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Effect of Solute Elements and Cooling Rate on Strain in Brittle Temperature Range of Continuously Cast Strand

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Abstract: A micro-segregation model of solute elements in mushy zone with δ/γ transformation during solidification was established based on the regular hexagon transverse cross section of dendrite shape proposed by finite difference method under the non-equilibrium solidification condition. The model was used to calculate the non-equilibrium pseudo binary Fe-C phase diagram and the strain of steels induced by variation of temperature in brittle temperature range. On the basis of the phase diagram and the strain, the strain curve in brittle temperature range as a function of carbon content for continuously cast strand was introduced and obtained. Solute elements change the position of the strain curve. And cooling rate changes the position and the shape of the strain curve. The comprehensive formula of the strain as functions of solute elements and cooling rate in brittle temperature range has been obtained by nonlinear fitting program.

Key words: solute element; cooling rate; non-equilibrium pseudo binary Fe-C phase diagram; strain; brittle temperature range

The continuous casting process has been adopted world-widely by steel industries over last three decades owing to its inherent advantage of low cost, high yield, flexibility of operation, and ability to achieve a high quality cast product[1-3]. However, there are still various defects in the strand[4-7]. Even though all the operating factors affecting the quality of strand have been analyzed, such as casting speed, mold cooling, secondary cooling system, soft reduction and so on, it is very difficult to analyze the effect of composition on the quality of strand because of interactions of complex components.

Many studies showed that the effect of carbon content is the most critical at the beginning of crack due to the enhanced shrinkage of steels undergoing the δ/γ transformation during casting. The first comprehensive investigation of the relationship between the mold heat flux and the carbon content was conducted by Singh and Blazek[8]. According to the experimental results, the value of the mold heat flux has a minimum at 0.1 mass% carbon steel, whereas for the carbon content higher than about 0.25 mass%, the mold heat flux is nearly constant. Grill and Brimacombe[9] suggested that this behavior arose from shrinkage of the solidified shell near the meniscus owing to the solid-state δ/γ transformation. Matsumiya et al.[10] suggested that the carbon content at which the strain developed in a brittle temperature range of $T_a - 30 < T < T_a$ is maximized, became 0.14 mass% C, where T_a is the temperature at which the solid fraction becomes 0.85 in the equilibrium binary Fe-C phase diagram. According to the non-equilibrium pseudo binary Fe-C phase, Kim et al.[11] studied the effect of carbon and sulfur on longitudinal surface cracks. However, the effect of steel composition and cooling rate on strain in brittle temperature range has not been reported yet.

The objective of present study is to analyze the effect of steel composition and cooling rate on strain in brittle temperature range of continuously cast strand. To accomplish this, the non-equilibrium pseudo binary Fe-C phase diagram has been calculat-

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ed and the effect of solute elements and cooling rate on the strain curve in the brittle temperature range has been analyzed.

1 Calculation Procedure

1.1 Calculation of microsegregation

The microsegregation in continuously cast strand has been calculated using a one-dimensional direct finite-difference model, based on the study of Ueshima et al. [12]. The γ phase develops from the interface between the δ phase and the liquid phase or from the last part solidification in the case where α/γ transformation takes place after complete solidification. Complete mixing of solute elements in the liquid phase and local equilibrium at the liquid/δ, liquid/γ, and δ/γ interfaces are assumed. Diffusion of solute along the axial direction of the dendrite is assumed to be negligible. This model solves the following diffusion equations in a hexagonal domain chosen to approximate the morphology of columnar dendrites, as shown in Fig. 1(a).

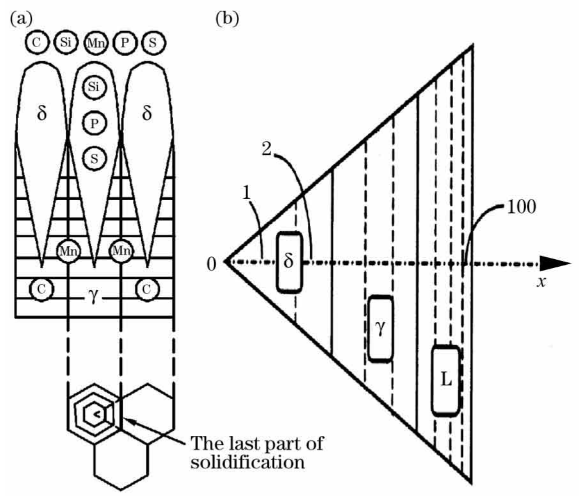

Fig. 1 Schematic drawing for the longitudinal and transverse cross sections of dendrites (a) and part of transverse cross section of dendrite (b)

$$\frac{\partial C_{z,i}}{\partial t}=\frac{\partial}{\partial x}\left[D_z(T)\frac{\partial C_{z,i}}{\partial x}\right] \tag{1}$$

where, $C_{z,i}$ is the concentration of the solute element z in the coordinate i; $D_z(T)$ is diffusion coefficient of the solute element z when the temperature is T; and t is the time.

The calculation was made by dividing the triangular transverse cross section into 100 thin nodal areas, as shown in Fig. 1(b). The first dendrite arm spacing λ is constant. The domain size is half of λ. The initial and boundary conditions are as follows.

Initial condition

$$C_{z,i}=k^{S/L}\cdot C_{0,i},\ \text{at}\ t=0 \tag{2}$$

Boundary condition

$$\frac{\partial C_{z,i}}{\partial x}=0,\ \text{at}\ t=0,\ x=\frac{\lambda}{2} \tag{3}$$

where, $C_{0,i}$ is the initial concentration of solute element in the coordinate i; and $k^{A/B}$ is the equilibrium distribution coefficient of the solute element between phases A and B.

When the liquidus temperature T_{liq} and the α/γ transformation temperature A_{r4} become equal to the actual temperature of the given nodal area, the solidification and δ/γ transformation in that area are assumed to be complete, and the interfaces move to the adjacent area. The parameters T_{liq} and A_{r4} are calculated using Eqs. (4)[13] and (5)[12], respectively.

$$T_{liq}=1\,536.0-78w_C-7.6w_{Si}-4.9w_{Mn}-34.4w_P-38w_S \tag{4}$$

$$A_{r4}=1\,392.0+1\,122w_C-60w_{Si}+12w_{Mn}-140w_P-160w_{Mn} \tag{5}$$

1.2 Calculation of non-equilibrium pseudo binary Fe-C

The non-equilibrium pseudo binary Fe-C phase diagram was calculated using the microsegregation model in the previous section. $k^{\delta/L}$, $k^{\gamma/L}$, $k^{\delta/\gamma}$, D^{δ} and D^{γ} of the solute elements are given in Table 1[14].

Shin et al. [15] measured ZDT (zero ductility temperature) and ZST (zero strength temperature) of 1.0Mn steel as a function of carbon content, which are compared with the calculated non-equilibrium phase diagram in Fig. 2. The calculated complete solidification temperatures are in good agreement with the ZDT measured by Shin et al. [15]. The measured ZST

Table 1 Equilibrium distribution coefficients and diffusion coefficients of solute elements

Element	$k^{\delta/L}$	$k^{\gamma/L}$	$k^{\delta/\gamma}$	$D^{\delta}/(\mathrm{cm^2\cdot s^{-1}})$	$D^{\gamma}/(\mathrm{cm^2\cdot s^{-1}})$
C	0.19	0.340	1.79	$0.0127\exp[-81\,379/(RT)]$	$0.0761\exp[-143\,511/(RT)]$
Si	0.77	0.520	0.68	$8.0\exp[-248\,948/(RT)]$	$0.3\exp[-251\,458/(RT)]$
Mn	0.76	0.780	1.03	$0.76\exp[-224\,430/(RT)]$	$0.055\exp[-249\,366/(RT)]$
P	0.23	0.130	0.57	$2.9\exp[-230\,120/(RT)]$	$0.01\exp[-182\,841/(RT)]$
S	0.05	0.035	0.70	$4.56\exp[-214\,639/(RT)]$	$2.4\exp[-223\,425/(RT)]$

Note: D^{d} is the diffusion coefficient of the solute element in phase d; R is gas constant of 8.314 J/(mol·K).