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# The Role of Grain Boundary Oxidation on Surface Crack Formation under Continuous Casting Conditions

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**Abstract:** This paper represents an extended abstract of a study presented at the ESTAD 2019 conference. In this contribution, the influence of different cooling strategies on the formation of intergranular surface cracks is observed with in-situ bending experiments under continuous casting conditions. The steel composition is equal to a 0.17 wt.% C construction steel. It is investigated with and without Al deoxidation at bending temperatures of 1100 °C to 700 °C. The results show the most critical situation prevailed for each testing condition at 900 °C. A holding temperature of 1200 °C leads to a selective grain boundary oxidation and therefore to the formation of notches at the austenite grain boundaries, which are the cause for stress concentrations and easier formation of cracks during a subsequent tensile deformation at critical temperatures. The experiments reveal a partially stronger influence of this phenomenon on the steel without Al deoxidation.

**Keywords:** Continuous casting, Surface cracks, Grain boundary oxidation, In-situ bending test

**Die Rolle von Korngrenzenoxidation auf die Oberflächenrissbildung unter Stranggießbedingungen**

**Zusammenfassung:** Diese Publikation ist eine gekürzte Veröffentlichung aus dem Programm der ESTAD 2019. In diesem Beitrag wird der Einfluss von unterschiedlichen Kühlstrategien auf die Bildung von interkristallinen Rissen an einem Baustahl mit 0,17 Gew.% C und unterschiedlichen Al-Gehalten mittels eines In-situ Biegeexperiments unter Stranggießbedingungen untersucht. Die Biegetemperaturen liegen bei 1100 °C bis 700 °C. Die Ergebnisse zeigen, dass die kritische Testtemperatur jeweils bei 900 °C liegt. Eine Haltetemperatur von 1200 °C führt zu selektiver Korngrenzenoxidation und im Zuge dessen zur Bildung von Oberflächenkerben an den Austenitkorngrenzen, welche für Spannungskonzentrationen und in weiterer Folge erleichterte Rissbildung im kritischen Temperaturbereich verantwortlich sind. Die Experimente zeigen einen stärkeren Einfluss dieses Phänomens für die Proben ohne Al-Desoxidation

**Schlüsselwörter:** Stranggießen, Oberflächenrisse, Korngrenzenoxidation, In-situ Biegeversuch

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## 1. Introduction

In modern continuous casting machines with high process control systems, the most common macroscopic surface defects—like macroscopic transversal cracks and longitudinal cracks along the broad face or the corner region—seem to be well controllable. Nonetheless, for some combinations of steel grades and casting machines, it seems that cracks cannot be entirely prevented [1]. For these cases, the main problems can be caused by microscopic cracks situated below the scale. The cracks occur at the austenite grain boundaries and can be transverse to the casting direction (Fig. 3a), singular unorientated or in networks, defined as crazing (Fig. 4a, b; [2]). Phenomena like crazing are often related to Cu, Sn, and Ni enrichment in the steel to scale interface and the austenite grain boundaries [3–5] or the presence of blown grains, which are unusual lager austenite grains with diameters of more than ~1 mm [2]. It is shown that such cracks and microcracks can lead to massive surface quality issues on finished sheets [2, 5].

Yet in fact, there are a lot of open questions regarding the formation of transverse cracks and crazing. There seems to be a high interaction of temperature history, scale formation, and the structure of the steel to scale interface on the formation of microscopic surface cracks. The aim of this paper is the investigation of the influence of thermal history and scaling phenomena on the formation of surface cracks by using an in-situ bending experiment.

## 2. Experimental Procedure

At Montanuniversitaet Leoben, Ferrous Metallurgy, a method for investigating the susceptibility to surface crack formation under continuous casting conditions has been developed in the past ten years [6, 7]. It is called the "In-Situ Material Characterization Bending" (IMC-B) test. The state of the art of the experiment allows investigations of several casting parameters, e.g. different cooling strategies and casting speeds.

Fig. 1 shows the schematic flow chart of the IMC-B test within the significant experimental points. A sample (180/60/24 mm; length/width/depth) is casted into a specific mould. After a residual time in the mould, it is cooled according to a defined sequence to a bending temperature $T_{bX}$. At $t_{b\text{-}s}$ the sample gets deformed in an isothermal three-point bending test, which simulates stresses and strains, e.g. during straightening. The material behaviour is simulated with adapted parameters in ABAQUS. After cooling the sample to room temperature and descaling, the sample surface is investigated with a microscope, and the cracks, defects, and their positions are documented.

The steel used for the present test series is shown in Table 1. It is tested for both an Al deoxidized version (003Al) and a version where no Al was added (0Al).

Table 2 lists the test conditions for the test series. The variations take place in the residual time, the holding temperature, and the bending temperatures. The bending starts in all cases at $t_{b\text{-}s} = 700$ s. This point is adjusted to the start of the straightening zone of a slab caster with a casting speed of 1.2 m/min and a slab thickness of 225 mm [6, 7]. The maximum strain rate is the same for all samples and reaches values of ~$5 \cdot 10^{-4}\,s^{-1}$, situated at the bending axis.

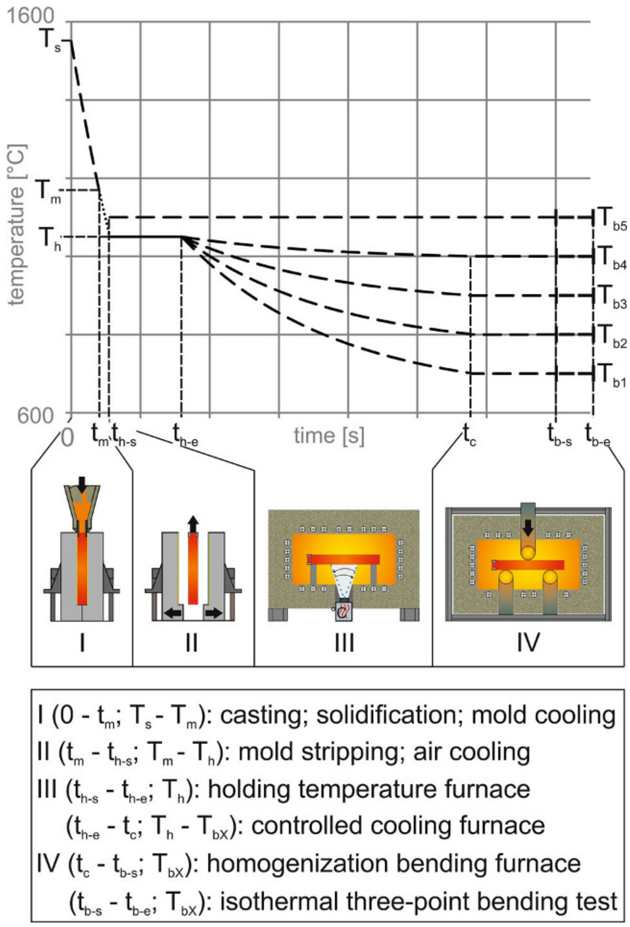

**Fig. 1:** Schematic temperature-time curves for the IMC-B test within marked significant points; graphics for the steps in the experiment with listed explanation in note form

TABLE 1
**Steel compositions for the present test series; all values in wt.%**

| Steel | C | Si | Mn | P | S | Al | Cu |
|---|---|---|---|---|---|---|---|
| 003Al | 0.17 | 0.4 | 1.55 | 0.01 | <0.004 | 0.03 | <0.015 |
| 0Al | 0.17 | 0.4 | 1.55 | 0.01 | <0.004 | <0.005 | <0.015 |

TABLE 2
**Test conditions for the differences in the significant experimental points—all samples**

| Steel | $t_m$ [s] | $T_m$ [°C] | $T_h$ [°C] | $T_{bX}$ [°C] |
|---|---|---|---|---|
| 003Al | 35 | ~1250 | 1200 | 1100; 1000, 900, 800; 700 |
| 003Al | 45 | ~1180 | 1050 | 1000, 900, 800, 700 |
| 003Al | 45 | ~1180 | – | 1100 |
| 003Al | 60 | ~1050 | – | 900 |
| 0Al | 35 | ~1250 | 1200 | 900 |
| 0Al | 45 | ~1180 | 1050 | 1000, 900, 800, 700 |
| 0Al | 45 | ~1180 | – | 1100 |
| 0Al | 60 | ~1050 | – | 900 |

  

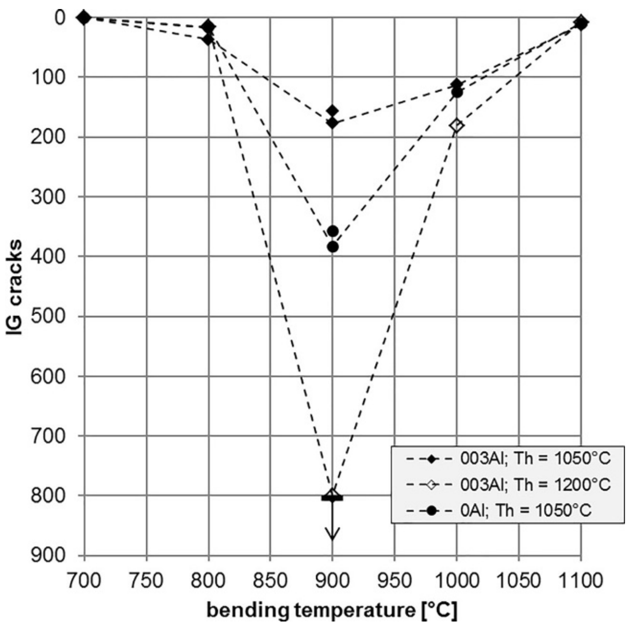


**Fig. 2:** Total number of IG (micro)cracks for samples with $T_h$ = 1050 °C and $T_h$ = 1200 °C

## 3. Results of Bending Tests

Fig. 2 shows the total number of counted intergranular (IG) cracks top-down for samples with $T_h$ = 1050 °C and $T_h$ = 1200 °C dependent on $T_{bx}$. The upper curve represents samples of steel 003Al with $T_h$ = 1050 °C. At 1000 °C and 900 °C, between 100 and 200 (micro)cracks formed on the sample surface. Some got detected at 1100 °C and 800 °C. At 700 °C no cracks formed. With no Al addition and the same testing conditions, the test temperature of 900 °C is even more critical. For the reproduction of the results, the tests for every Al variation are repeated at 900 °C. The experiments lead to similar results. Typical IG cracks from these samples are shown in Fig. 3b for 003Al and in (c) for 0Al. The cracks are always located at the austenite grain boundaries, mostly singular (no networks) and ~50 µm to 2000 µm in length. There is a similarity to continuous casting defects shown in Fig. 3a.

At 1100 °C, 800 °C, and 700 °C, the results of a $T_h$ = 1200 °C are nearly identical to $T_h$ = 1050 °C. But a bending temperature of 900 °C reveals a devastating effect on the formation of IG surface cracks. The crack morphology turns from singular to partial network cracks. Fig. 4c shows a strong damaged surface area of a sample with $T_h$ = 1200°C. It is a deep-notched austenite grain structure with a lot of IG cracks. For such areas, it is hardly possible to determine exact crack numbers. To convert the damage into a point in Fig. 2, the arrow indicates that at least 800 cracks are visible on the surface; in fact, for these extensive flaws, the absolute crack number is not the best damage indication anymore.

## 4. Influence of Selective Grain Boundary Oxidation

The bending tests reveal a significant influence of $T_h$ at the critical bending temperature of 900 °C. For that reason, a sample was produced for each Al content, where the high temperature oxidation is mostly suppressed. The samples stay in the mould for 60 s until a surface temperature of ~1050 °C. Afterwards, the sample is cooled immediately to 900 °C and held isothermally until the start of the bending test at 700 s.

Table 3 lists the total number of IG cracks for all samples with $T_b$ = 900 °C. The first notable point is the high value with $T_h$ = 1200 °C for both Al contents. The cracks are partially in networks. During holding at 1200 °C, notches form at the austenite grain boundaries due to selective grain boundary oxidation. The mechanism for the easier formation of cracks during tensile load is the stress concentration at these notches. As an example, a network of cracks and notches can be seen in Fig. 4c (steel 0Al). At this point it should be mentioned that the austenite grain size was measured for all of the samples and there is no clear correlation between the grain size and the crack appearance in the present study.

For the samples at $T_h$ = 1050 °C, the effect of grain boundary oxidation is already critical in the first seconds of oxidation. The cause of the higher number of IG cracks in steel 0Al happens right after the mould, where the surface temperature is ~1180 °C. In this case, the surface of steel 0Al is more damaged than with Al deoxidation, which can be seen in Fig. 3. The austenite grain boundaries are clearly visible in Fig. 3b (003Al), but the notches are very shallow. Fig. 3c shows steel 0Al, where deep notches are broken up and turned into cracks.

For a longer residual time in the mould, the sample temperature in the first contact with the atmosphere is ~1050 °C. The number of cracks for 0Al drops from 383 to 50. The same cooling strategy for steel 003Al now leads to

TABLE 3
**Comparison of the samples with a bending temperature of 900 °C**

| Steel | $T_b$ | $T_h$ | Number of IG cracks | Crack appearance |
|---|---|---|---|---|
| 003Al | 900 | 900 | 112 | Singular |
| 003Al | 900 | 1050 | 177 | Singular |
| 003Al | 900 | 1200 | >800 | Partially network |
| 0Al | 900 | 900 | 50 | Singular rare |
| 0Al | 900 | 1050 | 383 | Singular |
| 0Al | 900 | 1200 | >800 | Partially network |

  

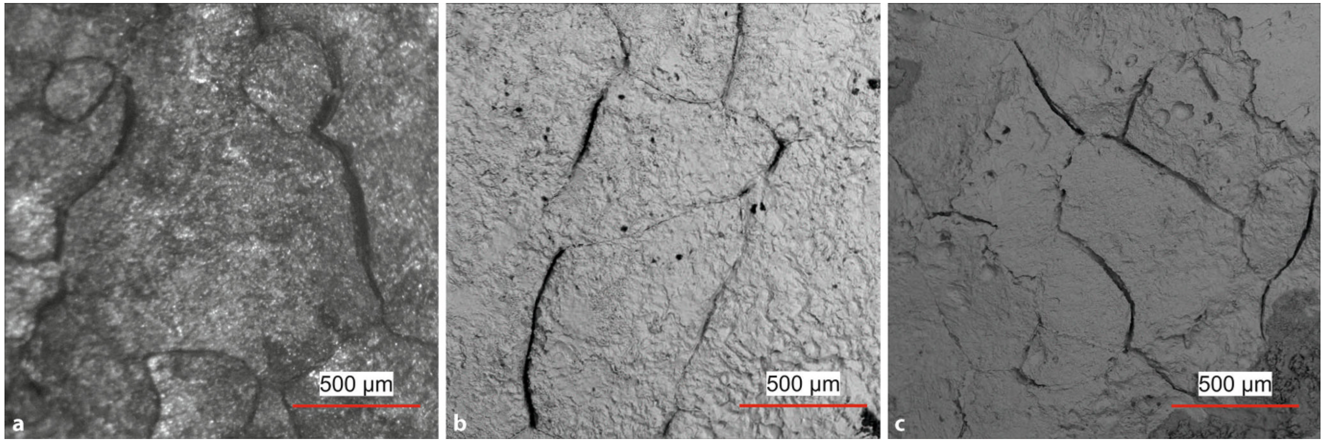


Fig. 3: **a** Microscopic IG cracks, oxidized grain boundaries on the lower part of the picture (billet surface); **b** IG cracks and slight selective grain boundary oxidation (sample steel 003Al, $T_h$ = 1050 °C); **c** IG cracks and strong selective grain boundary oxidation (sample steel 0Al, $T_h$ = 1050 °C)

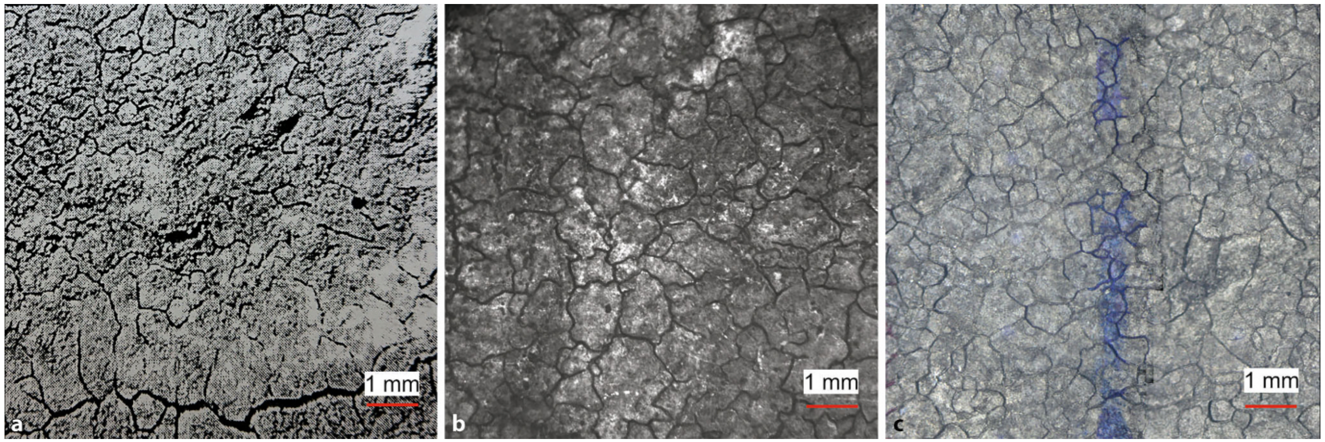


Fig. 4: **a** Crazing on a steel slab with a transverse crack on the lower part [2]; **b** crazing on a billet surface [8]; **c** crazing conditions with microcracks on the sample of steel 0Al with $T_b$ = 900°C and $T_h$ = 1200 °C

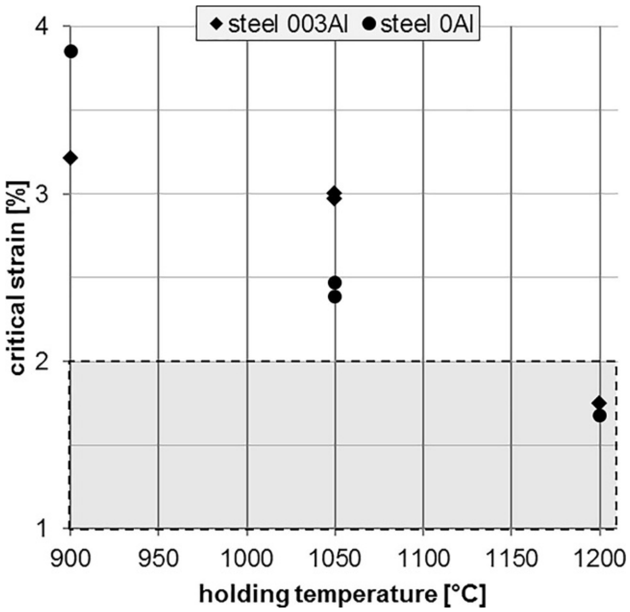


**Fig. 5:** Critical strain dependent on $T_h$ and Al content

more cracks than for steel 0Al. The selective grain boundary oxidation is suppressed for both samples, but at this stage, other damage mechanisms are getting more active for steel 003Al. Calculations show high amounts of AlN precipitates, especially for this temperature in the areas with higher strains, which indicates the harmful effect of deformation-induced AlN precipitates.

To classify the crack formation in the bending test with regard to the continuous casting process, a critical strain $\varepsilon_{crit}$ is defined. It represents the first strain value, dependent on the crack position and the distance to the bending axis, where the number of cracks rises to more than 2. Fig. 5 shows the values for the tests at 900 °C (Table 3) depending on $T_h$. Additionally, the reproduced tests with $T_h = 1050$ °C are plotted. At $T_h = 1200$ °C, $\varepsilon_{crit}$ drops for both Al contents to values in a critical strain range (~1.7%), which is already close to straightening conditions.

## 5. Conclusion

The present study confirms that cooling strategies may have a significant impact on the critical conditions for the deformation during straightening in cc of a 0.17 wt.% C construction steel with Al deoxidation and without Al addition. The most important results can be summed up as follows:

- Bending temperatures of 900 °C and 1000 °C are identified to be most critical with respect to surface defect formation. In addition, the harmful impact of longer holding at a temperature of 1200 °C is clearly remarkable for the subsequent deformation at 900 °C. The cause is a network of notches located along the coarsened austenite grain boundaries formed by selective grain boundary oxidation at these high temperatures. The notches lead to stress concentrations during tensile loads in the bending test at this critical temperature and can result in a drop of the critical strain for a first crack formation to ~1.7%. This value can be critical during straightening operations in continuous casting.
- The steel without Al addition tends to form deeper notches during high temperature oxidation. This leads to easier surface crack formation. When the high temperature oxidation is suppressed, more cracks form on the sample of the steel with Al deoxidation. This points to a harmful impact of deformation-induced AlN precipitates at higher strains.

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## References

1. Xia, G.; Burgstaller, K.; Fürst, C.; Harrer, B.; Milosch, E.; Samoilov, A.: Influence of Steel Composition on Crack Formation on the Continuous Casting Steel Slab, in: Proceedings of European Continuous Casting Conference, Graz, Austria, 2014, pp 729–739
2. Szekeres, E. S.: A Review of Strand Casting Factors Affecting Transverse Cracks; in: Proceedings of the 6th International Conference on Clean Steel, Balatonfüred, Hungary, 2002, pp 324–338
3. Burden, M. H.; Funnel, G. D.; Whitaker, A. G.; Young, J. M.: Origins of Defects in Continuously Cast Blooms Produced on a Curved Mould Machine, in: Proceedings Solidification and Casting of Metals, London, England, 1979, pp 279–286
4. Wolf, M.: Fine Intergranular Surface Cracks in Bloom Casting, Transactions of the Iron and Steel Institute of Japan, 24 (1984), no. 5, pp 351–358
5. van Wijngaarden, M. J. U. T.; Visagie, G. P.: The Effect of Residuals on the Presence of Intergranular Surface Cracks on Continuously Cast Billets, in: 79th Steelmaking Conference Proceedings, Pittsburgh, USA, 1996, pp 627–631
6. Krobath, R.; Bernhard, C.: A New Experimental Setup for the Simulation of Surface Crack Formation in the Continuous Casting Process, in: AISTech Proceedings, Nashville, USA, 2017, pp 1827–1837
7. Krobath, R.; Bernhard, C.; Ilie, S; Six, J.; Hahn, S.; Pennerstorfer, P.: A New Method for the Experimental Simulation of Surface Crack Formation in Continuous Casting, La Metallurgia Italiana, 4 (2017), pp 5–13
8. Gaiser, G.; Investigations on Surface Crack Formation of Continuously Cast Reinforcing Steel Billets; Bachelor Thesis, Leoben, Montanuniversitaet, Ferrous Metallurgy, 2018

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