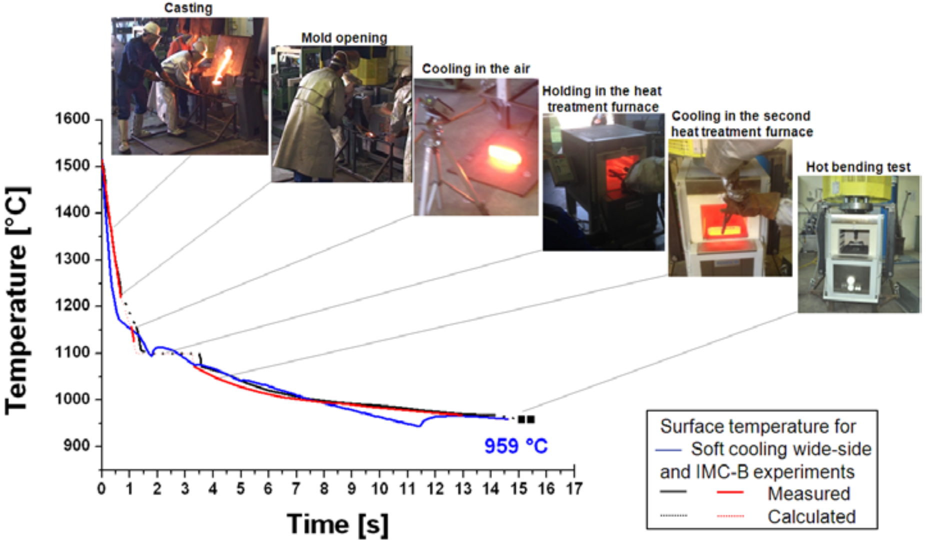

Fig. 5 Comparison of the calculated and experimental results of the simulations of IMC-B experiment under the soft cooling strategy on the wide-side of the slab [7]

The sample quality before the bending test was investigated in detail. Sample was bent under the hard cooling strategy on the corner and subsequent quenched into the water. The sample has typical cast structure with micropores. There were no thermal cracks found on the sample's surface.

The austenite grains were measured along the sample. Corners were marked and their areas were calculated using the program Clemex. After the calculation areas was recalculated on the diameters of grains. The mean value of austenite grains is found to be 0.88 mm. Fig.6 shows the investigated sample test with measurement position, investigated austenite grains and distribution of corners. The simulation of grain growth using the modified Andersen and Grong equation show the similar result [9-10].

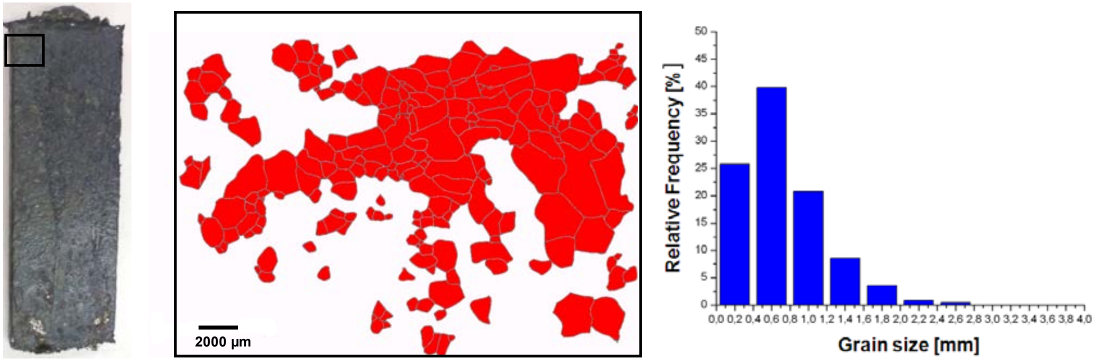

Fig. 6 (a) Sample with the measurement area, (b) corners and (c) their distribution

Fig. 7 presents the correlation between the maximum of calculated plastic strain and corresponding bending temperature.

Samples bent with the stamp movement between 1 mm and 3 mm is shown on the right side of the picture. Samples with and without cracks are marked with red and green color respectively. The results show that in the temperature below 830 °C the first cracks are visible under strains of 1.24 %. At a temperature of 830 °C steel seems not to be susceptible to surface cracks. The first cracks are formed with a plastic strain of 4.2 %.

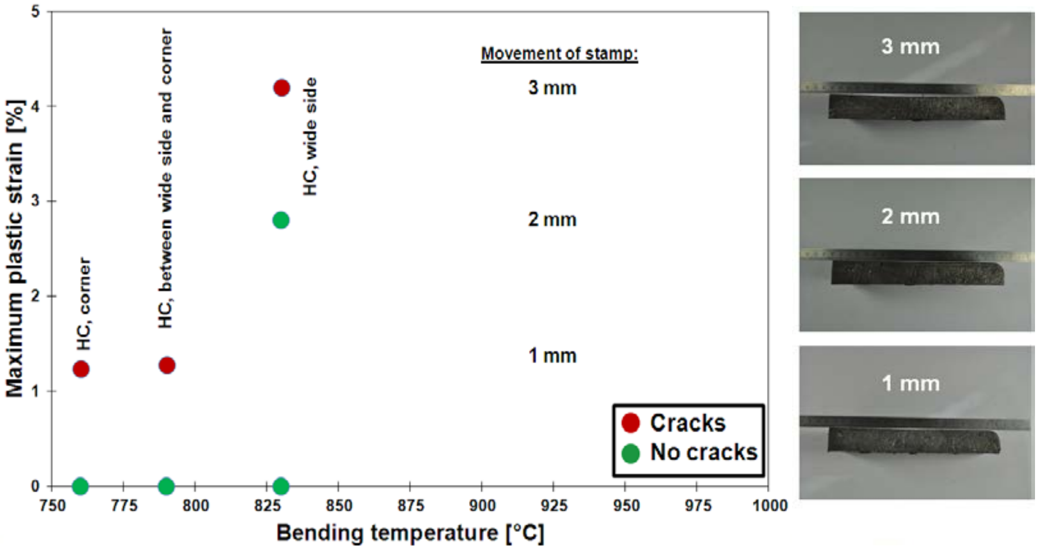

Fig. 7 (a) - The dependency between maximum plastic strain, calculated in Abaqus, and bending temperature, for experiments cooled under the hard cooling strategy; (b) – pictures with samples bent with different stamp way

The number and distribution of surface cracks on the two samples are compared in Fig.8. The positions of cracks were marked in the range of 80 mm of each of the sample using the stereo microscope. A sample bent in the temperature of 760 °C with the total number of nine cracks is very sensitive to surface cracks. In the second case the sample shows only few surface cracks. These cracks have also a shorter length. The metallographic investigation shows that cracks are intercrystalline type with the thin ferrite film at the surface. The thickness of ferrite film occurs between 2 µm and 4 µm, depending from the test temperature. Typical cracks found in these samples are shown in Fig.9.

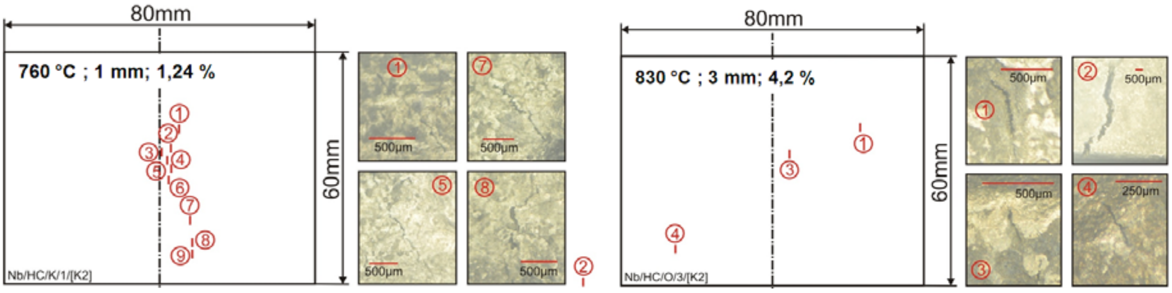

Fig. 8 Distribution of cracks at sample’s surface bent with the maximum of plastic strain of 1.24% at 760 °C and 4.2 % at 830 °C

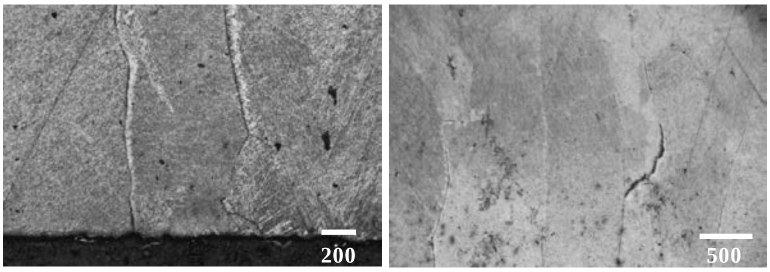

Fig. 9 Intercrystalline cracks at sample surface, nital etching

The results on the soft cooling strategy and bending temperature on the maximum plastic strain are put together with the results from investigation on hard cooling strategy (Fig.10). Samples bent after cooling in this strategy are very sensitive to the surface cracks. The results in 960 °C show that cracks form under tensile strain ≤ 1.34 %. A sample bent in the maximal strain of 2.95 % in this temperature shows more cracks at the surface than in the first one.

Cracks are both intercrystalline and transcrystalline (Fig.11).

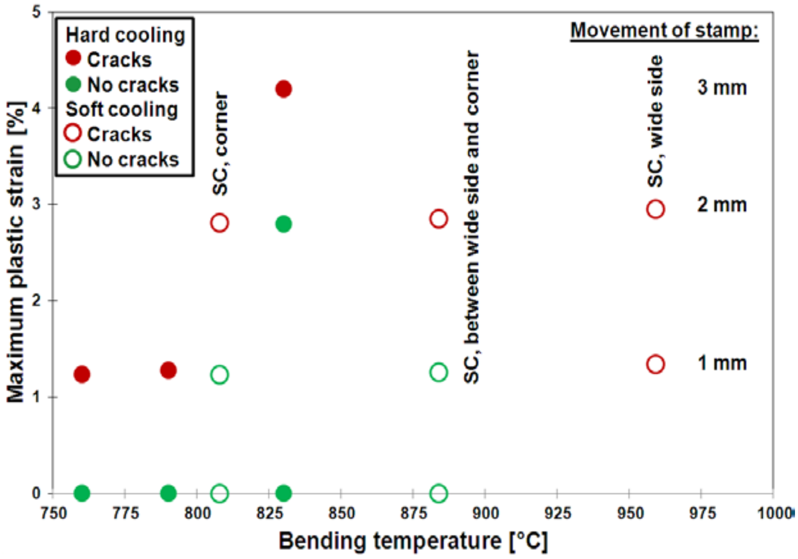

Fig. 10 Summary of investigation of surface cracks formation in hard and soft cooling strategy

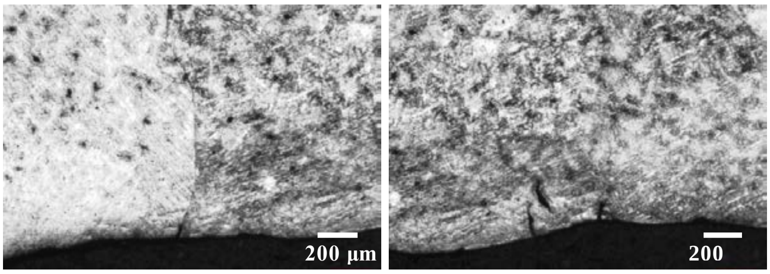

Fig. 11 Intercrystalline (a) und transcrystalline cracks at the samples bent in 960 °C, nital etching

Fig.10 shows an interesting correlation: using the IMC-B Experiment is the first time possible to measure critical strains to the surface cracks formation in the strain smaller than 1.24 %. Any another experiment described in the literature doesn't allow measuring so small critical strains.

8. Summary

This paper summarizes the results of an investigation of crack susceptibility in the straightening zone using the new IMC-B experiment. Fifteen samples from Nb - micro-alloyed steel produced and cold under two different cooling strategies to the test temperatures. Ten of them were bent with the maximum plastic strain between 1.24 % and 4.2 %. The bending temperatures were validated between 760 °C and 960 °C.

Samples bent under hard cooling strategy show critical strains as small as 1.24 % in the temperature below 830 °C. The investigated steel seems not to be susceptible to surface cracks at 830 °C. In comparison to these results, samples cooled under the soft cooling strategy are very susceptible to surface cracks at a temperature of 960 °C. The critical strain at this temperature is smaller or equal to 1.34 %. The metallographic observation shows that the samples include micropores and similar grain structure to those from CC. Samples show different amounts and distributions of cracks, depending on the test temperatures and the strain values respectively. There was no recrystallization in bending samples. The critical strain on the surface cracks was similar to those from the CC process. The defect indices implemented in IDS allow predicting the risk of surface cracks in CC. The first results are very promising: the risk of the surface defects in this particular case is the highest due to the formation of ferrite film under the temperature of 800 °C. The defect indices will be further developed and experimental checked.

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