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Solute distribution in columnar crystal zone of continuous casting billets①

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[Abstract] The periodic bending deformation in the direction of casting occurs at the liquid/solid interface of billet due to the roller supporting force and the pressure of molten metal in the process of continuous casting. Based on this fact, a qualitative expression of solute concentration in columnar crystal zone for continuous casting billet is established, which agrees with the experimental results basically. Therefore, it is favorable to gain a columnar structure with less segregation by adopting a caster with compactly distributed small rollers and enhancing the cooling intensity in secondary-cooling zone.

[Key words] solidification; segregation; continuous casting
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1 INTRODUCTION

Kusano et al[1] found that under the combining action of the roller supporting force and the pressure of molten metal, the moving track of liquid/solid interface in the direction of casting is a sine wave which is formed by the periodic bending deformation of billet shell. And this affects the flow of the molten metal within the dendrites in solidification process and solute distribution in solid phase. The change of solute concentration in columnar crystal zone was neglected in the previous research on the composition distribution[2~5] and method of decreasing the segregation[6~8] in billets. On the other hand, the solute distribution in columnar crystal zone was studied only for the case with flat liquid/solid interface in metal solidification theory[9,10]. In this paper solute distribution in columnar crystal zone of continuous casting billet is studied while the shape of liquid/solid interface changes forcedly in the form of sine wave.

2 MOLTEN METAL FLOW BETWEEN DENDRITES

While the billet with liquid core passes backing roller or flatter roller in the process of continuous casting, the shape of liquid/solid interface changes, as illustrated in Fig. 1. When the shape of liquid/solid interface is simplified as a sine wave, the interface equation is as follows.

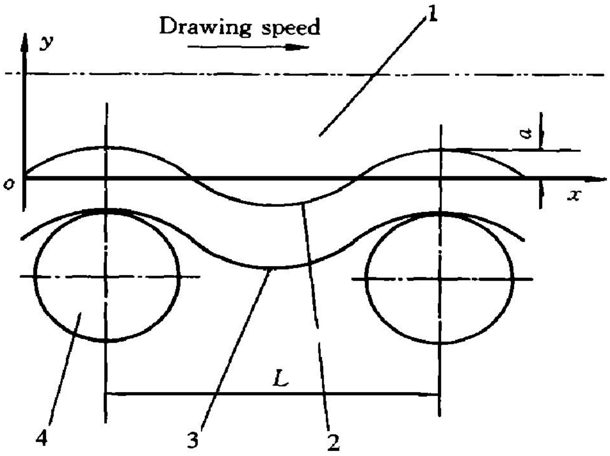

Fig. 1 Schematic diagram of liquid/solid interface of continuous casting billet
1 —Molten metal; 2 —Liquid/solid interface; 3 —Surface of billet; 4 —Roller

$$y = a\sin(2\pi x/L) \qquad (1)$$

where a is swing; L is period, basically equals to the distance between rollers.

When the columnar grain grows, the shape of solid/liquid two-phase region is illustrated in Fig. 2(a), and is simplified in Fig. 2(b). The change of the shape of solid/liquid two-phase region and molten metal flow condition is illustrated in Fig. 3. When the periodic bending deformation occurs in billet shell, molten metal flow between dendrites varies with the change of the space of molten metal between

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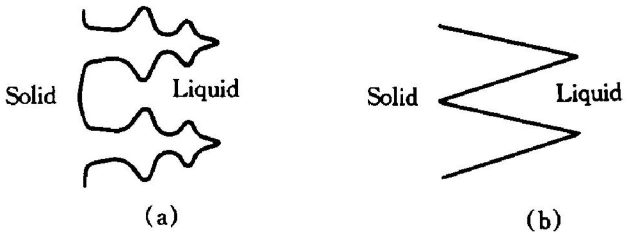

Fig. 2 Shape of solid/liquid two-phase region (a) and simplified model (b) for columnar grain growth

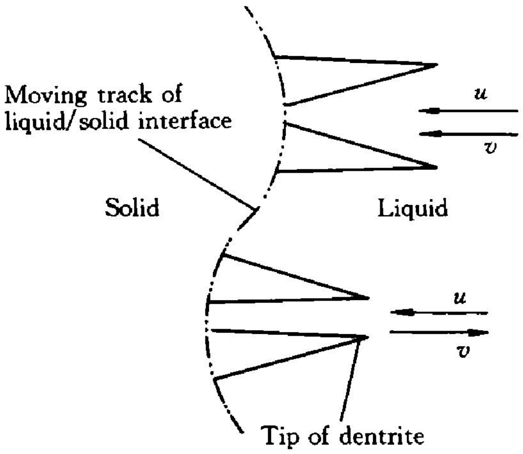

Fig. 3 Change of shape of solid/liquid two-phase region and molten metal flow condition (u —Flow rate caused by shrinkage of molten metal; v —Flow rate caused by change of dendrite space)

dendrites in the solid/liquid two-phase region. When dendrite space increases, molten metal flows into the space between dendrites, otherwise it flows out of the space. According to the change of dendrite volume (V), the average flowing speed (v) can be described as follows.

$$v = V\frac{\mathrm{d}h}{\mathrm{d}x} \tag{2}$$

where h is the height of molten metal in the growth direction of dendrite between dendrites, as illustrated in Fig. 4.

Because the dendrite space is much less than the sine wavelength, as shown in Fig. 1, the feet of close dendrites lie at the circumference with a radius of ρ. So Eqn. (3) is obtained according to the geometry relationship shown in Fig. 4:

$$h = h_0 - \lambda^2/\rho \tag{3}$$

where h_0 is the height of dendrite in solid/liquid two-phase region, λ is the half of dendrite space, and ρ is the curvature radius of sine wave at one point.

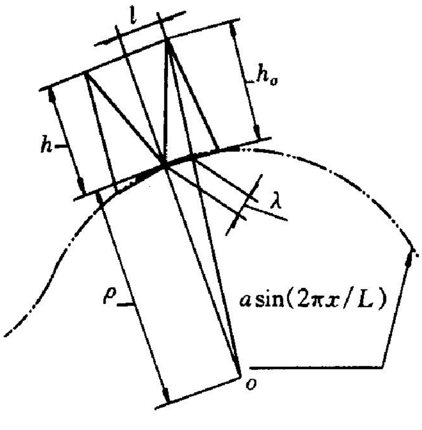

Fig. 4 Schematic diagram of geometry relationship between dendrites in solid/liquid two-phase zone and sine wave at one point

According to the Eqns. (1), (2) and (3), there is

$$v = \frac{aV\lambda^2\omega^3\cos\omega x}{(1+\omega^2a^2\cos^2\omega x)^{5/2}} \cdot \left[1+3a^2\omega^2\left(1-\frac{2}{3}\cos^2\omega x\right)\right] \tag{4}$$

where $\omega = 2\pi/L$.

Let

$$w = aV\lambda^2(2\pi/L)^3 \tag{5}$$

$$f(\cos\omega x) = \cos\omega x[1+3a^2\omega^2(1-2\cos^2\omega x/3)](1+\omega^2a^2\cos^2\omega x)^{-5/2} \tag{6}$$

where w is a parameter related to the distance between rollers, drawing speed and relevant columnar crystal space, and $f(\cos\omega x)$ is a function that controls the change of v. Thus Eqn. (4) becomes

$$v = wf(\cos\omega x) \tag{7}$$

It can be seen that v is a cosine function, which has the frequency equal to that of sine function of moving track of liquid/solid interface and the vibration amplitude of $8\pi^3a\lambda^2V(L^2+4\pi^2a^2)^{-3/2}$.

When ωx is between $(4n+1)\pi/2$ and $(4n+3)\pi/2$, v is negative, which indicates that molten metal flows out of the space between dendrites and the liquid/solid interface moves from the joint of continuous casting billet and roller to the space between rollers. When ωx is between $(4n+3)\pi/2$ and $(4n+5)\pi/2$, v is positive, which indicates that molten metal flows into the space between dendrites, and the liquid/solid interface moves from the space between rollers to the joint of continuous casting billet and roller. When $\omega x = n\pi/2$, v is equal to zero, which indicates that the flow of molten metal between dendrites is produced only by its shrinkage.

If u presents the average flowing speed in the dendrite growth direction caused by shrinkage of molten metal, flowing speed (v') of molten metal between dendrites is the sum of u and v:

$$v' = u + wf(\cos\omega x) \tag{8}$$

3 SOLUTE CONCENTRATION IN COLUMNAR CRYSTAL ZONE

According to the average local solute concentration expression in directional solidification[11] and Eqn. (8), there is

$$c = k_0c_0\kappa(1-\beta)/[\kappa(1-\beta)+(k_0-1)\cdot(\kappa-u)+(1-k_0)wf(\cos\omega x)] \tag{9}$$

where c is the solute concentration in columnar crystal zone, k_0 is the solute equilibrium distribution coefficient, c_0 is the initial concentration, β is the shrinkage ratio of solid, and κ is the solidification rate.

It is supposed that β, κ and u are constants, and let

$$A = \kappa(1-\beta) \tag{10}$$

$$B = \kappa(1-\beta) + (k_0 - 1)(\kappa - u) \tag{11}$$

Then Eqn. (9) is simplified as

$$c = k_0 c_0 \frac{A}{B + (1-k_0) w f(\cos \omega x)} \tag{12}$$

When $\omega x = n\pi/2$, $f(\cos\omega x)$ is equal to zero, and c is the solute concentration for the case with flat liquid/solid interface. Therefore liquid/solid interface lies in the sine wave crest or trough. When ωx is between $(4n+1)\pi/2$ and $(4n+3)\pi/2$, $f(\cos\omega x)$ is negative, and solute concentration of solid phase is larger than the initial concentration. When $\omega x = (2n+1)\pi$, c comes to a maximum. When ωx is between $(4n+3)\pi/2$ and $(4n+5)\pi/2$, $f(\cos\omega x)$ is positive, and solute concentration of solid phase is lower than the initial concentration. When $\omega x = 2n\pi$, c arrives at a minimum.

According to the above analysis, Eqn. (12) shows the solute concentration in columnar crystal zone along the direction of casting. Let Y be the thickness of solidification layer, thus the relationship between Y and x before the end of solidification is expressed as follows.

$$Y = \frac{\kappa}{V} x \tag{13}$$

Eqns. (12) and (13) are combined, then

$$c_Y = k_0 c_0 \frac{A}{B + (1-k_0) w f\left[\cos\left(\frac{V\omega}{\kappa} Y\right)\right]} \tag{14}$$

Eqn. (14) expresses the change of the solute concentration in columnar crystal zone with the thickness of casting billet.

4 DISCUSSION

4.1 Comparison of theoretical analysis with experimental results

Carbon content distribution of continuous casting billet (130 mm × 130 mm) is illustrated in Fig. 5(a). Carbon segregation of continuous casting slab with a thickness of 200 mm is illustrated in Fig. 5(b). In Fig. 5, carbon content in the direction of columnar grain growth increases and decreases by turns, which indicates that the change tendency of carbon content is a sine wave. Because sampling method is adopted to analyze the composition in different position, and many positions do not lie in the sine wave crest or trough, carbon distributions in Fig. 5 are not the whole sine waves.

According to the above experimental results, solute distribution showed in Eqn. (14) in columnar crystal zone of continuous casting billet is testified to be correct.

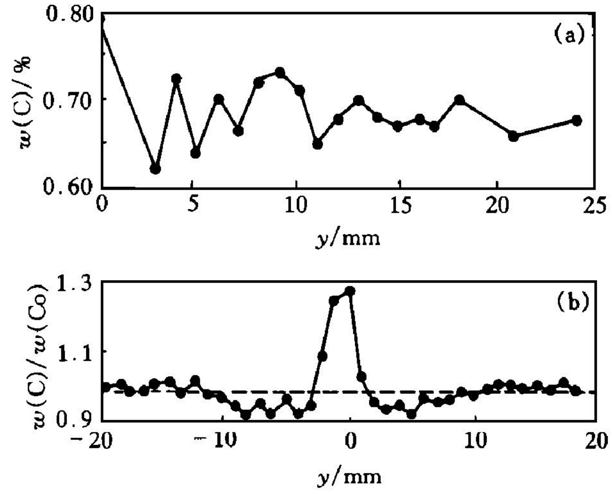

Fig. 5 Carbon distribution of continuous casting billet (a) and slab[12] (b)

4.2 Effect of technical process on solute distribution in columnar crystal zone

Because change of solute distribution in columnar crystal zone is a sine wave whose wavelength is kL/V and extremum lies on $8\pi^3 a\lambda^2 V(L^2+4\pi^2a^2)^{-3/2}$, there are:

1) In actual continuous casting, swing (a) is proportional to period (L). Increasing rate of $8\pi^3 a\lambda^2 V(L^2+4\pi^2a^2)^{-3/2}$ produced by swing (a) is larger than its decreasing rate produced by period (L). So in billet produced by continuous casting machine with small rollers arranged compactly, solute distribution in columnar crystal zone is more uniform correspondingly.

2) According to the Eqn. (14), change extent of c enlarges when dendrite space (λ) increases. So in Fig. 5, the nearer to the center of columnar crystal zone, the more the change extent of solute concentration in columnar crystal zone. Increasing cooling intensity in secondary-cooling zone can lead to decreasing of dendrite space (λ), increasing of solidification rate (κ), reducing of composition change in columnar zone and enlarging of wave length, so it is advantageous to retain columnar crystal in which composition distribution is more even.

5 CONCLUSIONS

1) On the basis of bending deformation of liquid/solid interface, a qualitative solute concentration expression in columnar crystal zone of casting billet is established, which is identical with the experimental results basically.

2) It is advantageous to obtain columnar structure with more even composition distribution when a continuous caster with small rollers arranged com-

pactly are adopted and the cooling intensity in secondary-cooling zone is increased.

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