Simulation of Crack Initiation on the Slab in Continuous Casting Machine by FEM

Keigo TOISHI,* Yuji MIKI and Naoki KIKUCHI

Steel Research Laboratory, JFE Steel Corporation, 1 Kokan-cho, Fukuyama, Hiroshima, 721-8510 Japan.

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In continuous casting of steel, prevention of surface cracks on the slab is an important issue. For quantitative evaluation of cracks that occur in the continuous casting machine, the critical strain for crack generation was analyzed by a high-temperature tensile test and FEM simulation. Based on obtained material property values, a model for crack generation by tensile strain was constructed. The local strain at the notch relative to the strain in the whole specimen was determined by a simulation of the tensile test, and the critical strain for crack generation εc was calculated. The results of a crack simulation by FEM using εc showed that the average strain until crack initiation was small under deep notch conditions. The average strain for crack generation calculated by the simulation model was in good agreement with the value measured in the tensile test. As a result of the simulation applying temperature distribution to the slab, the depth change of the oscillation mark was more influential to crack formation than the change of the width. The effect of the shape of the oscillation mark on the crack cannot be organized only by the stress concentration factor. Simulation analysis that includes the shape of the oscillation mark is considered to be effective. Using this simulation model, it is possible to predict the generation of cracking when the temperature distribution or the oscillation mark shape in actual operation changes.

KEY WORDS: continuous casting; crack; high-temperature tensile test; oscillation mark; FEM; critical strain.

1. Introduction

In continuous casting of steel, prevention of surface cracks on slabs is important. During bending or unbending of a slab, large tensile stress is generated on the surface of the slab, which may cause transverse cracking of the slab. Many researchers have studied the hot ductility and mechanical behaviors of continuous casting slabs. To prevent transverse cracks, hot ductility was evaluated based on the relationship between the reduction of area and the temperature measured in a high-temperature tensile test. To avoid a range where hot ductility is low, the secondary cooling conditions were controlled so that the surface temperature of the slab would not fall within the low ductility range, especially in the bending and unbending area. Awajiya et al. conducted compression tests of flange type specimens and measured the reduction of area of low carbon steel and ultra-low carbon steel. They concluded that high-temperature ductility occurred in both low carbon steel and ultra-low carbon steel.

As conventional studies which measured the critical strain for crack generation by melt bending test method conducted by Matsumiya et al. are known. In the bending test of steel ingots, Yasunaka et al. reported that the critical strain for crack generation εc, was 1 to 10% and displayed dependency on the steel grade. Fu et al. reported that the critical strain for crack generation of Nb-containing steel was 30% to 50% based on the compression test of flange type specimens. Hayashi reported on the critical strain for crack generation measured by a tensile test with a gradient temperature field simulating the temperature distribution of the solidified shell, and found that the critical strain for crack generation decreased with increasing notch depth. Matsumiya et al. reported that the critical strain for crack generation becomes smaller as Tl-Ts becomes larger. In addition, it was reported that crack susceptibility increases as the thickness of the solid-liquid coexisting layer becomes larger and the depth of the cut between the dendrite increases.

In this study, the critical strain for crack generation was measured by high temperature tensile tests and a simulation in order to obtain criteria for transverse crack generation in the continuous casting machine. Based on the obtained material characteristic values, a model of crack generation due to bending strain in the continuous casting machine was examined using FEM and the X-FEM technique, which is used for analysis of the crack growth of structures, etc.
2. Experimental and Calculation Methods

2.1. High Temperature Tensile Test Method

High temperature tensile tests were carried out to evaluate the critical strain for crack generation of slabs and the stress-strain curve.

Figure 1 shows the specimen used in the tensile test. The specimen was taken from a medium carbon steel (C: 0.17 mass%) and had a total length of 68 mm, a reduced section length of 15 mm, a reduced section diameter of 6 mm and a V-shaped notch with a width of 2 mm and depth of 1.5 mm in the center of the reduced section.

Figure 2 shows the heat pattern used in the tensile test. The specimen was first heated from room temperature to the temperature range of the δ ferrite phase. After holding at 1350°C for 600 s, the specimen was cooled to the test temperature at 5°C/s and held for 60 s at the test temperature, after which tension was applied. The strain rate of the specimen was 2 × 10⁻³/s.

In this test, the strain generated in the reduced section length of 15 mm including the notch portion is defined as the average strain.

In order to measure the critical strain for crack generation, it was evaluated the occurrence of cracking when the average amount of strain was changed. The tensile test was stopped before the specimen broke to change the average amount of strain. The surface of the specimen after the test was observed to evaluate the occurrence of cracking.

Furthermore, in order to measure the deformation resistance used in the simulation, stress-strain curve at 800°C was measured in the specimen without the notch. The specimen without the notch was a total length of 68 mm, a reduced section length of 15 mm, and a reduced section diameter of 6 mm.

2.2. Simulation of High Temperature Tensile Test

Figure 3 shows the simulation model of the high temperature tensile test. The simulation model was the same size as the tensile test specimen and had a ring-like V-shaped notch with a total length of 68 mm, a reduced section length of 15 mm, a reduced section diameter of 6 mm and a notch with a width of 2 mm and a depth of 1.5 mm at the center of the reduced section. The calculation dimension was three-dimensional, the element type was a 4-node linear tetrahedral element and the number of elements was about 300 000. For mechanical properties such as Young’s modulus, Poisson’s ratio and deformation resistance, Young’s modulus and Poisson’s ratio were measured from room temperature to 1200°C by the resonance method and stress-strain curve measured by tensile test using specimen without the notch was used for deformation resistance. As boundary condition, tensile condition by displacement was given to both ends of the specimen.

2.3. Crack Simulation Method by FEM

X-FEM (Extended Finite Element Method) is based on the finite element method and is an analysis method that defines a discontinuity plane of displacement by adding a new degree of freedom and interpolation function within the element, as shown in Eq. (1). X-FEM can analyze the crack behavior when a material is subjected to stress or strain and can estimate the crack propagation regardless of the mesh conditions. This technique is expected to improve analysis accuracy with a small number of mesh divisions. In this paper, X-FEM was applied to the simulation of crack generation.

\[ u^b(x) = \sum_{j=1}^{N_i} N_i(x) \left[ u_i + H(x) a_i + \sum_{a=1}^{N_a} F_a(x) b_i^a \right] \] ........ (1)

\[ N_i: \text{shape function for node}, \quad u_i, \quad a_i, \quad b_i: \text{node degree of freedom}, \quad H(x): \text{heaviside function}, \quad F_a(x): \text{crack tip asymptotic function} \]

Cohesive damage model was used as a crack initiation model. In the model, the criterion of crack initiation was defined on the basis of stress and strain (maximum principal stress, maximum principal strain, maximum nominal stress). The criteria for crack generation and the propagation direction were defined on the basis of the stress/strain values at the element center ahead of the crack tip. As shown in Eqs. (2) and (3), damage occurs when the maximum principal stress or the maximum principal strain exceeds the threshold (f=1).

\[ f = \frac{\sigma_n}{\sigma_{0 \text{max}}} \] ........ (2)

\[ f = \frac{\varepsilon_n}{\varepsilon_{0 \text{max}}} \] ........ (3)

Fig. 1. Schematic views of sample used in tensile test.

Fig. 2. Temperature pattern used in tensile test.

Fig. 3. FEM simulation model of tensile test.
3. Results and Discussion

3.1. High Temperature Tensile Test

A high temperature tensile test was carried out to evaluate the critical strain for crack generation of the slab. First, a tensile test specimen having a V-shaped annular notch with a depth of 1.5 mm was subjected to a tensile test at test temperatures from 600°C to 1,000°C until breaking of the test piece, and the cross-sectional reduction of area (RA) was measured. RA was extremely small at 800°C. In the stress-strain curve, the specimen broke at the maximum tensile strength of 130 MPa and average strain around 0.035 to 0.05. Based on this result, the tensile test was stopped when strain reached 0.035 to 0.055, at which cracking seemed to start at 800°C, and the critical strain for crack generation was evaluated.

Table 1 shows the tensile test conditions. In these tests, tension was stopped under the five conditions of strain of 0.038, 0.041, 0.044, 0.048 and 0.049.

Cracks were not confirmed in the sample when tension was stopped at the average strain of 0.038, but crack generation at the center of the notch was confirmed at the strain of 0.041.

Figure 5(a) shows the fracture morphology of the tensile test sample by SEM, and Fig. 5(b) shows an enlarged view of the fracture surface. After the tensile test, the specimen was cooled with liquid nitrogen and fractured in the transverse direction from the notch. As shown in these images, dimples were observed on the crack fracture surface, indicating that it was a ductile fracture surface. Figure 6 shows the solidified microstructure around cracks observed by optical microscopy. After the tensile test, the sample was cut, etched with nital and observed. It was found that cracks had initiated along the prior austenite grain boundary from the notch and propagated.

3.2. Evaluation of Critical Strain for Crack Generation by Simulation of High Temperature Tensile Tests

In order to evaluate the critical strain for crack generation, a high temperature tensile test simulation was performed by FEM.

The simulation model was the same size as the tensile test specimen, and a round bar tensile test specimen having a notch width of 2 mm and a depth of 1.5 mm was formed in the parallel portion. As the material characteristic value, measured values obtained from the stress-strain curve at 800°C without a notch were used for deformation resistance. The temperature of the test specimen was kept constant at

| Notch depth (mm) | Temperature (°C) | Strain (–) | Stress (Mpa) | Crack |
|------------------|------------------|------------|--------------|-------|
| Case①            | 1.5              | 800        | Break        | 130   | –     |
| Case②-A         | 0.038            | 122        | No           |       |
| Case②-B         | 0.041            | 131        | Yes          |       |
| Case②-C         | 1.5              | 800        | 0.044        | 109   | Yes   |
| Case②-D         | 0.048            | 130        | Yes          |       |
| Case②-E         | 0.049            | 123        | Yes          |       |

Fig. 4. FEM simulation model of continuous casting slab.
800°C, and tensile condition by displacement was given to both ends of the specimen.

Figure 7 shows the calculated and measured (notch depth: 1.5 mm) stress-strain curve. The stress-strain curve obtained by the simulation was in good agreement with the measured values.

Next, the local strain relative to the strain in the whole specimen was determined by a simulation of the tensile test to evaluate the local strain at the notch. Figure 8 shows the relationship between the average strain and the local strain at the notch. In the simulation, when the average strain was 0.041, the local strain at the notch was 0.3. From this result, the critical strain for crack generation ($\varepsilon_c$) was determined as 0.3.

Figure 9 shows the measurement results of the critical strain for crack generation reported by Hayashi et al. and Fu et al. Hayashi evaluated the average strain for crack generation by measuring the mark interval attached to the side of the specimen. Although a simple comparison with the local strain obtained in this paper is not possible, the critical strain for crack generation obtained by Hayashi et al. and Fu et al. was 12% to 30%, and the critical strain for local crack generation obtained by the tensile test and the simulation in this work was strain of 30% (800°C, $C=0.17\%$).
3.3. Simulation of Crack Initiation

A simulation of crack generation in the tensile test was carried out by X-FEM using the critical strain for crack generation obtained by the high temperature tensile test and simulation. As material characteristic values, measured values obtained from the stress-strain curve at 800°C without a notch were used for deformation resistance, and the critical strain for crack generation was 0.3. Tensile condition by displacement was given to both ends of the specimen. As shown in Table 2, crack generation during the tensile test was simulated under the condition of a constant notch width of 2 mm and notch depths of 0.5 mm to 2 mm, and a constant notch depth of 1.5 mm and notch widths of 1.0 mm to 3.0 mm.

Figure 10 shows the distribution of the maximum principal stress and an enlarged view of the area around the notch for the notch depth of 1.5 mm. Under tension from both ends of the specimen, cracks initiated in the center of the notch.

Figure 11 shows the calculated average strain for the case of crack generation corresponding to the notch depth obtained by the simulation. The average strain for crack generation decreases with increasing notch depth. When the notch depth is 1.5 mm, the calculated average strain for crack generation is 0.04, which is in good agreement with the measured value.

Hayashi et al.\(^9\) machined a V-shaped groove and a semi-circular groove on one side of rectangular rod specimens and investigated the effect of the surface groove shape on the critical strain for crack generation in a gradient temperature field tensile test. According to their results, no effect of the groove shape on crack generation was observed, and crack generation depended only on the groove depth. It has been reported that the critical strain is approximately 35% on a smooth surface and decreases to 10% with a groove of 0.5 mm to 1 mm.

Although there are differences between the experimental method and evaluation method for the critical strain for crack generation, this method also shows that a surface notch reduces the critical strain for crack generation, indicating that the depth of oscillation marks in continuous casting greatly affects crack generation.

Figure 12 shows the relationship between the average strain for crack generation and the notch depth obtained by the simulation. Although the average strain for crack generation decreases with decreasing notch width, the influence of the notch width is smaller than that of the notch depth.

Maehara et al.\(^{18}\) investigated the influence of the notch shape on the high temperature ductility of low alloy steel. They reported that strength increased due to a change in the notch depth, while ductility decreased, but the influence of the sharpness (stress concentration factor) of the notch was small. Similarly, in the simulation of the notched tensile test shown in Figs. 11 and 12 of this study, the average strain for crack generation is influenced more strongly by the notch depth.

### Table 2. Conditions of simulation of tensile test.

| Notch depth (mm) | Notch width (mm) | Temperature (°C) | Critical strain (-) |
|------------------|------------------|------------------|---------------------|
| Case-A           | 0.5              |                  |                     |
| Case-B           | 1.0              |                  |                     |
| Case-C           | 1.5              | 2.0              | 800                | 0.3                 |
| Case-D           | 2.0              |                  |                     |
| Case-E           | 1.5              | 1.0              |                     |
| Case-F           | 1.5              | 3.0              |                     |

Fig. 9. Influence of cool side temperature on critical strain (Hayashi, Fu et al.).

Fig. 10. Maximum principal stress distribution of tensile test in simulation (notch: 1.5 mm, deformation × 5).

Fig. 11. Relationship between average strain for crack generation and notch depth by simulation (notch width = 2 mm).
depth than by the notch width. This was the same trend as past findings.

Next, crack generation in a continuous casting slab was simulated by using the critical strain for crack generation obtained by the high temperature tensile test and simulation. The critical strain for crack generation that was obtained by three-dimensional tensile test was used to simulate oscillation mark shape of actual cast slab. Since oscillation mark shape was evaluated in two-dimension, there are differences in terms of stress multiaxiality. However, analysis based on the tensile test results seems to be a reasonable method for qualitative evaluation of the effect of the shape of the oscillation mark on crack generation. Therefore the critical strain for crack generation obtained in the experiment was applied to the simulation of crack generation at the oscillation mark part. A heat transfer analysis was performed by FEM, and the simulation of crack generation was calculated using X-FEM.

**Figure 13** shows the temperature distribution at the upper bending point obtained by the heat transfer analysis. As the slab temperature, temperature distribution previously obtained by the heat transfer analysis.

**Figure 14** shows the relationship between the strain for crack generation and the stress concentration factor with different oscillation mark depths. The average value of the strain for crack generation was defined as the average strain of the slab surface with a length of 55 mm when the crack generated in the oscillation mark. The average value of the strain for crack generation in Fig. 14 was an index based on the condition of an oscillation mark depth of 0.6 mm and width of 4 mm. Figures 14(a) to 14(c) show examples of the maximum principal stress distribution at the time of crack occurrence in the simulation under each condition. The stress concentration factor was obtained from the oscillation mark depth and the curvature of the tip portion of the oscillation mark by the following equation:

$$\alpha = 1 + 2 \sqrt{\frac{a}{\rho}} \quad (4)$$

\(\alpha\): stress concentration factor (–), \(a\): oscillation mark depth (mm), \(\rho\): curvature radius (mm).

The stress concentration factor increases due to an increase in the oscillation mark depth or a decrease in the oscillation mark width.

As shown **Fig. 15**, the average strain until crack generation decreases as the oscillation mark depth becomes deeper and the stress concentration factor increases. This is in agreement with the relationship between the notch depth and the critical strain for crack generation in this tensile test. Moreover, even when the temperature distribution was considered, the tendency that cracks tend to occur as the oscillation mark becomes deeper did not change.

**Figure 15** shows the relationship between the average...
strain for crack generation and the stress concentration factor with different oscillation mark widths. The stress concentration factor increased due to the decrease in the oscillation mark width, and the average strain for crack generation decreased, but the influence was smaller than when the oscillation mark depth increased. That is, the influence of the shape of the oscillation mark on the average strain for crack generation is affected more strongly by the change in the stress concentration factor when the depth changes than by the width of the oscillation mark. Thus, the depth of the oscillation mark is more important than its width. From these results, the effect of the shape of the oscillation mark on the crack cannot be arranged only by the stress concentration factor. Therefore, a method of inputting the actual oscillation mark shape in the simulation and evaluating the critical strain for crack generation is considered effective. Using this simulation model, it is possible to predict the generation of cracking when the temperature distribution or the oscillation mark shape in actual operation changes.

4. Conclusion

The following knowledge was obtained as a result of a high temperature tensile test and FEM simulation of cracking.

(1) In the high-temperature tensile test, the test was stopped in the region (average strain: 0.035–0.05) where it was considered that cracking initiated in the preliminary test, and crack generation at the center of the notch was confirmed at the strain of 0.041. The local strain at the notch depth becomes deeper, and this tendency did not change when the temperature distribution was considered. Change in the depth of the oscillation mark had a greater influence on crack formation than change in the width. The effect of the shape of the oscillation mark on crack generation cannot be arranged only by the stress concentration factor. A simulation analysis that includes the shape of the oscillation mark is considered to be effective.

Using this simulation model, it is possible to predict the generation of cracking when the temperature distribution or the oscillation mark shape in actual operation changes.

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