Effect of Bulging and Solidification Structure on Segregation in Continuously Cast Slab*

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Synopsis

By the use of a center segregation simulator evaluation method, a test of center segregation was made quantitatively in relation to the amount of bulging and solidification structure.

It became clear from the test that segregation is insignificant when the amount of bulging is zero but intensifies when the amount of bulging exceeds 200 μm .

On the basis of the test result, short-pitch divided roll segments were installed on a continuous slab caster and a segregation alleviating test was made. The test results revealed that center segregation can greatly be alleviated if the solidification structure of the slab is changed to an equiaxed structure, and the bulging of slab is reduced by the use of a short-pitch divided roll stand.

Solidification phenomena in the part of segregation-spot are discussed theoretically. And the EPMA data of spot segregation are well explained by the results of theoretical analysis.

I. Introduction

Many papers have already been reported on segregation of elements in continuously cast slabs, such as the studies from a point of view of the solidification phenomenon or the researches under which the operating conditions and the characteristics of continuous caster are incorporated as factors being responsible for such segregation. Some researchers have proposed low-temperature casting as a method of reducing segregation^{1,2)} whereas others have advanced high-temperature casting as the means of reducing segregation with columnar solidification.³⁾

An important machine role is to prevent the bulging of the strand being cast. This bulging can be suppressed by decreasing the spacing of strand support rolls or by using divided rolls.⁴⁾ Meanwhile, electromagnetic stirring was introduced and spread as a technique of forming equiaxed crystals in the central part of slab and of dispersing the segregated elements.⁵⁻¹⁵⁾ The technology of reducing the slab lightly with rolls was developed to alleviate center porosity as well as segregation.^{3,16)} The quality of continuously cast slabs has been improved substantially by the above mentioned means, but there have been still increasing demands for lessening segregation in such slabs.

In the present study, tests by the use of a center segregation simulator have been made to evaluate center segregation quantitatively in relation to the amount of bulging and solidification structure. On the basis of the test results, short-pitch divided roll segments were installed on a continuous slab caster,

and a segregation alleviating test was made.

There are many papers¹⁷⁻²¹⁾ in which microsegregation of chemical elements was measured by EPMA. In this paper the microsegregation was measured by EPMA and macroanalyzer (MA) in order to distinguish the test slabs.

II. Test Method and Results Using Center Segregation Simulator

The center segregation simulator is schematically illustrated in Fig. 1.

Liquid steel is poured through a pot into a box-type mold shaped like a slab. The pot is then covered and exerted pressure, the pressure causing the slab to bulge. In order to give a specified amount of displacement like bulging to the slab, the following method was used. The mold is grooved on the outside to a specified depth (0 to 1.2 mm) in the lateral direction. The slab moves right and left as shown in Fig. 1, supported by three pairs of rolls, these rolls are always in contact with the mold surface. When three grooved parts of the mold come to the three roll positions, the mold and solidified steel make displacement together like a bulging.

Segregation similar to that found in actual slabs forms in the central part of the slab thus solidified.

The test results obtained without the application of pressure to the pot are first described. Slabs were cast at mold surface groove depth levels of 0, 0.25, 0.5 and 1.0 mm. Sulfur prints of the slabs thus obtained are shown in Photo. 1. Slabs manufactured

Internal dimension of mold
80 mm thickness $\times$ 215 width $\times$ 1 700 mm length
Roll pitch = 500 mm
Stroke = 500 mm
Amount of steel = 270 kg

Fig. 1. Schematic view of simulator of center segregation.

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Pressure in the pot: 0 kgf/cm²

Photo. 1.
Solidification structure of slab cast by the simulator. (In the case of columnar solidification)

Pressure in the pot: 6.0 kgf/cm²

Photo. 2.
Solidification structure of slab cast by the simulator. (In the case of columnar solidification)

Pressure in the pot: 6.0 kgf/cm²

Photo. 3.
Solidification structure of slab cast by the simulator. (In the case of equiaxed structure)

in this way usually exhibit columnar structure. Center segregation intensifies as the mold surface groove depth increases, but is extremely weak as shown in Photo. 1 when the mold surface groove depth is zero.

The test results obtained under an applied pressure of 6 kgf/cm² to the pot are described next. As shown in Photo. 2, center segregation intensifies as the mold surface groove depth increases in the same manner as shown in Photo. 1. Segregation intensity becomes greater when a pressure is applied to the pot as compared with the case that no pressure is applied to the pot. All the slabs in these photos show columnar

structure.

Photograph 3 shows the solidification structures of slabs cast by the addition of 2.2 % steel powder to liquid steel in order to produce an equiaxed structure on solidification. When an equiaxed solidification structure is obtained, V segregation is formed and at the same time, center segregation is alleviated. The susceptibility of center segregation to the mold surface groove depth also decreases.

The intensity of center segregation judged and rated by sulfur print is shown in Fig. 2. Center segregation intensifies as the pot pressure and the mold surface groove depth increase. If the mold

surface is smooth under an applied pot pressure of 6 kgf/cm² a slab with a segregation rate of about 0.5 can be obtained.

Center segregation is far worse when the mold surface groove depth corresponding to the amount of bulging is 0.2 mm than the case that the mold surface groove depth is 0 mm. That is, 200 μm of bulging greatly affects center segregation.

Figure 2 also shows that center segregation changes to V segregation and that the bulging susceptibility decreases by equiaxed solidification.

III. Short-pitch Divided Roll Test Method

On the basis of the center segregation simulation experiments, short-pitch divided rolls were installed on a continuous slab caster and the effect on alleviating slab segregation was studied by minimizing bulging.

The specifications of the short-pitch divided rolls are compared with those of the conventional rolls in Table 1, and the installation of the short-pitch divided rolls is schematically illustrated in Fig. 3. The slab caster used in the test is No. 1 caster at Nagoya Works, Nippon Steel Corp. No. 11 and No. 12 segments of

No. 1 strand were the test segments, each with seven pairs of short-pitched divided rolls. The roll spacing of No. 11 and No. 12 segments of No. 2 strand was the same as that of No. 9 segment which is 471 mm.

Slabs were cast with a casting speed of 1.3 m/min so that they finally solidified in No. 12 segment. The casting conditions were given in Table 2. The tests were made with or without the short-pitch divided rolls and electromagnetically stirring. The grade of steel cast was SM 50K.

The effect of the short-pitch divided rolls was judged by comparing the slabs cast on the two strands. In general, the solidified shell bulges depending on the dynamic balance among the head of liquid steel, the strength of shells, support rolls and other factors involved. As the test slabs were cast, the amount of bulging was measured with the bulging sensor shown in Fig. 4.

The bulging sensor was raised on the foundation of the caster and designed to measure roll displacement and slab movement at the same time. The positions of two adjacent rolls and the bottom surface position of slab at the center of the distance between two rolls were measured with time. The amount of bulging was determined from the positional relationship between the roll and slab surfaces.

The measurements made when a completely solidified slab passed over the sensor or when no bulging occurred were taken as the reference value or zero. The amount of bulging when a liquid-core slab passed over the sensor was determined accordingly.

Fig. 2. Effect of solidification structure and bulging on segregation intensity.

Table 1. Specification of conventional roll, short-pitch divided roll.

	Conven- tional roll (horizontal zone)	Short-pitch divided roll
Roll dia. (mm)	420	240×3 div.
Roll pitch (mm)	471	272
Setting position (m)	—	21~25
Roll stand length (m)	—	4

Fig. 3. Schematic view of roll arrangement.

Table 2. Casting conditions.

Test No.	Strand*		Casting speed (m/min)	Temperature in tundish (°C)	EMS		Cooling water (l/kg)	An example of steel analysis (%)	
	No. 1	No. 2			on	off			
1	0		1.30	1 552		0	1.92	C	0.15
2		0	1.30	1 552		0	1.55	Si	0.41
3	0		1.30	1 539	0		1.92	Mn	1.32
4		0	1.30	1 539	0		1.55	P	0.018
								S	0.005

* Short-pitch divided roll~No. 1 strand
Slab: width 1 890 mm, thickness 245 mm

Fig. 4. Schematic view of bulging sensor.

Fig. 5. Measurement of bulging.

The results are given in Fig. 5. The average amount of bulging with the conventional rolls was 100 μm and the maximum was 250 μm. In the case of the short-pitch divided rolls, bulging detected was within the measurement errors.

IV. Solidification Structure of Test Slabs

Photograph 4 shows center segregation in a slab cast with the conventional rolls and not electromagnetically stirred. The solidification structure of Photo. 4(a) was revealed by using a 3 % ammonium persulfate $\{(NH_4)_2S_2O_8\}$ aqueous solution as an etchant. This etching method is suited for revealing segregation. The as-cast solidification structure is shown in Photo. 4(b). Since the slab was not electromagnetically stirred, the columnar structures meet at the center of the slab with a linear segregation. A 40 mm by 40 mm central square of the slab was analyzed with a macroanalyzer (MA) for manganese, and the areas with a manganese content of 1.32 as high as that of ladle steel were identified. Such areas are shown in Photo. 5. Manganese segregations are linearly connected with each other, and are supposed to affect adversely the properties of steel.

Photograph 6 shows center segregation in a slab electromagnetically stirred and supported with the conventional rolls. The solidification structure is equiaxed, and center segregation is not linear but is V shaped and finely dispersed. The MA analysis of

a) Etching, expressing segregation b) Solidification structure

Conventional roll, Non-EMS
Slab center, L section

Photo. 4. Segregation pattern of slab.

Conventional roll, Non-EMS
MA analysis
 Mn_0 : Mn analysis of liquid steel

Photo. 5. Mn segregation. ($Mn/Mn_0 > 1.32$)

a) Etching, expressing segregation b) Solidification structure

Conventional roll, EMS
Slab center, L section

Photo. 6. Segregation pattern of slab.

Conventional roll, EMS
Photo. 7. Mn segregation. ($Mn/Mn_0 > 1.32$)

the slab with respect to manganese is shown in Photo. 7. It is a characteristic of the electromagnetically stirred slab that manganese segregations are not linearly connected with each other but are finely dispersed. There is a new problem, however, that V shaped segregation is formed more than 10 mm apart from the center of the slab.

Photograph 8 shows the solidification pattern of a slab electromagnetically stirred and supported with short-pitch divided rolls. The MA analysis of the slab with respect to manganese is given in Photo. 9. Both the V shaped segregation and center segregation are more finely dispersed than those in the slab of Photo. 7.

V. Detailed Observation of Spot Segregation

Figure 6 shows the position where the EPMA samples were taken. The slabs were cut in the longitudinal direction at the center of the slab width. Spot segregation on the longitudinally cut surface was observed with the aid of an electron probe micro-analyzer at the center of the slab thickness (Sample A, 10 mm) and the position (Sample B) 10 mm apart from the slab center to the loose side of continuous caster.

The specimen was lightly etched with a 1.3 % picric acid aqueous solution, and the position of each spot segregation was marked by the indenter of a Vickers microhardness tester. The specimen was polished until the etching pattern completely disappeared. Spot segregation in the specimen was analyzed by an electron probe microanalyzer with a beam diameter of 2 μ m for manganese and phosphorus (line analysis). The specimen was re-etched with a 1.3 % picric acid aqueous solution for 3 min. The relationship between the size of segregation and the concentration of segregated element was determined in this way.

Short-pitch divided roll, EMS
Slab center, L section
Photo. 8. Segregation pattern of slab.

Short-pitch divided roll, EMS
Photo. 9. Mn segregation. ($Mn/Mn_0 > 1.32$)

Fig. 6. Samples from a slab for EPMA.

The procedure is schematically shown in Fig. 7. The minimum width L_{min} and the axis ratio are defined as

Fig. 7. Definition of a minimum segregation distance.

$$L_{\min} = L_{E \min} \times L / L_E \dots\dots\dots(1)$$
$$\text{Axis ratio} = L_{E \max} / L_{E \min} \dots\dots\dots(2)$$

where, $L_{\min}$: minimum segregation distance
 $L_{E \min}$: minimum distance in etched area
 $L_{E \max}$: maximum distance in etched area
 L : segregation distance along measurement direction
 L_E : segregation distance in etched area along measurement direction.

The minimum width $L_{\min}$ of segregation spot was determined from the etching pattern and the analysis result, and it was taken as the size of segregation spot.

The results of manganese and phosphorus analyses of three different sizes of spot segregation are shown in Fig. 8. In the part of large spot segregation, the segregation ratio of phosphorus increases more sharply than that of manganese, and the segregation ratio of phosphorus reaches a maximum of 60. In the part of small spot segregation, the segregation ratio of phosphorus falls more drastically than the segregation ratio of manganese.

Calculated relations are also shown in this figure as examples with a parameter $L_{\min}$. Discussion on this calculation are made in a later section.

Figure 9 shows the relation between the maximum segregation ratios of phosphorus and manganese at the position in the slab stated below. The relation at the position A is

$$(C_{\max} / C_0)_{\text{Mn}} = (C_{\max} / C_0)_P^{0.20} \dots\dots\dots(3)$$

The relation is nearly equal to the theoretical relation that is introduced under the condition of solid-liquid equilibrium being maintained during solidification as discussed in Section VII.

On the other hand, the following relation was obtained for the position B.

$$(C_{\max} / C_0)_{\text{Mn}} = (C_{\max} / C_0)_P^{0.16} \dots\dots\dots(4)$$

From this relation, a theoretical estimation of diffusion resistance can be made.

The relationship between the size of spot segregation and the segregation ratio of phosphorus is shown in Fig. 10 by selecting the axis ratio of the segregation area as a parameter. When segregation has a small axis ratio or in other words, it becomes spherical in

Fig. 8. Relation between segregation ratios of P and Mn at various positions in segregation region. (A case when segregation shapes of Si and Mn are similar to that of P.)

Fig. 9. Relation between maximum segregation ratios of P and Mn.

Fig. 10. Relation between maximum segregation ratio of P and minimum segregation distance.

shape, the segregation ratio of phosphorus increases. Since most segregations in the central part of continuously cast slabs are nearly spherical, the segregation ratio in the central part is high.

VI. Results of Short-pitch Divided Roll Test

Figure 11 shows the relationship between the manganese content and the ratio of area with a higher manganese content and the relationship between the phosphorus content and the ratio of area with a higher phosphorus content in the slabs cast supported with the conventional rolls and short-pitch divided rolls.

A: Conventional roll, EMS
B: Short-pitch divided roll, EMS

Fig. 11. Relation between Mn (%) and area ratio more than the Mn (%) at abscissa in the middle part of slab and the same for P.

The slabs supported with short-pitch divided rolls have smaller ratios of areas with higher contents than the stated phosphorus and manganese contents, and are thus improved in terms of segregation.

Segregation degrees can also be determined by the size and number of segregation spots. MA analysis is used to determine these values.

The test surface (40 mm×80 mm) of the slab was divided by 100 μm-meshes into 320 000 parts, and MA analysis of manganese was made for every 320 000 parts with a MA beam diameter of 100 μmφ. From the data obtained a segregation region was defined by the next equation.

$$Mn/Mn_0 > 1.32 \dots\dots\dots(5)$$

where, Mn: manganese content determined by MA
Mn₀: manganese content of ladle liquid
If *n* parts of segregation lie contacting each other, these segregation parts make one segregation spot. The diameter of segregation spot is calculated from Eq. (6), if the segregation spot is assumed to be a sphere,

$$Diameter = \sqrt{4n \times 10^{-2} / \pi} \dots\dots\dots(6)$$

Figure 12 shows the relationship between the diameter of manganese segregation and the number of manganese segregation spots having the diameter larger than the stated one in the test slabs.

The number of manganese segregation spots in the slab electromagnetically stirred and supported with short-pitch divided rolls is far less than that in the slab electromagnetically stirred but supported with the conventional rolls. The number of manganese segregation spots of 1.0 mm diameter or more, for instance, is only 3 in the former slab against 19 in the latter. The number of manganese segregation spots of 1 mm diameter or more is 8 in the slab not electromagnetically stirred and supported with short-pitch divided rolls against 15 in the slab not electromagnetically stirred and supported with the conventional rolls.

The non-electromagnetically stirred slabs are characterized by containing manganese segregation spots of larger diameter than those of electromagnetically stirred slab.

○: With ×: Without

Fig. 12. Relation between amount of segregation spots and casting conditions.

*1) Segregation spots smaller than 1 mmφ are not counted.		A	B	C	D
Short-pitch divided roll		○		○	
Conventional roll			○		○
EMS	off	○	○		
	on			○	○

Fig. 13. Relations between segregation area ratio or maximum segregation area and casting condition.

There are other methods of rating slab segregation as

Segregation area ratio
= (Area of Mn > 1.32Mn₀) / Total area analyzed
.....(7)

(Segregation spots smaller than 1 mmφ are omitted.)

Maximum segregation area
= area of the largest segregation spot(8)

Figure 13 shows the relationship between the casting conditions and the manganese segregation area ratio and the relationship between the casting conditions and the maximum manganese segregation area. When the slab is not electromagnetically stirred (A or B), it shows a large manganese segregation area, and when it is electromagnetically stirred, it shows a smaller manganese segregation area. When the slab is electromagnetically stirred and supported with short-pitch divided rolls (C), both the number and

the area of manganese segregation become small.

The formation of equiaxed solidification structure is effective in reducing segregation, and the prevention of bulging is effective in preventing the coarsening of segregation spots.

VII. Discussion

(On the Solidification Phenomena of Spot Segregation)

The results obtained by the analysis of spot segregation in the continuously cast slab by EPMA are the following a) to d). These results a) to d) and e) are discussed here.

- Relationship between $(C_{\max}/C_0)_{Mn}$ and $(C_{\max}/C_0)_P$
- Relationship between $(C_{\max}/C_0)_P$ and the position of segregation spot in the slab
- Relationship between $(C_{\max}/C_0)_P$ and the axis ratio of segregation spot
- Relationship between the segregation ratio and the spot size
- Discussion on the diffusion resistance of solute during solidification of liquid spot

1. Solute Redistribution during Solidification

When a thin film of liquid solidifies, solute redistribution can be written as

$$-dZ(C_L - C_i) = ZdC_L \quad \dots\dots\dots(9)$$

$$C_i = K_E C_L \quad \dots\dots\dots(10)$$

From Eqs. (9) and (10)

$$C_L/C_0 = (Z_0/Z)^{(1-K_E)} \quad \dots\dots\dots(11)$$

$$C_i/C_0 = K_E(Z_0/Z)^{(1-K_E)} \quad \dots\dots\dots(12)$$

where, C_0 : initial liquid composition in mass fraction

C_L : actual liquid composition in mass fraction

C_i : solid composition in mass fraction

Z : half thickness of liquid steel

Z_0 : half thickness of initial liquid steel

K_E : effective partition ratio.

Equation (12) is derived by Scheil,²²⁾ under the assumption that K_E is equal to K_0 . The equation is often referred to explain solidification phenomena.

When liquid, shaped like a long cylinder, solidifies, solute redistribution is written as

$$-2\pi R dR(C_L - C_i) = \pi R^2 dC_L \quad \dots\dots\dots(13)$$

where, R : radius of liquid steel

R_0 : initial radius of liquid steel

thus

$$C_L/C_0 = (R_0/R)^{2(1-K_E)} \quad \dots\dots\dots(14)$$

$$C_i/C_0 = K_E(R_0/R)^{2(1-K_E)} \quad \dots\dots\dots(15)$$

In the case of a sphere, the next equations are obtained

$$C_L/C_0 = (R_0/R)^{3(1-K_E)} \quad \dots\dots\dots(16)$$

$$C_i/C_0 = K_E(R_0/R)^{3(1-K_E)} \quad \dots\dots\dots(17)$$

Equation (17) is also the same as that derived by Scheil. Equations (11), (14) and (16) can be applied to two kinds of solute (for example, phosphorus and

manganese at the same time. The next equation can be obtained.

$$\log (C_L/C_0)_{Mn} / \log (C_L/C_0)_P = (1 - K_{E \cdot Mn}) / (1 - K_{E \cdot P}) \quad \dots\dots\dots(18)$$

When K_E is equal to K_0 as a special case, it becomes

$$\log (C_L/C_0)_{Mn} / \log (C_L/C_0)_P = (1 - 0.84) / (1 - 0.14) = 0.186 \quad \dots\dots\dots(19)$$

This relation is shown in Fig. 9 with a line expressed by a parameter of $f\delta/D=0$.

The EPMA analysis data of the center part (position A) are nearly equal to the theoretical line which is calculated under the condition of $K_E=K_0$. However, the data obtained at the position apart from the center of the slab (position B) are larger in the phosphorus segregation ratio, as compared with the relation between manganese and phosphorus segregation expressed by Eq. (19). Discussions are made on this point.

The effective partition ratio K_E in Eq. (10) is written as

$$K_E = K_0 / \{K_0 + (1 - K_0) \exp(-f\delta/D)\} \quad \dots\dots\dots(20)$$

where, K_0 : equilibrium partition ratio

D : diffusion coefficient

f : solidification rate

δ : thickness of diffusion layer.

This equation is called Burton equation.²³⁾ Although the diffusion coefficients of manganese and phosphorus are not the same, here it is assumed that the diffusion coefficients of phosphorus and manganese are the same. Thus $f\delta/D$ can be considered as a parameter which depends on the solidification conditions.

If the effective partition ratios of phosphorus and manganese are expressed as $K_{E \cdot Mn}$ and $K_{E \cdot P}$, there values can be calculated from Eq. (20), taking $f\delta/D$ equal to 0 and an arbitrary value. The values of Eq. (18) thus determined are shown in Fig. 9. The EPMA data obtained at the position B are near the line of $f\delta/D$ of 0.224. A difference in the results of EPMA analysis at the positions A and B may be caused by the difference in solidification rate. Solidification rate is faster, and the parameter $f\delta/D$ is larger at the position B than those at the position A. It causes higher segregation ratios of phosphorus at the position B.

2. Effect of Form on the Segregation Ratio

The effect of form of liquid steel on the segregation ratio will be discussed here, compared the cases of cylindrical and spherical forms with each other.

From Eqs. (14) and (16), it becomes

$$\log (C_{\max}/C_0)_{P \cdot A} / \log (C_{\max}/C_0)_{P \cdot B} = 3/2 = 1.5 \quad \dots\dots\dots(21)$$

where, $(C_{\max}/C_0)_{P \cdot A}$: segregation ratio for spherical liquid

$(C_{\max}/C_0)_{P \cdot B}$: segregation ratio for cylindrical liquid.

R: Distance (μm) from the center of segregation spot

Fig. 14. Relation of $(C_i/C_0)_P$, $(C_i/C_0)_{Mn}$, $f\delta/D$ and R .

The calculation result shows that the segregation ratio for spherical liquid is 3~4 times as large as the value for cylindrical liquid.

The segregation ratio for the group of the axis ratio of 1.0~1.2 is 1.6 times as large as the value for the group of the axis ratio of 1.2~2.4 as shown in Fig. 10. By a comparison of the results with the theoretical calculation, it may be concluded that the two groups of data in Fig. 10 are those for spherical and ellipsoidal liquids.

Solute concentration at every position in the segregation spot is expressed by Eq. (17) but K_E is an unknown parameter, so $(C_i/C_0)_P$ and $(C_i/C_0)_{Mn}$ can not be calculated. In order to make this calculation, K_E was estimated from the results of segregation ratio for the preparation.

Figure 14 shows the relationship between $(C_i/C_0)_{Mn}$ and $(C_i/C_0)_P$. And the calculated relations between them mentioned above are also shown in the same figure. The values of R shown in Fig. 14 indicate the distances (μm) from the center of segregation spot. The relationship between $f\delta/D$ and the distance (R) obtained from the segregation data is shown in Fig. 15, and it is expressed by the following equation.

$$f\delta/D = 2.0 \times 10^2 R \dots\dots\dots(22)$$

From the Eqs. (17), (20) and (22), $(C_i/C_0)_{Mn}$ and $(C_i/C_0)_P$ can be calculated with an arbitrary radius of liquid steel. This calculation can be made by stepwise calculation dividing R into sections where K_E can be taken as a constant.

An example of calculated result is shown in Fig. 16. In this example the radius of initial liquid was set to be 90 μm. The result shows that phosphorus gives negative segregation in the region of 90 to 45 μm and positive segregation in the region of 45 μm to the center. The value of $2R$ at $(C_i/C_0)_P=1.0$ was defined as a segregation size (L_{min}).

This calculation was also made for $(C_i/C_0)_{Mn}$ and the relationship between $(C_i/C_0)_{Mn}$ and $(C_i/C_0)_P$ is shown in Fig. 8 with the calculated segregation size (L_{min}) as a parameter. The result shows that the relationship between $(C_i/C_0)_{Mn}$ and $(C_i/C_0)_P$ depends on the segregation size.

Solidification phenomena in the part of segregation-

Fig. 15. Relation between $f\delta/D$ and R .

Fig. 16. An example of calculated segregation profile.

spot are discussed theoretically. Therefore the EPMA data of spot segregation are well explained by the theoretical analysis.

VIII. Conclusions

It became clear from the center segregation simulator test results that segregation is insignificant when the amount of bulging is zero but intensifies when the amount of bulging exceeds 200 μm.

The amount of bulging with the conventional rolls was measured to reach a maximum of 250 μm, and the eccentric rolls or bent rolls were known to cause center segregation in continuously cast slabs. To counter these problems, a center segregation alleviating test was made, by the use of a short-pitch divided roll stand.

The test results revealed that center segregation can greatly be alleviated if the solidification structure of the slab is changed to an equiaxed structure, and the bulging of slab is reduced by the use of a short-pitch divided roll stand.

Solidification phenomena in the segregation spot are discussed theoretically. From a comparison of the EPMA analysis data and the theoretical calculation, the following conclusion can be drawn.

Diffusion resistance of solute during solidification of segregation-spot part is expressed as

$$f\delta/D = 2 \times 10^2 R, \quad R(\text{cm})$$

The solute distribution in a segregation-spot can

be explained quantitatively if the diffusion resistance is taken into consideration. At the final stage of solidification in a segregation-spot $f\delta/D$ becomes small and the relation between the theoretical and the examined segregation ratios becomes nearly equal to

$$\log (C_L/C_0)_{Mn}/\log (C_L/C_0)_P = 0.186$$

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