Improvement of Hot Ductility of Continuously Cast Carbon Steels*

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Synopsis

To improve the quality of continuously cast carbon steels, the characteristics of the hot ductility were studied via in-situ melted and solidified tensile testing method. Special emphases were placed on the effect of C and P on the hot ductility in the temperature range between melting temperature and 700 °C.

It was found that zero strength temperature (ZST_c) and zero ductility temperature (ZDT_c) have a linear relationship with the equilibrium solidus temperature in Fe-C binary alloys ranging from 0.003 to 1.6 % C and does not have the singularity between 0.1 to 0.2 % C content. The embrittlement due to P exists only in the carbon steels having C content higher than 0.25 %, which are subjected to the melting thermal history. This embrittlement is caused by the segregation of P along the austenite grain boundary.

Mild cooling in the secondary cooling stage is very effective to diminish the embrittlement resulting in producing defect free cast slabs.

I. Introduction

Related to the improvement of surface quality of continuously cast steels, it is important to study the hot ductility behavior of steels subjected to the in-situ melting and solidifying thermal history.

In the previous paper,¹⁾ we have reported that there exist three temperature regions where typical embrittlement is noticed in the carbon steels, i.e., $T_m \sim 1200$ (I), $1200 \sim 900$ (II) and $900 \sim 600$ °C (III). The cause of the embrittlement in the region I is the existence of residual liquid film along the dendritic interfaces. The ductility was found to be independent of the strain rate. In the region II, the precipitation of finely distributed oxy-sulfides at the austenite grain boundary weakens the boundary strength, and thus overaging treatments such as slow cooling, holding for certain time, or slow rate of straining result in good ductility. On the other hand, the embrittlement in the region III is manifested by the slower rate of straining. Controlling factors of this embrittlement are grain boundary sliding and the localization of strain to the proeutectoid ferrite film along austenite grain boundary, which is produced by the γ - α transformation.

Present paper describes the effect of C and P on the hot ductility and discuss the prevention method of cracking occurring in the continuously cast steels.

II. Experimental

Present experiment was done to elucidate the embrittlement occurring during cooling stage followed by the solidification in the continuous casting process

of carbon steels. Gleeble testing machine (Model 1500) was used for this purpose, which is a kind of horizontal tensile machine and is designed to subject specimens to a wide preprogrammed range of thermal history and strain rate.

Test pieces were round bars of 10 mm in dia. and 120 mm long. As shown in Fig. 1 (a), a specimen was in-situ melted, solidified and tensile tested at the specified temperature on subsequent cooling at a cooling rate of 20 °C/s. This type of specimens is referred to as 'melted specimens'. A quartz tube 10.2 mm in dia. and 30 mm in length was installed on the specimen to support the molten zone (about 15 mm long). For the purpose of comparison, as received specimens were sensitized (Fig. 1 (b)), or reheated (Fig. 1 (c)) and tensile tested. These two types of specimens are called here 'reheated specimens'. Test temperature was directly measured by PR-13 thermocouples spot-welded to the surface of each specimen. The temperature at the center position is about 50 °C higher than that of surface. In this report, deformation temperature indicates surface temperature.

Hot ductility and strength were appreciated here by the reduction of area (RA) and maximum tensile strength (σ max). Metallographic analyses were done by optical microscope as well as scanning electron microscope (SEM).

III. Experimental Results and Discussion

1. Embrittlement due to Carbon

Figure 2 shows the effect of C content on the hot ductility and strength in Fe-C binary alloys (Table 1). These data were taken by the melted specimens. As the content of C increases, zero ductility temperature (ZDT_c) drops down, which is very similar result with Weinberg's.²⁾ The characteristic temperatures such as ZST_c , ZDT_c and MDT_c are

Fig. 1. Thermal histories of hot stage tensile test.

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defined as shown in Fig. 3 schematically. These values show a linear relationship with the equilibrium solidus temperature, which is shown in Fig. 3, *i.e.*, $ZST_c = 1.14T_s - 231$. This result indicates that ZST_c and/or ZDT_c mean the temperature at which dendritic solid phases connect with each other and start plastic deformation after a considerable progress of solidification. Fractographic analyses showed approximately 10 % of residual liquid steels exists at ZDT_c . It was also found that there was no singularity of ductility behavior in between 0.1 and 0.2 % C content. Concerning with higher cracking tendency of longitudinal surface cracks in 0.1 to 0.15 % C steels,^{3,4} some of papers^{5,6} suggested the reason to be the existence of poor ductility. However, from the present results, it is clear that higher cracking tendency in 0.1 to 0.15 % C steels is not because of poor ductility, but other reasons such as dilatometric change due to the δ - γ transformation^{4,7} and the dif-

ference of segregation behavior of P and S.⁸⁾ In order to check the effect of impurity elements on ZDT_c , impurity doped-electrolytic irons containing 0.003 % C were examined. The result is shown in Fig. 4. The chemical species which are easy to segregate to the dendritic interface during solidifica-

Fig. 2. Hot ductility and strength in Fe-C binary alloys with melted specimens ($\dot{\epsilon}=5/s$). Numerical values in each curve show C content.

Fig. 3. Relation between ZST_c , ZDT_c , MDT_c and equilibrium solidus temperature in Fe-C binary alloys.

Fig. 4. Effect of impurity elements on ZST_c , ZDT_c . Each element is doped in Fe-0.003%C binary alloy.

Table 1. Chemical composition of alloys. (wt%)

No.	C	Si	Mn	P	S	Al	N	O
1	0.003	0.02	0.02	0.003	0.004	0.01	0.0015	0.0040
2	0.053	0.01	0.01	0.002	0.0003	0.016		
3	0.11	0.01	0.01	0.002	0.0003	0.013		
4	0.15	0.01	0.01	0.002	0.0003	0.019		
5	0.19	0.01	0.01	0.002	0.0003	0.013		
6	0.21	0.01	0.01	0.002	0.0003	0.013	0.0017	0.0015
7	0.40	0.01	0.01	0.002	0.0003	0.013		
8	0.61	0.01	0.01	0.003	0.0007		0.0016	0.0010
9	0.79	0.01	0.01	0.003	0.001		0.0014	0.0010
10	0.88	0.20	0.49	0.003	0.003	0.022		
11	1.03	0.01	0.01	0.0006	0.0004	0.001		
12	1.33	0.01	0.01	0.0008	0.0007	0.001		
13	1.60	0.23	0.50	0.004	0.001	0.007	0.0013	0.0010

tion lower ZDT_c.

It is concluded from these results that there is no singularity of the hot ductility in between 0.1 and 0.2 % C content and the embrittlement near the melting temperature occurs due to the segregation of impurity atoms which result in the decrement of a solidus temperature. Thus, it is necessary to reduce impurity elements for the reduction of the cracking tendency.

2. Embrittlement due to Phosphorus

In this section, the effect of P on the embrittlement is described.

Figure 5 shows the hot ductility *vs.* deformation temperature ($\dot{\epsilon}=5/s$) for the different amount of P in the 0.4 % C steels with melted specimens. As the content of P increases, the hot ductility around 1 000 °C drops down significantly and if P content exceeds more than 0.03 %, the ductility from near the melting temperature to 900 °C becomes poor. Figure 6 shows good and poor ductility

Fig. 5. Effect of phosphorus on hot ductility in 0.4 % C steels. Chemical compositions of each heat are also shown above this figure.

regions against C and P contents. Here, good ductility region is defined as the region where minimum reduction of area (RA) value is higher than 60 % in the temperature range of 1 200 and 900 °C, pulled at $\dot{\epsilon}=5/s$ with melted specimens. It was found that the embrittlement due to P is seen only for the carbon steels having C content higher than 0.25 % and becomes more detrimental as C content increases. In addition to this fact, the embrittlement is only observed in the melted specimens. Even a high carbon steel such as 0.7 % with 0.04 % P does not show the embrittlement in the reheated specimens. This point is a big difference from the embrittlement due to S, which shows even in the reheated specimens.⁹⁻¹²⁾

Figure 7 shows the cooling rate dependence of the hot ductility in the 0.7 % C steel with 0.04 % P. In this figure, numerical value shows RA values and the shaded area indicates poor ductility region where RA is less than 60 %. It is noted that higher cooling rate causes significant embrittlement for the wide range of temperature, while slower cooling rate

Fig. 6. Effect of C and P contents on the embrittlement. Good ductility region is defined as the region where minimum RA value is higher than 60 % in the temperature range of 1 200 and 900 °C, pulled at 5/s with melted specimens.

Fig. 7. Effect of the cooling rate on hot ductility in 0.7 % C steel with 0.04 % P. Shaded area shows poor ductility region. Chemical compositions of this heat are; 0.7%C-0.25%Si-1.2%Mn-0.04%P-0.002%S.

less than 1 °C/s suppresses this embrittlement. Figure 8 shows the effect of isothermal holding on the way of cooling (C.R.=20 °C/s) from the melting temperature with the same 0.7 % C steel shown in Fig. 6.

Fig. 8. Effect of the isothermal holding on hot ductility in the same 0.7 % C steel with in Fig. 6. Shaded area shows poor ductility region.

The embrittlement disappears by the short time holding in the holding at 1 200 °C. The improvement is also attained if the strain rate of tensile test becomes slower as shown in Fig. 9.

Photograph 1 shows typical result of fractographic analysis of the embrittled specimens due to P. Fracture occurs along austenite grain boundary, and

Fig. 9. Effect of the strain rate on hot ductility in the same 0.7 % C steel with in Fig. 6. Melted specimens were pulled at 1 000 °C.

(a): Optical micrograph near the fracture surface (b), (c): Fractured surfaces taken by SEM
Photo. 1. Fractographs showing austenite grain boundary fracture, fractured at 900 °C on the way of cooling in the 0.7 % C steel with 0.04 % P.

Photo. 2. Fractographs and result of energy dispersive analysis revealed after electrolytically etching the fractured surface shown in Photo. 1, showing the presence of metastable phosphide, $(\text{FeMn})_3\text{P}$, on the surface.

fractured surfaces show very smooth facet. The trace of liquid film is sometimes recognized on the fractured surfaces even in the case of the specimen fractured at 900 °C. Photograph 2 shows the fractograph taken after the electrolytic etching (SPEED method¹³⁾) of the fractured surface. Plate-like, metastable phosphide, $(\text{FeMn})_3\text{P}$, is observed, which is supposed to be formed by the eutectic reaction of $L \rightarrow \gamma\text{-Fe} + (\text{FeMn})_3\text{P}$ around 950 °C at grain boundary.

From these results, it is concluded that the embrittlement due to P is caused by the segregation of P along dendritic interfaces during solidification. The liquid film enriched in P remains stable along the dendritic interface, which is inherited the stable austenite grain boundary to the temperature of about 900 °C.

Therefore, the slower rate of cooling, isothermal holding on the way of cooling and slow rate of pulling are all effective means to reduce P segregation along the austenite grain boundary. Thus, these treatments improve hot ductility leading to the suppression of cracking tendency of surface cracks as well as internal cracks in the continuous casting operation.

3. Method to Improve the Quality of Continuously Cast Steels

Based on the present results and previous ones,¹⁾ two methods are proposed in order to get defect free slabs or blooms produced by continuous casting.

One is the refining of molten steels. As shown in Fig. 5, dephosphorization in higher carbon steels is very effective to increase hot ductility. The problem at the present moment is the development of an economical process of the dephosphorization. Another method is the optimization of processing variables in the continuous casting. As shown in Fig. 7 as an example, a mild cooling in the secondary cooling stage is useful to reduce the cracking tendency.

IV. Conclusion

In order to improve surface quality as well as internal quality of continuously cast carbon steels, hot ductility was studied *via in-situ* melted and solidified tensile testing method.

Main results are as follows:

(1) Zero strength temperature (ZST_c) and zero ductility temperature (ZDT_c) have a linear relationship with the equilibrium solidus temperature (T_s) of Fe-C binary alloy ranging from 0.003 to 1.6 % C; $\text{ZST}_c = \text{ZDT}_c = 1.14T_s - 231$, and there was no singularity between 0.1 to 0.2 % C content.

(2) The embrittlement due to P exists only in the carbon steels having C content higher than 0.25 %, and melted specimens which are subjected to the melting thermal history.

(3) The embrittlement is caused by the segregation of P along the dendritic interface where ends up with austenite grain boundary.

(4) Mild cooling and/or holding on the way of cooling from the melt are effective to diminish the embrittlement. Tensile deformation with slow rate of pulling is also effective to reduce this embrittlement.

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