An Evaluation of Critical Strain for Internal Crack Formation in Continuously Cast Slabs*

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Synopsis

An in-situ melt-bending test method has been developed, which permits the simple evaluation of the critical strain for the internal crack initiation in continuously cast slabs. In this testing method, the center of the top surface of a specimen in the form of rectangular parallelepiped is melted by high-frequency induction heating and the heating current is then lowered to form a solidified layer about 20 mm in thickness. The specimen under this condition is deformed by bending. The amount of strain applied to the solid-liquid interface is changed by changing the amount of bending. This test is conducted in an argon gas atmosphere. After the test, the internal cracking in the specimen is investigated and the critical strain for the internal crack initiation is determined by comparing the cracking condition with the amount of the strain applied. The critical strain was measured in six carbon steels by the above-mentioned method. It has been found that the difference in the critical strain among the steel grades is correlated to the difference between the calculated liquidus temperature and the calculated solidus temperature and that the greater the difference, the smaller the critical strain will be. It is also revealed that the critical strain values obtained by the other researchers show the same tendency.

I. Introduction

The internal cracks in continuously cast slabs are caused by the embrittlement near the melting point of steel. This embrittlement cannot be eliminated even by adjusting the chemical compositions and the secondary cooling conditions, and differs in this respect from that in the temperature ranges of 1 200 to 900 °C and 900 to 600 °C.¹⁾ Therefore, unless the solidification of a slab is completed, some parts of the slab in its thickness direction are in this brittle temperature range in which internal cracks are apt to occur, and the internal cracking is induced by small strains due to straightening deformation, bulging deformation, thermal deformation, etc.

From the reason mentioned above, for the prevention of the internal cracking, the critical strain for the internal crack initiation in the poor ductility range near the melting point is measured on the one hand and the strain generated at the solid-liquid interface of the slab is accurately determined on the other hand. Based on the results of this measurement and the calculation, the operating conditions and the equipment that do not generate strains exceeding the critical strain are examined.

The critical strain for internal crack initiation has been measured by many researchers.²⁻⁹⁾ However, these measurements were made mainly by the method where a side surface of a solidifying ingot was deformed by the application of a punch, and the estimation of the strain in the solid shell was not so precise. In

recent years, the critical strain seems to have been measured with high accuracy by the testing methods capable of the accurate determination of strains in specimens and actual slabs, such as the ingot bending method^{10,11)} and the intentional guide-roll misalignment method.¹²⁾ However, these methods are large in scale. Furthermore, the poor ductility range near the melting point is constantly moving since the solidification proceeds during the test, and it is not assured that all the strains applied act in the poor ductility range. In addition, errors occur if thermal and transformation strains are ignored since these strain are also induced in the specimen during the test. Accordingly, the authors have developed a testing method in which these drawbacks are eliminated, and measured the critical strain for the internal crack initiation.

II. Experiment

1. In-situ Melt-bending Test Method

The continuously cast slabs of the chemical compositions shown in Table 1 were selected and specimens 45 cm long, 8 cm wide and 3.5 cm high in the form of rectangular parallelepiped were cut off from the columnar crystal zone of each slab so that the longitudinal direction coincided with the casting direction.

The center of the top surface of the specimen was heated by high-frequency induction heating in an argon gas atmosphere and melted to a depth of about 2.5 cm. After the melting, the heating current was reduced to form a solidified layer about 2.0 cm in thickness. The form of the induction heating coil was set in a manner that the temperature distribution in the width direction of the specimen (the direction vertical to the paper in Fig. 1) became uniform.

The liquid pool was enclosed with alumina plates

Table 1. Chemical compositions. (%)

No.	C	Si	Mn	P	S	T.Al
1	0.042	0.011	0.224	0.020	0.010	0.022
2	0.088	0.013	0.476	0.014	0.018	0.041
3	0.150	0.183	0.500	0.016	0.011	0.017
4	0.181	0.349	1.360	0.019	0.003	0.034
5	0.230	0.220	0.440	0.024	0.014	
6	0.640	0.230	0.770	0.016	0.015	

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Fig. 1. Schematic diagram of the *in-situ* melt-bending test method (1-induction heating coil, 2-ram, 3-fulcra, 4-specimen being bent, 5-liquid pool, 6-*in-situ* solidified layer and 7-thermocouple).

5 mm in thickness to prevent the overflow of molten steel. Alumina plates containing no binder were used because phosphorus dissolves in the liquid pool from alumina plates containing phosphoric acid as a binder. The top surface of the specimen was covered with a silica plate to prevent a short circuit between the induction heating coil and the specimen. The bottom surface of the specimen was cooled with an argon gas stream at a flow rate of about 0.3 m³/min. When the specimen reached almost thermal steady state after about 3 min, a ram was pushed up from the center of the bottom surface of the specimen and the specimen was bent (Fig. 1). The ram pushing up speed was 10 mm/min, corresponding to about 5×10⁻⁴/s in terms of the strain rate at the solid-liquid interface. It had been found from the results of a preliminary experiment (*Appendix*) that the temperature distribution in the thickness direction at the center of the specimen on this occasion changes linearly with an increase in the thickness. Therefore, this temperature distribution was estimated from the temperature monitored during the test at a point 5 mm from the bottom surface of the specimen (Fig. 1, the solidus temperature minus about 200 °C) and the liquidus temperature in the position of the liquidus isotherm.* The method for determining the position of the liquidus isotherm will be described later. The heating current was cut immediately after the bending. The specifications of the apparatus are summarized in Table 2.

The test was conducted at the various degrees of bending. After the test, the longitudinal section at the center of the specimen width was polished and etched. The existence or nonexistence of cracks, the position of the cracks, and the position of the liquidus isotherm during the bending were examined under an optical microscope. Photograph 1 shows examples. Photograph 1(a) shows a specimen etched with Overhoffer's reagent, and Photo. 1(b) that etched with picric acid. The part which was a liquid phase during the bending shows a fine solidification structure since the solidification rate was fast in this part. It might be thought, therefore, that the position in which the solidification structure changed abruptly was the position of the liquidus face. For this reason, the temperature in this position was considered equal to the liquidus temperature, T_L , calculated using Hirai's equation.¹³⁾ The position corresponding to the solidus temperature, T_s , calculated using Hirai's

Table 2. Specifications of experimental apparatus.

High frequency induction heating	Maximum power :	150 kW at 9.9 kHz
	Ordinary power :	110 kW at 9.7 kHz
	Dimension of liquid pool :	80 mm (width)× 100 mm (length)× 25 mm (thickness)
Bending	Rum driving :	400 W D.C. motor
	Rum speed range :	0~100 mm/min
	Rum speed control :	Tachogenerator (Fluctuation is less than 0.5 % of the set value.)
	Maximum rum displacement :	35 mm

(a) Etched with Overhoffer's reagent
(b) Etched with picric acid

Photo. 1. Internal cracks in the longitudinal section at the center of specimen width.

equation also is shown in the photograph.

2. Method of Calculating Strain in Specimen

The creep bending theory of a beam has been applied by supposing that the flow stress of steel follows Eq. (1):

* During bending, the induction heating coil rises in synchronization with the movement of the ram. Therefore, variations in the specimen temperature resulting from the bending are small.

$\dot{\epsilon} = A \exp(-28\,392/T) \sigma^{3.15} \dots\dots\dots(1)$

where, $\dot{\epsilon}$: Strain rate
 σ : Stress
 T : Absolute temperature
 A : Constant.

The strain is given by the following equation:

$\epsilon = (y - y_0)/\rho \dots\dots\dots(2)$

where, y : Distance from the bottom surface of the specimen
 y_0 : Position of the bending neutral axis
 ρ : Bending radius.

σ is calculated from Eqs. (1) and (2). Since the resultant force of stresses in the longitudinal direction of the specimen is zero, Eq. (3) is obtained. The position of the bending neutral axis, y_0 , is determined so that Eq. (3) is satisfied.

$$\int_0^h \sigma dy = \frac{d(1/\rho)^{1/m}}{A^{1/m} dt} \int_0^h \frac{|y - y_0|^{1/m-1} (y - y_0)}{\exp(-28\,392/T/m)} dy = 0$$

(m : stress index of Eq. (1) = 3.15) $\dots\dots\dots(3)$

where, h : Solid phase thickness (position of the solidus isotherm).

Next, the radius of curvature was measured by moving a curvature measuring instrument along the bottom surface of the specimen after the bending (Fig. 2). This instrument has three probes at intervals of 15 mm. The middle probe is extensible and retractable. The amount of the extension was measured and the radius of a circular arc passing

Fig. 2.
Instrument for curvature measurement.

Fig. 3.
Profile of curvature along the specimen length after the bending test.

The numbers in the upper part indicate the steel grade numbers in Table 1. For the same steel grade, the amount of bending increases from left to right.
Fig. 4. Crack positions in the specimen.

through three points was calculated by an arithmetic unit based on the measurement results. Figure 3 shows the examples of the measurement. It can be seen from the figure that the radius of curvature is a minimum at the center of the specimen and increases with the increasing distance from the center. Since the radius of curvature is almost constant within 10 mm from the center, this value was regarded as the bending radius. When y_0 and ρ are determined, ϵ in each part of the specimen can be calculated from Eq. (2).

3. Method of Determining Critical Strain

Photograph 1 shows that cracks are formed in the solid-liquid zone to below the solidus face. Figure 4 shows the top and bottom positions of cracks in all the cracked specimens for each steel grade. In this figure, the amount of the bending increases from left to right. The distance in the thickness direction of the specimens on the ordinate was normalized by the difference between the positions of the liquidus and solidus isotherms obtained by the method described in Sec. II. 1 and the position of the solidus line was chosen as the origin. Cracks exist generally from the position of the solidus isotherm to the solid-liquid zone. The strain in the position of the solidus isotherm is correlated to the existence limit of the crack which determines the critical strain.

III. Results of Experiment

Figure 5 shows the relationship between the amount of strain in the position of the solidus isotherm and the existence limit of cracks. The broken line in the figure indicates the critical strain determined from the boundary between the existence and the non-existence of the cracks. In this figure, steel grades are plotted as the abscissa with the carbon content increasing from left to right. When the condition of

Fig. 5.
Cracking condition as a function of strain and steel grade, and Fe-C binary phase diagram.

the critical strain and the iron-carbon binary equilibrium phase diagram are taken into consideration, it seems that the wider the solid-liquid zone, the smaller the critical strain. Figure 6 shows the relationship between the difference between the liquidus temperature, T_L , and the solidus temperature, T_s , calculated by the Hirai's equation and the critical strain. As is apparent from the figure, the larger the difference $T_L - T_s$, the smaller the critical strain ϵ_c .

IV. Discussion

1. Examination of Propriety of Strain Calculation Method

The bending of the specimen was analyzed by the finite element method. As shown in Fig. 7(a), half the specimen was divided into 50 parts and the temperature distribution obtained by the preliminary experiment was adopted. Elastic and creep deformations were analyzed using the multi-purpose program of finite element method, MARC.¹⁴⁾ A load F was applied from the center of the bottom surface of the specimen so that the calculated displacement rate at the center of the bottom surface of the specimen

became almost equal to the ram pushing up speed. Figure 7(c) shows the results of the analysis. It is apparent that the amount of strain increases almost in proportion to the lapse of time after the load application and that the strain distribution from the top to the bottom surface of the specimen deviates from a linear distribution when the amount of strain increases. However, when the amount of bending is such that the strain in the position of the solidus isotherm is 2 % or less, the deviation from the linear distribution is not very great and the bending theory of a beam can be applied.

Next, the strain measurements were made. Markers were put on the sides of the specimen at its center at 9 mm intervals in the longitudinal direction and at 1 to 4 mm intervals in the thickness direction. The amount of strain was determined by measuring the distance between the markers before and after the bending. Figure 8 shows a comparison of the measured strain values with the strain distribution calculated from Eqs. (1) to (3). The calculated values are in good agreement with the measured

Fig. 6. Relationship between critical strain and liquidus-solidus temperature difference.

Fig. 8. Comparison between the calculated and measured values of strain distribution in the specimen after the bending.

Fig. 7. Analysis of the bending specimen deformation by the finite element method.

values. Thus, the strain calculation method presented in this paper seems to be valid.

2. Dependence of Critical Strain for Internal Crack Initiation on Steel Grades

The difference in the critical strain among steel grades reported by the other researchers is discussed from the same viewpoint. As shown in Fig. 6, the larger the difference $T_L - T_S$, the smaller the critical strain ϵ_c , which is the same tendency as observed in the present work.* This seems to mean that the larger the thickness of the solid-liquid layer and the deeper the interdendritic notch, the higher the cracking sensitivity will be. The reason for the difference in the critical strain among the reports is explained variously. First, the depth of the interdendritic notch is different since the temperature gradient in the specimen is different although the $T_L - T_S$ is the same. Secondly, the actual T_S is different due to a difference in the degree of nonequilibrium because the decrease in the solidus temperature due to the nonequilibrium segregation is not taken into consideration in the Hirai's equation. Thirdly, a difference in the cooling rate during the solidification *etc.*, results in the different sizes and shapes of dendrite, leading to a difference in the cracking sensitivity.

3. Initiation and Propagation of Cracks

Figure 4 shows the top and bottom positions of the internal cracks in the cracked specimens of each steel grade. In this figure, the amount of bending increases from left to right. Therefore, the crack initiation point can be estimated from the crack position in the leftmost specimen and how a crack propagates can be estimated from the crack position in the right-hand specimen. When Fig. 4 is viewed from this standpoint, it is found that in Steels 3, 4 and 6, the crack initiation point exists midway between the calculated liquidus and solidus isotherms and that the crack propagates toward both isotherms as the amount of strain increases. In Steels 2 and 5, the crack initiation point exists near the position of the solidus isotherm and the crack seems to propagate toward the liquidus isotherm as the amount of strain increases.

In this experiment, the thermal stress generated by the solidification and the stress induced by the transformation are relieved during the holding before the start of bending and the solid-liquid interface does not change during the bending. Therefore, the poor ductility range near the melting point does not move and all the strains applied to some places of the specimen act in the poor ductility range. This seems to eliminate the disadvantages of the conventional methods mentioned in *Introduction*.

V. Conclusion

An *in-situ* melt-bending test method has been developed, which permits the simple evaluation of the

ductility in the poor ductility range just under the melting point of steel, *i.e.*, the critical strain for the internal crack initiation in continuously cast slabs.

With this testing method, the center of the top surface of a specimen in the form of rectangular parallelepiped is melted in an argon gas atmosphere by high-frequency induction heating and the heating current is then decreased to form a solidified layer about 20 mm in thickness. The specimen in this condition is deformed by bending. The amount of strain applied to the solid-liquid interface is changed by changing the amount of bending. After the test, the condition of the internal cracking in the specimen is investigated and the critical strain for the internal crack initiation is determined by comparing the cracking condition with the amount of strain applied.

Figure 6 is summarized to show the results of the measurement of the critical strain in six types of carbon steels. It is found that the difference in the critical strain among the steel grades is correlated to the difference between the calculated liquidus and solidus temperature, $T_L - T_S$, and that the larger $T_L - T_S$, the smaller the critical strain. It is also revealed that the critical strain values obtained by the other researchers can be rearranged from a similar point of view. Physically, this seems to mean that the larger $T_L - T_S$, the deeper the interdendritic notch and the higher cracking sensitivity.

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* For Ref. 11), data of 5×10^{-4} /s were used as in the present work. For Ref. 10), however, some steel grades lack data of 5×10^{-4} /s and hence, data of 1×10^{-3} /s were used.

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Appendix

Measurement of Temperature Distribution and Changes in Specimens

The temperature in the specimen was measured with 6/30 Pt–Rh thermocouples 0.3 mm in diameter embedded in drilled holes 3.2 mm in diameter. The temperature measurement was repeated under the same heating conditions. The temperature was measured at six points at a time. The measuring points always included the point $x=0, y=40, z=5$ and the point $x=120, y=40, z=5$ (Figs. A-1 and A-3) to make sure of the reproducibility.

Figures A-2 and A-4 show the results of the

Fig. A-1.
Section in which the temperature distribution was measured and how to set the coordinate system.

Fig. A-2.
Transition of temperature in measuring points in the longitudinal section ($y=40$) at the width center of specimen. (The measuring point numbers are shown in Fig. A-3.)

crosssections normal to y axis						
	x=200mm	160mm	120mm	80mm	40mm	0mm
z=30mm	18 295	15 400	12 588	930	1400	y = 40mm TM(1520)
15mm	17 285	14 410	11 590	6 920	5 1230 1325 1310	1 1367
5mm	16 320	13 410	3 580	880	1140 1220	4 1260 1223
						2
	293	400	560	900	1370	
	315	405	560	8 890	7 1227 1300 1308	y = 20mm 1260
	310	410		805	1095 1230	
	285	373	510	915	1398	
	285	373		10 880	9 1205 1300	y = 5mm 1080
	293	395	510	800	1060 1193	

Fig. A-3.
Temperature distribution in the specimen 15 min after the start of heating.

Fig. A-4. Reproducibility of transition of temperature.

measurement of the temperature changes in each position of the specimen during the above-mentioned test. It is apparent from the figures that the temperature distribution in the specimen at the beginning of bending reaches a thermal quasi-steady state condition. (The start time of the bending was so selected.) It is also apparent that the temperature distribution changes little in the width direction of the specimen (Figs. A-2 and A-3). This is because the high-frequency induction heating coil has been designed in manner that the melting of the specimen and the

temperature distribution proceed two-dimensionally, *i.e.*, in the length and thickness directions of the specimen, for the purpose of simplifying the later analysis of the specimen deformation. Because the reproducibility of the temperature distribution was confirmed by repeating the multi-point temperature measurements in the specimen (Fig. A-4), a point 5 mm from the center of the bottom surface of the specimen was selected as the monitoring point during the ordinary experiments as mentioned above.