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Analysis of transverse corner cracks from continuous casting process and comparison to laboratory experiments

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ABSTRACT

Low alloyed steel slabs produced by continuous casting can present transverse corner cracks, which are critical due to the oxide layer formed within the crack. Understanding this type of failure and reproducibility of the phenomenon through laboratory tests is of great value for dealing with this problem. The present work analyzed samples from slab corners, where cracks were identified. The fracture surfaces were examined using a scanning electron microscope (SEM) and cut to have their microstructure analyzed with a light optical microscope (LOM). Using etching to reveal the microstructure of the samples from the slabs, it was seen that the cracks were initiated and propagated at the prior austenite grain boundaries. Furthermore, the SEM images from the corner samples were compared to those from the physical simulation of the continuous casting process from previous work, and the structure found was like the ones tested at critical temperatures. The same was noted for the microstructure analysis, where cracks were also seen to follow the grain boundaries. Therefore, it was concluded that the behavior resulted from the laboratory tests performed with in-situ melted samples with the BETA 250-5 machine were in good accordance with the reality of the continuous casting process.

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1. Introduction

Continuous casting has become the dominant steel process around the world by bringing more quality to the final product, plus significant cost savings. During this process, the steel slab generally already goes through bending and straightening operations after partial solidification, usually in the temperature range of 700-1000°C (Revaux, Bricout, & Oudin, 1996; Mintz, Yue, & Jonas, 1991; Mintz & Crowther, 2010). During these operations the slabs are subjected to mechanical and thermal stresses, which are the cause for the initiation and growth of transverse corner cracks if the steel presents a low ductility (Mintz & Crowther, 2010; Lankford, 1972; Wang et al., 2021; Matveev, Kolbasnikov, & Kononov, 2017). The transverse corner cracks usually initiate where the oscillation marks are present and are not easily repaired once the oxide layer is formed on its surface (Pel'Ák, Misicko, Fedáková, & Bidulská, 2009; Huitron, Lopez, Vuorinen, Jentner, & Kärkkäinen, 2020), making it necessary to perform other processes such as grinding and scarfing, which increase production costs and decrease the process efficiency (Mintz et al., 1991; Wang et al., 2021; Yang et al., 2018; Huitron, 2020; Banks, Tuling, & Mintz, 2013). Against this background, continuing to improve the most widely used process in steel production is an issue of great interest.

In this context, the investigation of the hot ductility behavior is thus helpful to identify the best parameters for performing the most optimized continuous casting process, to avoid the formation of cracks and improve quality. Extensive investigations into this have been carried out by many different authors in laboratory conditions by performing hot tensile tests at different temperatures and following different thermal paths in a procedure that was defined as a good approach for the ductility behavior definition (Revaux et al., 1996; Mintz et al., 1991; Mintz & Crowther, 2010; Matveev et al., 2017; Banks et al., 2013; Lanjewar, Tripathi, Singhai, & Patra, 2014). On determination of the reduction of area following the tests at each temperature, the hot ductility curve can be determined and as a result of this the ductility trough, when present. The ductility trough, also referred to as the 2nd ductility minimum, is the indication of the critical temperature range for the steel in question, when the cracks are more easily initiated. Different test parameters, microstructure analysis of the samples tested, and simulations can also be helpful for the investigations into the reasons that might lead to crack initiation in the low alloyed steel under investigation.

Despite being a widely used attempt in reproducing the industrial process in the laboratory, however, the comparison between the results obtained experimentally and those ones seen from the cast slabs are not always reported for each different test set-up and thermal cycle used. Therefore, knowing the correspondence between the experimental results obtained via the test mode used and those from the industrial process is of importance for the consideration of the disparities.

The present work shows a comparison between the samples obtained from the continuous cast slab transverse corner cracks and those resulting from the laboratory tests previously published for validation of the experimental procedure chosen (Caliskanoglu, 2015).

2. Materials and methods

The industrial samples containing the transverse corner cracks were taken from slabs of two different microalloyed steels produced by the continuous casting process. The composition of each is as shown in Table 1, where they are identified as C1 and C2.

The cut from each slab was made in a way that the crack was completely present in the sample. The pieces were submerged in liquid nitrogen to be further broken apart, without damaging the original crack path. These samples were first observed with scanning electron microscope (SEM) to identify the fracture structure. Subsequently they were cut perpendicularly to the fracture surface, embedded, and polished for a first observation with the light optical microscope (LOM). In sequence, the etching procedure was done with 3% Nital. Since the results of this etching did not reveal the prior austenite grain boundaries as well as desired for this case, a modified Bechet-Beaujard etchant based on picric acid was used, specific for the revelation of prior austenite grain boundaries in low alloyed steels. The samples were submerged in the etchant for 12 minutes and subsequently rinsed with distilled water. After the etching procedure, the microstructure was once again observed with LOM for identification of grain boundaries and crack path.

The hot tensile tests used for comparison were performed by Caliskanoglu (2015), where dog-bone shaped samples of a low alloy steel were used, with its axis parallel to the rolling direction. The composition of the alloy used is also shown in Table 1, where it was named T1 (Caliskanoglu, 2015).

The machine used for the tests was the BETA 250-5, an in-house built thermomechanical simulator that can melt the samples in-situ without a protective melt cover around it, by means of an induction coil and a

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	с	Mn	Cr	S	AI	Ni	Ν	Р		
C1	0.188	1.590	0.016	0.0005	0.028	0.021	0.0231	0.0099		
C2	0.153	1.240	0.029	0.0067	0.038	0.028	0.0046	0.0120		
T1	0.158	1.100	0.034	0.0060	0.041	0.011	0.0036	0.0094		

 Table 1. Chemical composition in wt%

fine-vacuum atmosphere. The upper tension arm of the machine is responsible for the displacement and the lower part supports the sample and compensates for the thermal expansion. As the tensile test progresses, the induction coil moves upwards with half of the sample speed so that the coil continues heating the center of the sample. The temperature is measured during the entire test by a spot-welded thermocouple at the surface, in the center of the specimen.

To replicate the industrial process as close as possible in the laboratory, the samples were heated until the melting point, with the temperature measured at the surface of approximately 1 440°C, held at this temperature for 60 s for dissolution of precipitates, and then controlled cooled until the desired test temperature, as shown in the thermal cycle presented in Figure 1.

After reaching the test temperature, this was held for 10 s before each sample was pulled until fracture with a strain rate of 10^{-3} s^{-1} , usual for representing the deformation occurring during the industrial process. After rupture, the samples were quenched with pressurized air to freeze the microstructure at the point of failure.

The range of temperatures chosen for the tests was of 650–1000°C to identify the critical range of the ductility trough. From the ruptured samples the reduction of area (RA) was calculated in percentage as follows.



Figure 1. Experimental thermal cycle used by Caliskanoglu (Caliskanoglu, 2015).

Where A_i is the initial cross section in the middle of the sample and A_j is the cross section after fracture measured with the aid of a stereo microscope after the tensile test.

The crack surfaces were observed with SEM for investigation of the fracture mode and visual aspects of the crack, the same that was done for the industrial samples. Afterwards, these specimens were also cut perpendicularly to the fracture surface, embedded, polished, and etched with 3% Nital for microstructure analysis, which satisfactorily revealed the grain boundaries and microstructure.

3. Results

With the calculated RA values, the hot ductility curve of the material tested in the laboratory was defined and the ductility trough was identified to be between 700 and 850°C, with its minimum at 750°C, as shown in Figure 2 (Caliskanoglu, 2015). Two samples were chosen for the comparisons, one was tested at 750°C and the other at 950°C. The one tested at 750°C was chosen because of its lower ductility, which is the parameter used as an indicator of a tendency for crack initiation during the continuous casting process. The second one tested at 950°C is shown for exemplifying the contrast between the structures when the ductility is improved.



Figure 2. Hot ductility curve for the steel tested in the laboratory (Caliskanoglu, 2015).

The images of the fracture surface of the samples tested in the laboratory at both chosen temperatures taken with SEM by Caliskanoglu (Caliskanoglu, 2015) are shown in Figure 3a and 3b. The images of the sample tested at 750°C show that a clear intergranular fracture took place, which is the typical behavior when a lower ductility is observed. The opposite is seen in Figure 3b, taken from the sample tested at 950°C, which presented a better ductility. In this, a dendritic structure is present in the center, together with a transgranular fracture and a plastic deformation.

The samples taken from the cast slabs, C1 and C2, where transverse corner cracks were identified, were also observed with SEM for analysis of the fracture structure after the exposure of the crack and the images are shown in Figure 4a and 4b. The images present an intergranular type of fracture, with clear grain surfaces. This indicates a brittle behavior of the material, that caused the initiation and growth of the cracks in the steel slab.

After cutting, embedding, and preparing the samples, the microstructure of the specimens from the tensile tests and the continuous cast slab



Figure 3. SEM images of the fracture surfaces of the samples from the tensile tests at (a) 750 and (b) $950 \degree$ C (Caliskanoglu, 2015).

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could be observed using a light optical microscope (LOM). The results are shown in Figure 5a and 5b for the samples from the hot tensile tests and in Figure 6a and 6b for the samples from the cast slabs. In Figure 5a, from the sample tested at 750°C with lower ductility, it is possible to see that the fracture followed the prior austenite grain boundaries, where ferrite films were also present. Figure 5b shows the difference when a better ductility is seen, which was the case for the sample tested at 950°C. No clear fracture along grain boundaries was present and an elongation of the structure was noted.

In the Figure 6a and 6b photographs of the microstructure of the samples from the slab corners shows the initiation and growth of the cracks along the prior austenite grain boundaries. The different etching method had to be used in this case to reveal the prior austenite grain boundaries due to the dendritic microstructure formed in the solidified shell during the slower cooling of the industrial process. The grain



Figure 4. SEM images of the fracture surfaces of the samples from two different continuous cast slabs, (a) C1 and (b) C2.



Figure 5. LOM images of the microstructure of the samples from two hot tensile test conditions (T1), (a) 750 °C and (b) 950 °C.



Figure 6. LOM images of the microstructure of the samples from the cast slabs etched with Nital (left side image) and with modified Bechet-Beaujard etchant (right side image), (a) C1 and (b) C2.

boundaries revealed are very thin and light, therefore they and the cracks formed were highlighted for easier identification (in blue the grain boundaries and in red the cracks). This reiterates the brittle fracture identified in the SEM images from Figure 4.

4. Discussion

When comparing the images and the structures presented in the previous section, similarities can be identified between the samples tested in the laboratory and those from the continuous casting process. The brittle fracture seen in Figure 3 for the critical temperature of 750°C, characterized by the propagation of cracks along the grain boundaries, can be seen with the clear identification of grain surfaces. These features can be compared to the samples (a) and (b) shown in Figure 4, from the cast slabs, which also present clear grain surfaces. Brittle fractures are associated with the lower ductility of the steels, and it can be therefore concluded that the appearance of cracks in the slab corners, represented by the samples in Figure 4, are due to a low ductility at the moment and the temperature when stresses were applied to the slab. This corresponds to the low ductility and brittle fracture reported for the sample tested in the laboratory at 750°C. The equivalence between what is seen in the samples from the industrial process and the samples tested in the laboratory that showed a critical behavior shows that the samples tested using the experimental method presented can reproduce the structure seen in the failed specimens from the continuous casting process.

The difference in the fracture type when the ductility is better can be seen in the images of the sample tested at 950°C shown in Figure 3b. In these images there are no distinct grains, and clear signs of ductile fracture are present, which are due to the better ductility reported at this temperature, shown in Figure 2. In this condition, it is less likely that a crack will initiate when the bending and straightening operations are applied to the slab produced. The absence of such features in the transverse corner crack samples is also an indication of correspondence between the conditions simulated in the laboratory and those of the industrial process.

Observing the microstructure of the images from Figures 5 and 6, the results can be compared once again. The samples tested in the laboratory can be quenched at the point where the cracks were originated, making it possible to analyze the microstructure at the point that led to the failure, what is not the case for the industrial samples. In the industrial process, it is difficult to detect the exact point of failure since the microstructure changes significantly during the slow cooling path of the continuous casting. That implies in different etching methods necessary for laboratory or industrial samples to reveal well the different microstructures, as shown in the figures, especially the prior austenite grain boundaries, which are areas of interest regarding the growth of cracks.

Figure 5a shows that the cracks are originated and propagate along the prior austenite grain boundaries at 750°C, where ferrite films are

also present. In the case of the sample tested at 950°C, which showed a much better ductility, the fracture clearly does not follow grain boundaries and the structure is elongated at the edge, indicating that it could withstand more strain before failure.

To be able to compare the structure observed in the samples from the steel slabs to the samples from the experiments, a second etching method had to be used for revealing the prior austenite grain boundaries, since the dendritic structure formed in the solidifying shell of the slab does not respond the same to the method used for the tensile test samples. Therefore, after etching with the modified Bechet-Beaujard etchant, the structure shown in Figure 6a and 6b can be compared to the results mentioned from the sample tested at 750°C, with lower ductility. In these samples, a propagation of cracks along the prior austenite grain boundaries, that could be revealed with the adequate etchant, was clearly seen, very similar to the samples from the laboratory test that showed the lowest ductility.

This confirmed that the outcome from both processes is comparable and that the thermal cycle applied is a good approach for the prediction of the ductility behavior of the low alloy steel. Through the experiment routine presented it is possible and reliable to indicate at which temperature the failure might have occurred during the process.

5. Conclusion

The aim of this work was to compare the results obtained from the samples tested in the laboratory with those from the industrial process, as a mean of evaluating the reliability of the reproduction of the continuous casting process by means of the thermal cycle presented.

The outcome showed that the fracture and its behavior regarding the microstructure (growth along the prior austenite grain boundaries) resulted from the laboratory tests was comparable to what was seen in the transverse corner cracks formed during the industrial continuous casting process. This confirms that the test method defined, where the samples are heated until the melting point, and then subjected to strain until fracture occurrence with a strain rate of 10^{-3} s⁻¹ at high temperatures, is adequate for a good reproducibility of the ductility behavior of low alloyed steels during the continuous casting. The method presented can be a tool to identify the temperature at which the cracks are most probably formed during the casting.

The chosen investigation approach allows a better evaluation of the effects of each parameter in the low alloy steel to be produced, reducing losses in the industrial process, since the variables can be more easily changed in the laboratory before changes are applied to the steel production. This results in less resources needed for better product quality results.

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Disclosure statement

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