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A Novel Approach for the Simulation of Surface Crack Formation in Continuous Casting

Pawel Krajewski[1], Roman Krobath[1], Christian Bernhard[1], Jyrki Miettinen[2], Seppo Louhenkilpi[2], Sergiu Ilie[3] and Thomas Schaden[4]

[1]Chair of Ferrous Metallurgy, Montanuniversität Leoben, Leoben, Austria
[2]Aalto University, Espoo, Finland
[3]voestalpine Stahl GmbH, Linz, Austria
[4]Siemens VAI Metals Technologies GmbH, Linz, Austria

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Abstract: The present study describes the possibilities of new experimental and numerical methods to predict the crack susceptibility of steels under continuous casting (CC) conditions. The first method—the In-Situ Material Characterization by Bending (IMC-B) Experiment allows measuring 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 is based on the 3-point bending test. Strains are calculated directly after the experiment has used a simulation in Abaqus. The risk of surface cracks is shown by 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. Samples cast at two different cooling conditions show another distribution of surface defects and critical strain value.

Keywords: IMC-B, Bending test, Surface cracks, Continuous casting

Ein neuer Ansatz für die Simulation der Oberflächenrissbildung beim Stranggießen

Zusammenfassung: Die vorliegende Publikation beschreibt neue Methoden der experimentellen und numerischen Prognose der Rissanfälligkeit von Stählen unter Stranggießbedingungen. Die erste Methode – In-Situ Material Characterization by Bending (IMC-B) – ermöglicht während des Biegeversuchs die Messung der kritischen Dehnungen zur Oberflächenrissbildung unter den wichtigsten Prozess- und Materialparametern. Der IMC-B Versuch basiert auf dem 3-Punkt Biegeversuch unter Verwendung einer direkt aus der Schmelze erstarrten Probe. Die Dehnungen werden direkt nach dem Experiment mit Hilfe von Abaqus berechnet. Die Gefahr der Rissbildung ist durch numerische Simulationen, mit sogenannten Defekt Indizes, dargestellt. Diese Defekt Indizes sind in IDS implementiert. Im Rahmen der Versuchsserie wird die Rissanfälligkeit eines Nb-mikrolegierten Stahls nach der anschließenden Abkühlung bis auf Raumtemperatur untersucht. Die bei zwei unterschiedlichen Abkühlbedingungen gegossenen Proben zeigen eine andere Verteilung der Oberflächenrisse sowie unterschiedliche kritische Dehnungswerte.

Schlüsselwörter: IMC-B, Biegeversuch, Oberflächenrisse, Stranggießprozess

1. Introduction

Surface cracks are one of the most common 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 alloys or micro-alloyed steel, are more sensitive to crack formation compared to other steel grades.

To some extent surface cracks are already formed during initial solidification but mainly during and after secondary cooling or during the straightening process.

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 [1], hot bending [2–4], or hot tensile tests [5].

The quantification of the hot ductility of steels by means of the measured reduction of area (RA) and the adjustment of the secondary cooling in order to avoid the usu-

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Dipl. -Ing. Dr. mont. P. Krajewski (✉)
Chair of Ferrous Metallurgy, Montanuniversität Leoben,
Franz-Josef-Straße 18,
8700 Leoben, Austria
e-mail: Pawel.Krajewski@unileoben.ac.at

ally observed and so-called second ductility trough is the dominating strategy of today to avoid transverse surface cracks. Regardless of the success of this strategy, some limitations exist: The prediction of critical strain values from RA is delicate and, in addition the elongation to fracture in a tensile experiment, exceeds the maximum tensile strain at the surface of the strand in the CC process by an order of magnitude. Thus, effects like recrystallization and strain induced precipitation as well as strain induced phase transformations influence the measured RA.

Within the framework of a K2-MPPE project at the Materials Center Leoben, the Chair of Ferrous Metallurgy in collaboration with Siemens VAI Metals Technologies, and voestalpine Stahl started to develop an experimental setup for the in-situ bending of samples after solidification and subsequent controlled cooling. The bending parameters like strain rate and maximum strain are adjusted to the unbending in CC. The metallographic observation of the samples finally permits the definition of a critical strain to avoid surface defects. The method and also some first experimental results are presented further on.

2. Motivation and Characteristic Features of the IMC-B Experiment

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 CC 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 CC 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 of the IMC-B Experiment

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

- Step 1: Steel melting in an induction furnace and production of a sample in the dimensions 180 × 60 × 23 mm by casting in the special mold.
- Step 2: Mold opening, samples cooled in air and subsequent cooling or holding in the heat treatment furnace.
- Step 3: 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.

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, the sample thickness, and temperature are according to the simulated hot bending test. Figure 2 presents an example of the simulation with the material properties of the sample used for this calculation. Material 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.

5. Defect Indices

Defect indices are implemented in IDS to predict the risk of surface cracking. This numerical tool has been developed at 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 [7]:

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

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

$$C = \exp(v^{0.2}) \qquad (2)$$

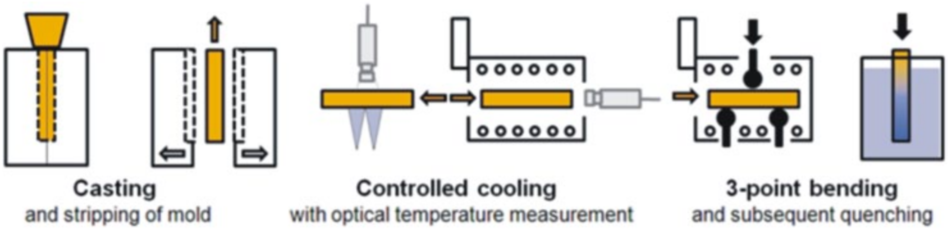


Fig. 1: Performing of the IMC-B experiment [6]

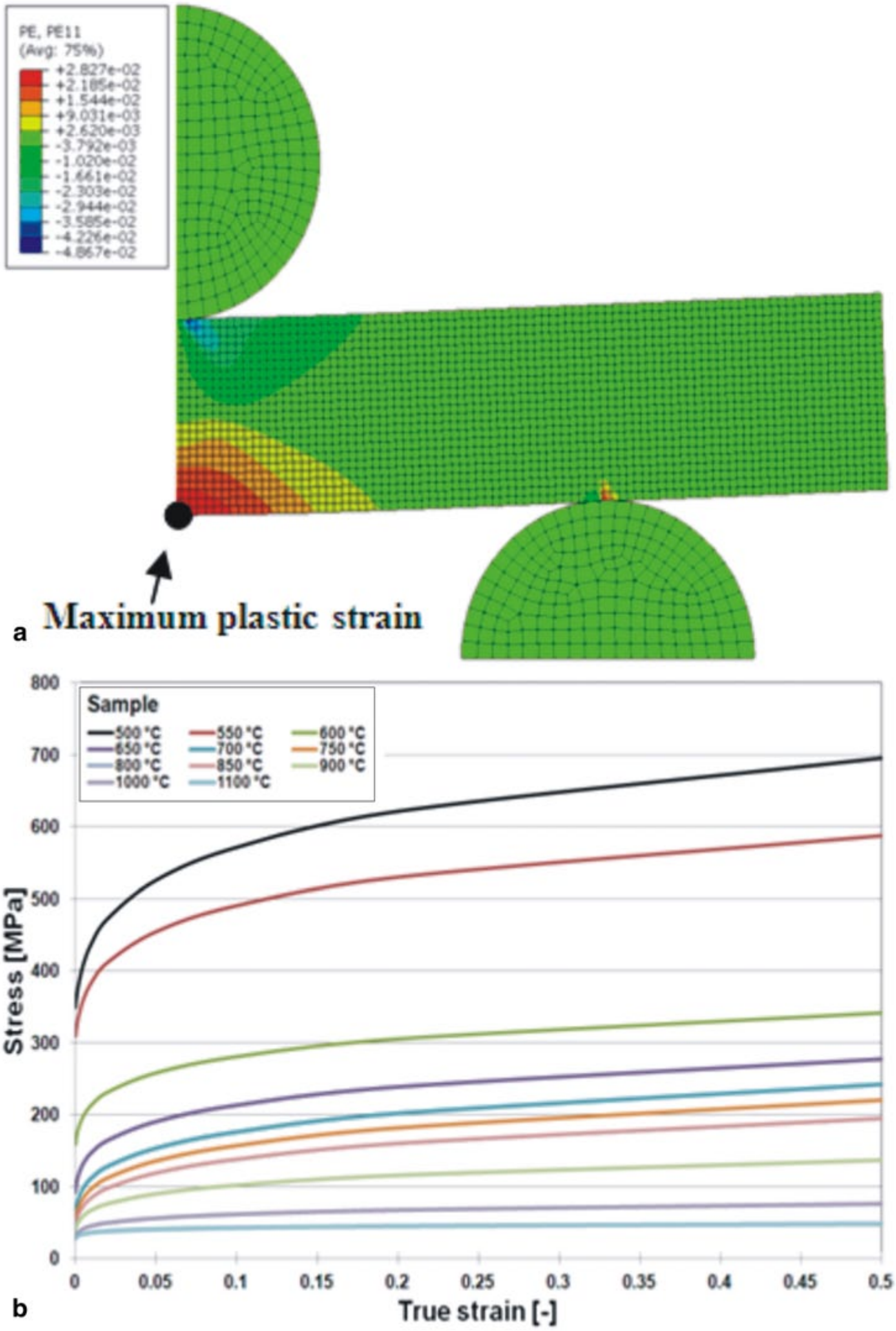


Fig. 2: (**a**) An example of the simulated hot bending, stamp way occurs 1 mm; (**b**) stress-strain curves for the sample

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

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

- 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; $\Sigma f^{C}{}_{k}$—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 $A = 10 \cdot (f^{DIP} / f^{ROD})^{0.5}$

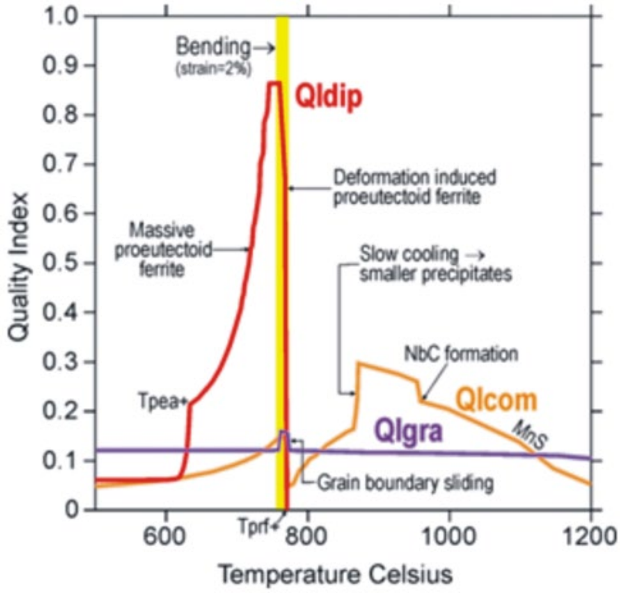


Fig. 3: Influence of parameters on the defect indices

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

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 voestalpine Stahl. The basic steel composition is shown in Table 1. Samples were produced in the mold and cooled using two different cooling strategies (hard and soft cooling strategies) and subsequently bent in the hot bending test at the temperature of the beginning of straightening zone. The difference between two of these strategies was another intensive cooling. Samples cooled using the hard cooling strategies were cooled harder in comparison to those cooled with 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.

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

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

In total, fifteen experiments were performed: seven—for the simulation of crack formation using the hard cooling strategy, and eight—using the 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 min. The samples were subsequently placed in a second furnace and cooled down to bending temperature. Afterwards the samples were placed in the bending apparatus. The bending tests were performed with a different stamp way but with a 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

Figure 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.

The sample quality before the bending test was investigated in detail. The sample was bent with the hard cooling strategy on the corner and subsequently quenched into the water. The sample has the typical cast structure with micropores. 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 the area was recalculated on the diameters of grains. The mean value of austenite grains is found to be 0.88 mm. Figure 6 shows the investigated sample test with measurement position, the investigated austenite grains, and distribution of corners. The simulation of grain growth using the modified Andersen and Grong equation shows a similar result [8, 9].

Figure 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 are shown on the right of the picture. Samples with and without cracks are marked in red and green 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, the steel does not seem to be susceptible to surface cracks. The first cracks are formed with a plastic strain of 4.2 %.

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

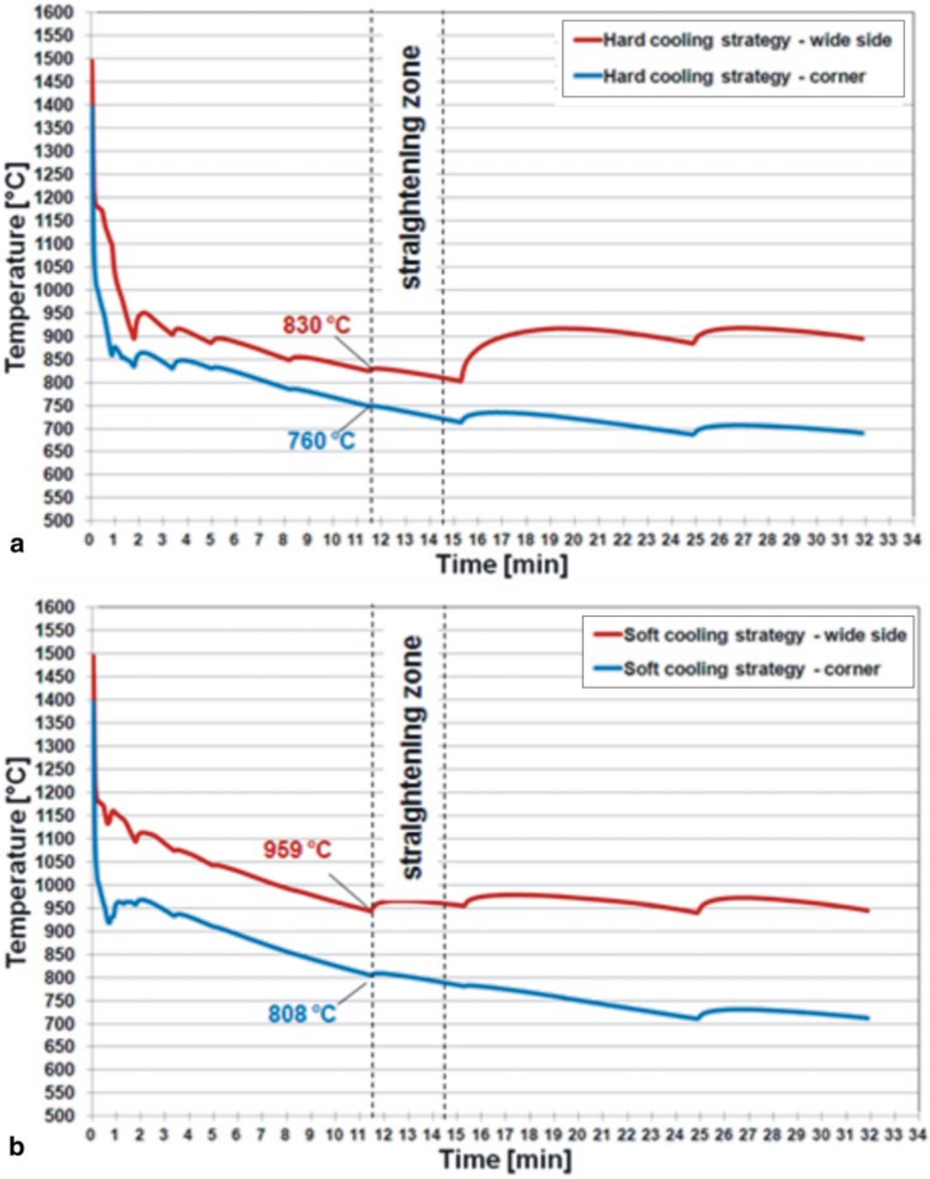


Fig. 4: Two calculated secondary cooling strategies, bending test at the beginning of straightening temperature, slab 225 mm, casting speed 1.2 m/min

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 of intercrystalline type with a thin ferrite film at the surface. The thickness of the ferrite film ranges between 2 µm and 4 µm, depending on the test temperature. Typical cracks found in these samples are shown in Fig. 9.

The results on the soft cooling strategy and bending temperature on the maximum plastic strain are put together with the results from the investigation on the hard cooling strategy (Fig. 10). Samples bent after cooling in this strategy are very sensitive to the surface cracks. The results of 960 °C show that cracks form under tensile strain ≤ 1.34 %. Cracks are both intercrystalline and transcrystalline (Fig. 11).

Figure 10 shows an interesting correlation: by using the IMC-B Experiment, it is possible for the first time to measure critical strains to the surface cracks formation in the strain smaller than 1.24 %. No other experiment described in the literature allows a measurement of 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—microalloyed steel produced and cooled by using two different cooling strategies to the test temperatures. Ten samples were bent with the maximum plastic strain between 1.24 % and 4.2 %. The bending temperatures were validated between 760 °C and 960 °C.

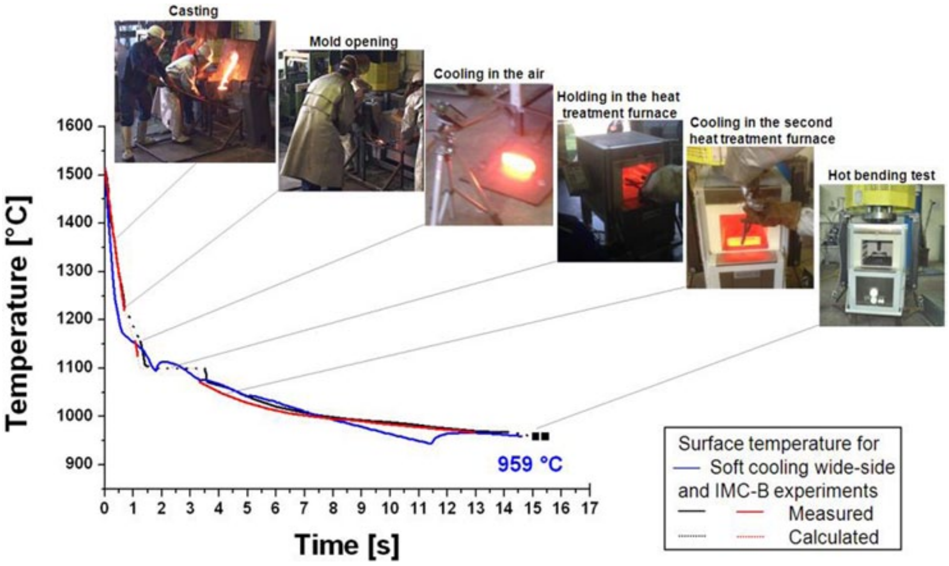


Fig. 5: Comparison of the calculated and experimental results of the simulations of IMC-B experiment under the soft cooling strategy on the wide-side of the slab [6]

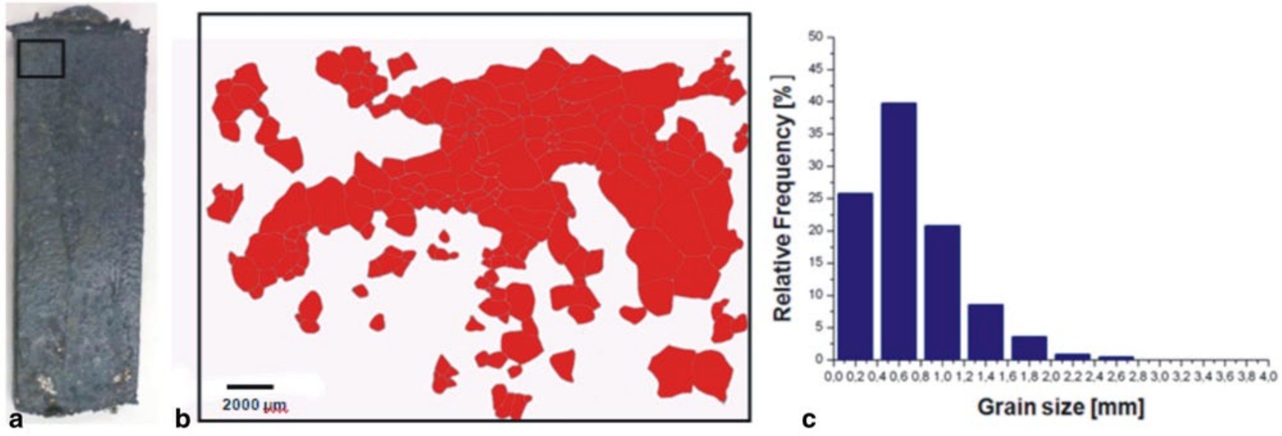


Fig. 6: (**a**) Sample with the measurement area, (**b**) corners, and (**c**) their distribution

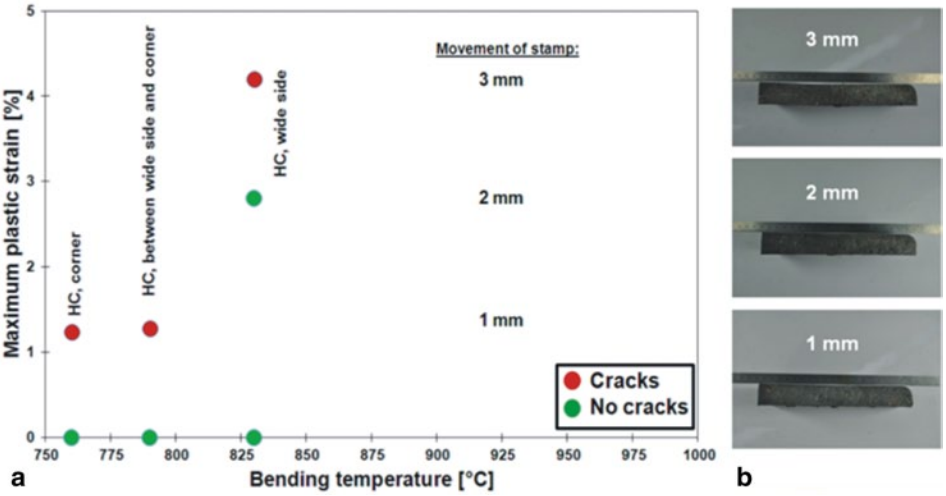


Fig. 7: (**a**) The dependency between maximum plastic strain, calculated in Abaqus, and bending temperature, for experiments cooled under the hard cooling strategy; (**b**) pictures with samples bent with different stamp way

Samples bent using the hard cooling strategy show critical strains as small as 1.24 % in the temperature below 830 °C. The investigated steel does not seem to be susceptible to surface cracks at 830 °C. In comparison to these results, samples cooled using the soft cooling strategy are very susceptible to surface cracks at a tem-

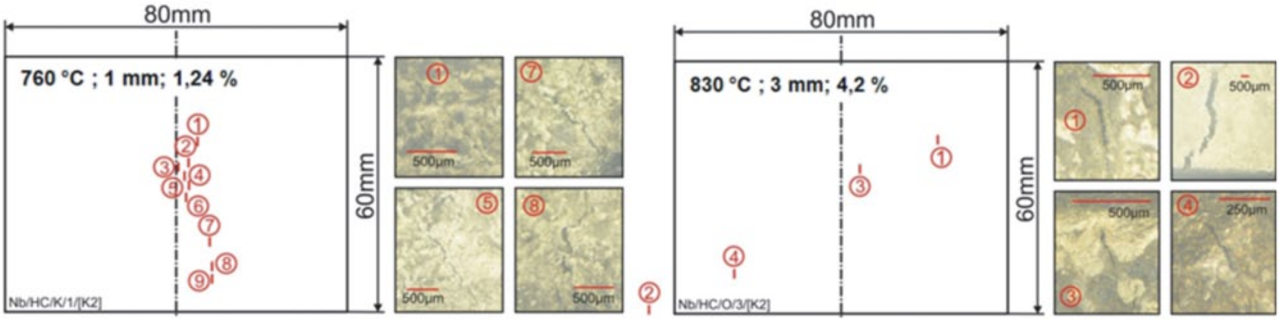


Fig. 8: Distribution of cracks at sample's surface bent with the maximum of plastic strain of 1.24 % at 760 °C and 4.2 % at 830°C

Fig. 9: Intercrystalline cracks at sample surface, nital etching

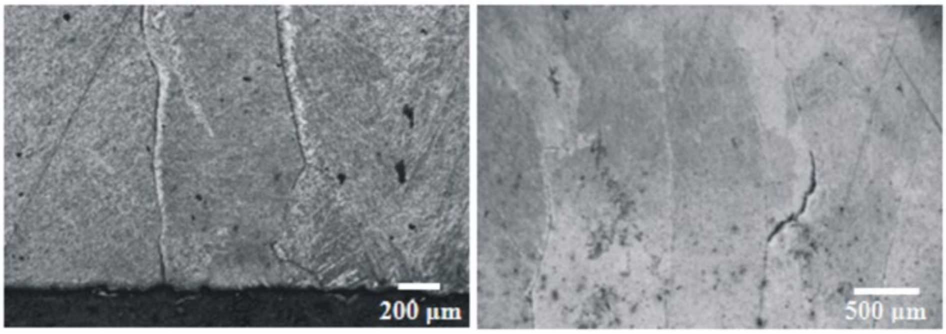
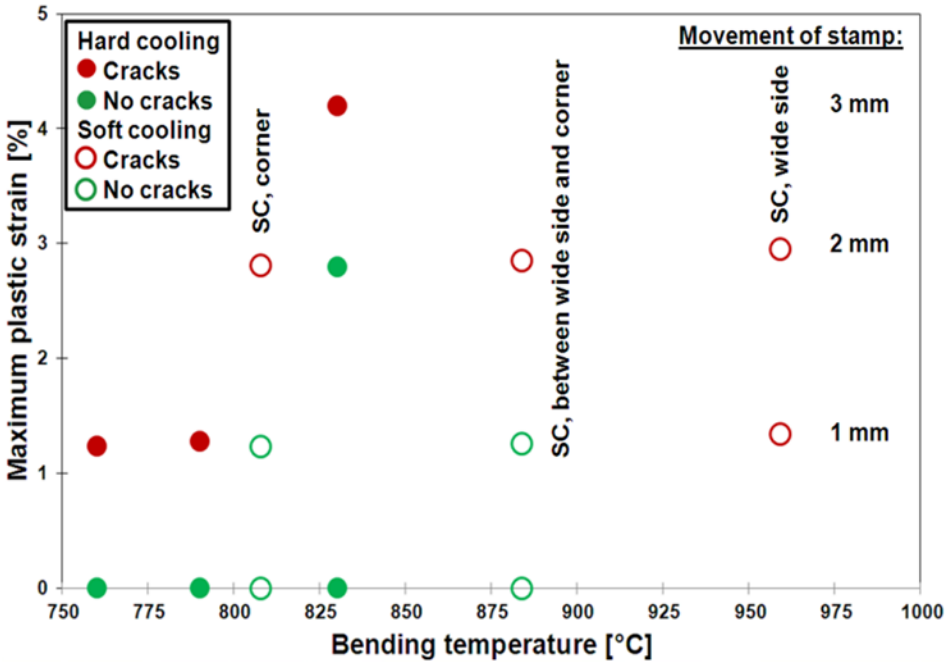


Fig. 10: Summary of investigation of surface cracks formation in hard and soft cooling strategy



perature 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

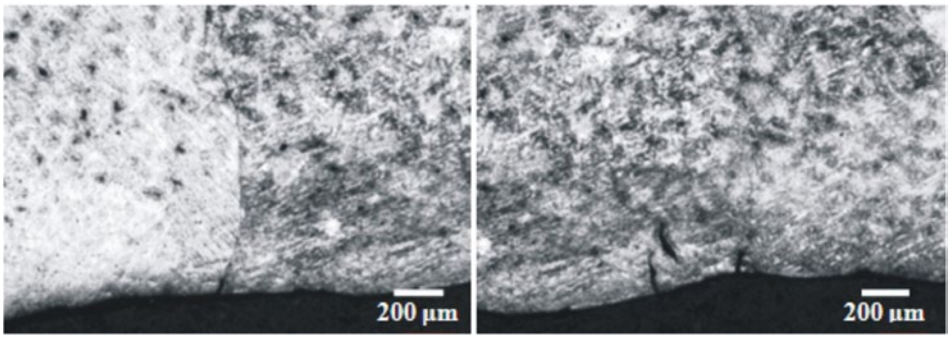


Fig. 11: Intercrystalline (**a**) und transcrystalline (**b**) cracks at the samples bent in 960 °C, nital etching

under the temperature of 800 °C. The defect indices will be further developed and experimentally checked.

9. Acknowledgements

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