Macro- and

Segregation

Semi-macroscopic

in CC Slabs and

Features of

'T'heir
Effect

the Centerline

on Product Quality*

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Synopsis
The effect of Electro Magnetic Stirring (EMS) and the soft reduction or the reduction of slab thickness by 0.8 mm/m at near the crater end on the centerline segregation in CC slabs has been revealed by macroscopic and semi-macroscopic investigations of slabs and plates. The degree of the centerline segregation has been evaluated in two methods; a macroscopic one by use of sulfur prints and a semi-macroscopic one by use of an EPMA Macro Analyzer.
It has been found that the centerline segregation is composed of inter-connected semi-macro segregates the size of which is 300 pm-' 3 mm, being medium between the inter-dendritic micro segregation and the macro one such as the centerline, V and A segregations in ingots. In the slab cast with the soft reduction, the centerline segregation is narrow in thickness (TM=1.6mm) but high in segregation ratio (Pmax/Po=2.¢), because the mutually interconnected segregates are distributed densely in the narrow thickness. Quite contrary to this, the centerline segregation in the slab cast with EMS is wide in thickness (T1 1~= 3.2 mm) but low in segrega-tion ratio (Pmax/Po=1.7) because the isolated globular semi-macro segregates are sparsely distributed in the wide thickness. Owing to these characteristics of the semi-macro segregates, the degree of the macroscopic centerline segregation visually measured from the sulfur prints is substantially improved by the application of EMS or the soft reduction. It has been estimated, however, by use of the measured values of T1 and Pmax/Po that the volume of the solute enriched liquid transported due to bulging to form the centerline segregation is not significantly influenced by EMS or the soft reduction.
It has been revealed that the degree of the semi-macro segregation or the segregation ratio in the semi-macro segregates increases a little by EMS and substantially increases by the soft reduction. This phenomenon has been qualitatively explained by the effect of EMS and the soft reduction to decrease the volume of liquid steel which forms the segregates after mixed with the solute enriched liquid transported due to the bulging.
The frequency of the occurrence of the Hydrogen Induced Cracking (HIC) in plate has been correlated not to the degree of the macro segrega-tion but to the degree of the semi-macro segregation. It has been also found that the less degree of the semi-macro segregation and, therefore, the improvement of the anti-HIC property of plates is performed by lowering the bulk concentration of phosphorus from 0.010 to 0.005 % and the heat treatment of slab at 1 250 °C for 16 hr.

I. Introduction

The centerline segregation has been one of the long last quality problems in continuous casting of slab. Accordingly, there have been abundant studies on the mechanism of the formation of the segregation and the countermeasures to diminish it. The most popu-lar countermeasure has been the Electro Magnetic Stirring (EMS) of the liquid steel by which the equiaxed crystal increase. It has been described by many authorsl~ that the aggromerate of the equiaxed crystals has the lower permeability of the solute en-

riched liquid steel than the array of columnar den-drites and is preferable to minimize the segregation. New method has been proposed recently to minimize the movement of the solute enriched liquid steel.2~ This method named the soft reduction is composed of reducing slab thickness at near the crater end by giving a steeper taper for the roll gap than the con-ventionally adopted taper to compensate the thermal contraction of the solidified shell. In this work, the effect of the two measures, EMS and the soft reduc-tion, on the centerline segregation has been studied in slabs and plates.
For an improvement of the centerline segregation, the countermeasure has been usually judged in slabs and rarely correlated to the improvement of product quality. The measurement for the Hydrogen In-duced Cracking (HIC) in plates has been included in this work to establish an example of the correlation between the qualities of slab and plate. Incon-sistency has been found, however, between the sus-ceptibility to the HIC in plate and the degree of the centerline segregation visually measured from the sulfur prints.
In order to resolve the above described inconsis-

tency, the morphology and the solute distribution of the semi-macro segregates have been investigated by use of an EPMA Macro Analyzer by which the two-dimensional mapping of solutes can be done for sam-

ples with a relatively large surface area. The term " semi-macro segregates " is used in this paper for the
segregates which constitute the centerline segregation and are larger in size than the interdendritic micro segregation. The effect of EMS and the soft reduc-tion on the susceptibility to HIC in plates has been reasonably interpreted through their effect on the de-

gree of the semi-macro segregation or the segregation ratio in the semi-macro segregates. The EPMA macro analysis has also resulted in the consideration on the mechanism of the formation of the semi-

macro segregates in the slab cast with EMS or the soft reduction.

It has been also revealed that the less degree of the semi-macro segregation is obtained by lowering the bulk concentration of phosphorus and the heat treat-ment of slab. These countermeasures have been

found to improve the anti-HIC property of plates again confirming the correlation between the semi-macro segregation and HIC.

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II. Experimental

1. Casting
Steels for plate and UO pipe were cast by use of Nos. 2 and 3 continuous casting machines in Chiba Works. The No. 2 machine is vertical-bending type Voest machine and characterized by its short roll pitches for the less bulging. The No. 3 machine is vertical-bending type Demag machine and equipped with EMS apparatases at 5.4 and 10.4 m from the meniscus. The EMS at 5.4 m is intended to increase the equiaxed crystals while the EMS at 10.4 m is intended to stir the liquid steel near the crater end. The latter effect on the centerline segregation was studied as a function of the thickness of the liquid core in the strand at the location of the EMS by changing the casting speed. Also tested by use of the No. 3 machine was the soft reduction method2}

proposed to minimize the movement of liquid steel in mushy zone caused by solidification shrinkage and, therefore, the degree of the centerline segregation. The soft reduction was performed by giving two roller segments near the crater end a steeper taper (0.8 mm/m) than the conventional one (0.25 mm/m) which was designed to compensate the thermal con-traction of the solidified shell. The measurement of

the actual roll gaps in the soft reduction zone was carried out by use of different transformers. The results revealed that difference in the taper between the set value (0.8 mm/m) and the actual one during casting (0.72 mm/m), was not substantial. As shown in Table 1, these casting experiment with EMS and the soft reduction were carried out concurrently by use of the two strands of the CC machine to remove

the effects of the superheat in tundish and the solute concentration on the centerline segregation.
Steels with the phosphorous content of 0.005 and 0.010 % were cast by the No. 2 machine to reveal the effect of purification of steel on the centerline segregation.
Slab samples taken from these experimental heats and plate samples rolled from the slabs were subjected to the following examinations.

2. Evaluation of Centerline Segregation
1. Macroscopic Examination of Slabs
A study on the relation between the morphology of the centerline segregation and the solidification structure was pursued by the hydrochloric acid etching on the transverse section (C-cross section) of the slab samples.

The S-prints were taken on the C-cross section of the slab samples and the degree of the centerline segregation was measured visually as AFCS (Areal Fraction of Centerline Segregation) which is defined by:

o ~t2li AFCS(/o)= x
TXW x100 ...............(1)

where, ti, l2: the thickness and the length of i-th segregation line
T, W : the thickness and the width of a slab
as shown in Fig. 1.
This evaluation method for the degree of the center-line segregation is convenient in the sence that the whole area of each C-cross section is covered without too much work.

2. Semi-macroscopic Examination of Slabs
The two-dimensional mapping of solute elements by use of the conventional EPMA has been a con-venient tool for the investigation of interdendritic or micro segregation.3) The inspection area of this method has been limited, however, because of the long time needed for the measurements. The adop-tion of high intensity (120 ciA) electron beam in this work made it possible to map the surface area large enough to study the local feature of the centerline segregation. In this paper this new type of EPMA apparatus is designated as Macro Analyzer in order to distinguish it from the conventional EPMA apparatus. Samples of the size 40 x 40 mm2 for the macro analysis were taken at 1 /2 and 1 /4 width of the slab samples for the transverse and longitudinal cross sections as shown in Fig. 2. The electron beam diameter was adjusted to be 100 and 50 pm for the measurement of the C- and Z-cross sections, respec-tively, and the points of measurement to cover 40 x 40 mm2 was 16 x 104 for the former and 64 x 104 for

the latter section. On the Z-cross sections, segregates including small ones distributed more densely than those on the C-cross sections. Therefore, smaller beam diameter was adopted for the EPMA Macro

Table 1. Casting conditions for the
No. 3 CC machine.

experiments at

Fig. 1. Procedure for measuring Areal Fraction of Center-line Segregation (AFCS).

Fig. 2. Location and direction in the slab of the specimens taken for the macro analysis.

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Analysis of the Z-cross sections to diminish the diffusing effect at the boundary of the segregates Owing to the high intensity of the electron beam, the integral time for one measurement can be shortened to 2 msec and the points of 64 X 104 can be measured within several ten minutes. As will be described

later, the study by the Macro Analyzer has revealed that the centerline segregation is composed of small segregates. The term " semi-macro ", which was first introduced by Tsuchida et a1.,4> is used in this

paper for the segregates to distinguish them from a macroscopic centerline segregation observed as a whole.

3. Test for Hydrogen Induced Cracking (HIC) in Plates Test pieces (20 X 100 X t mm3) of plate were dipped in the corrosive aqueous solution prescribed by BPS or NACE5 and hydrogen induced cracks (HIC) in the pieces were detected by the scanning ultrasonic testing (C-scanning UST), The total area of the cracks projected on the surface of 20 X 100 mm2 was measured by the C-scanning UST. The index of HIC was obtained through the normarization of the measured total projected area of the cracks by a cer-tain reference number.

The hydrogen induced crack is initiated at an elongated manganese sulfide inclusion and propagates along the band structure.6~ The centerline segrega-tion enhances the occurrence of the HIC because the

positive segregation of manganese and sulfur acceler-ates the precipitation of manganese sulfide and the

positive segregation of phosphorus and manganese causes the band structure. The amount of the man-

ganese sulfide inclusions, however, is also dependent upon the degree of sulfide shape control by calcium, which can be evaluated by the Atomic Concentration Ratio (ACR) of sulfur to effective calcium.7~ Thus, the index of HIC can be used, after the effect of ACR is removed, as a measure to evaluate the degree of the centerline segregation.

III Results and Discussion

1, Soft Reduction and EMS to Reduce Macro Segregation

The effect of the soft reduction is shown in Fig. 3 as a relation between AFCS and the casting speed. The high casting temperature is advantageous to

reduce AFCS, but this effect is not so significant as reported by Tsuchida et al.8 The observed value of AFCS is minimized at the casting speed of 1.1 m/min. To interpret this result, the solidus lines calculated with the solidification coefficient of 28 mm•min12

are depicted in Fig. 4. The locations of the soft reductions can be also found in the figure by the broken line which shows the change in the roll gap at each roller segment. The roll gap is reduced by 1.5 mm at the two roller segments used for the soft reduction while it is reduced by 0.5 mm at the other roller segments. By comparison between Fig. 3 and Fig. 4 it may be said that the effect of the soft reduc-tion to decrease AFCS is maximized at the casting speed of 1.1 m/min because the position of the crater end coincides with the one of the soft reduction.

In Fig. 5, the results of the present work (closed circle) for the soft reduction experiments are com-

pared with those reported by Tate et al. (open circle).2) Fair agreement between their and our results indi-cates that the difference in the method, i.e., the adjust-ment of the individual roll2~ or the segment, has minor influence to the effect of the soft reduction.

The effect of EMS was detected in slab samples as two white bands on the sulphur prints. By the approximation that the white band caused when the EMS was applied at 10.4 m indicated the solid/liquid boundary, the fraction of liquid core, f L, was calcu-lated as the ratio of the thickness of the liquid core to

Fig. 3. Change of AFCS with changing VR, for casting with soft reduction.

casting speed,

Fig. 4, Location of crater end in relation to the location of soft reduction.

Fig. 5. Relation
tion.

between AFCS and degree of soft reduc-

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the one of the slab. As shown in Fig. 6, the observed value of AFCS steeply decreases with decreases in

f L from ca. 0.4 to 0.2. It is interesting to note in Fig. 6 that this effect is virtually the same under the single and double EMS conditions. Single EMS condition here stands for the casting with EMS at 10.4 m while the double EMS the one with both EMS's at 5.4 and

10.4 m. Thus, the results in Fig. 6 indicates that EMS near crater end is more effective to minimize

AFCS than that at upper location. The effect of EMS near crater end, however, is diminished when the value of f L is further decreased below 0.2.
The solidification structure observed on the central

zone of the C-cross sections of the slabs is compared in Photo. 1 for the conventional casting (Photo. 1(a)), the casting with the soft reduction (Photo. 1(b)), and the casting with EMS (Photo. 1(c)). It is clear from these photographs that the area of the centerline segregation detected as dark lines or grains is con-siderably reduced by the application of the soft reduc-tion or EMS. This corresponds the decreasing AFCS under the soft reduction or EMS.

Quenching of the crater end by adding lead to the liquid pool has revealed that there is the irregularity of the order of 3-4 mm on the front of solidifying shell.9 When the two solidification fronts growing from upper and lower sides meet at the center of thickness, small cells of liquid steel are formed between the two fronts due to the irregularity. The centerline segre-gation seems to be formed in the small cells by the movement, due to the bulging, of the solute enriched liquid in the mushy zone into the cells. Thus the centerline segregation is originated as the aggromerate of the semi-macroscopic segregates which are formed at the location of the cells and are mutually inter-connected. Here the term " semi-macroscopic " is used because the size of the segregates is intermediate between the sizes of the interdendritic micro segrega-tion and the macro segregation like the center line segregation as a whole or the V and A segregations in ingots. When the soft reduction is applied to the strand near the crater end, the compression force makes the two solidification fronts come closer and

decreases the volume of the small cells. The indica-

tion of the compression can be seen in Photo. 1(b) as the deflection of dendrite arms (enclosed by circle A) and the crack between dendrite arms (enclosed by circle B). The decrease of AFCS can be attributed macroscopically to the decrease of the thickness of the centerline segregation or more microscopically to the decrease of the volume of the segregates due to the compression.
The centerline segregation in the slab cast with EMS is composed of isolated globular segregates which are enclosed by circles in Photo. 1(c). It is also to be noted in the photograph that the globular segregates are distributed over a wider zone than the segregates in Photos. 1(a) and (b). The gradual transformation of the morphology from the one in Photo. 1(a) to the one in Photo. 1(c) explains the decreasing AFCS with EMS because the isolated segregates in Photo. (c) are dismissed in the measurement of the AFCS ac-

cording to the procedure shown in Fig. 1.

2. Investigation of Slabs by the Macro Analyzer

A typical example of the macro analysis for the C-cross section of a slab sample is shown in Fig. 7(a).

Fig. 6. Dependence of AFCS on liquid at the location of EMS.

core fraction, f L'

Photo. 1. Solidification structures
ally (a), cast with the
EMS (c).

in
soft

the slabs cast convention-
reduction (b), and with

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The observed two-dimensional distribution of phos-

phorus or manganese is transformed into one-dimen-sional thicknesswise distribution of the element by averaging the observed concentrations at a thickness-wise ordinate. The one-dimentional distribution is then used to obtain the thickness, TM, and the maxi-mum concentration, Cmax, of the centerline segrega-tion as shown in Fig. 7(b). In Table 2, the thickness and the maximum segregation ratio thus determined for phosphorus, of the centerline segregation are com-

pared for the conventional casting and the castings with the soft reduction and EMS. The slab cast with

the soft reduction has the larger maximum segrega-tion ratio of phosphorus and the smaller thickness than those of the conventionally cast slab. The latter characteristics of the soft reduction slab has been

already interpreted by the compression of the solidifi-cation fronts in the previous section. It is to be noted here that this compression results in the higher maxi-mum segregation ratio because of the higher density of the segregate in the narrow thickness. Quite con-trary to this, the slab cast with the EMS has the smaller maximum segregation ratio of phosphorus and the larger thickness than those of the conventionally cast slab. This is because the globular segregates are dispersed over the wider space as shown in Photo. 1(c). If we assume that the solute enriched liquid steel which moves to form the centerline segregation has the same segregation ratio of phosphorus for the three casting modes in Table 2, the peak area of P/Po>_ 1 in the phosphorous content res. thicknesswise position curve like Fig. 7 (a) may be used as a parameter to represent the volume of the solute enriched liquid steel. Thus, the parameter, ~b, is defined by Eq. (2) to give twice, for simplicity, of the area under the approximation that the peak is a triangle.

~5 = T M x (Pinax/Po-1) ..................(2)

The values of c/i calculated from the observed values of TM and Pmax/Po are listed in Table 2. There is no substantial difference in the values of ~b between

the three casting modes shown in the table. This implies that the bulging is the predominant factor in determining the value of ~b or the volume of the solute

enriched liquid steel moved to form the centerline segregation.
Shown in Fig. 8 are typical examples of the macro analysis for the Z-cross section of slabs cast with EMS and the soft reduction. For the slab cast with EMS, the segregates are globular and isolated and, therefore, the determination of the diameter, D, of the segregates is significant. This was performed, as schematically shown in Fig. 8(c), by use of the line analysis through the maximum segregation point which was determined for each segregates by the two-dimensional mapping. The number distribution of the determined diameter

for the globular segregates is plotted in Fig. 9. It is seen in the figure that the number of segregates with the diameter more than around 2 mm decreases with decrease in f L from 0.4 to 0.2. The decrease, shown in Fig. 6, of AFCS with decrease in f L from 0.4 to 0.2, therefore, corresponds to the decrease in the size of the semi-macro segregates.
Another application of the two-dimensional solute distribution on the Z-cross section is the determination

of the areal fraction which has a certain range of segregation ratio. This application is very important because of the capability of the quantitative compari-son of the centerline segregation between the slabs cast with the soft reduction and EMS despite the dif-ference in the morphology of the segregates, i.e., the isolated globular shape for EMS and the network shape for the soft reduction, as shown in Fig. 8. As an example, the areal fractions for the manganese segregation ratios of 1.0 N 1.2, 5 intervals of 0.1 from 1.2 to 1.7, and more than 1.7 were determined on the

Fig. 7.
Two-dimensional distribution of Mn
cross section, (a), and one-dimensional
bution of Mn, (b), calculated from (a).

on C-
distri-

Table 2. Comparison of parameters to repesent degree
of centerline segregation.

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Z-cross sections for the conventional casting and the castings with the soft reduction and EMS. The re-sults are shown in Fig. 10.
It is important to note in the figure that the areal fractions with the higher segregation ratio for the casting with the soft reduction or EMS is much larger than the ones for the conventional casting; the areal fraction, S1.6, with the manganese segregation ratio larger than 1.6, for example, is 3.3 % for the soft reduction, 0.6 % for the EMS and 0.1 % for the conventional casting. This result shows that both the soft reduction and EMS are not effective to diminish

the degree of the semi-macro segregation.
As shown in Table 2, the thickness, TM, of the cen-terline segregation has the different values for the three casting modes. It is better, for the more precise comparison of the three casting modes, to take into account this difference in the thicknesswise distribu-

tion of the centerline segregation in the evaluation of the degree of the semi-macro segregation, although the at most two times difference in T M shown in Table 2 does not reverse the above discussion based on the

thirty three or six times difference in S1,6.
In Sec. III. 2, it is discussed that the volume of the small cells is decreased by the soft reduction. Figure 9 implies, on the other hand, that the equiaxed crys-tals are more densely filled in the mushy zone and the

volume of the free space among the crystals is de-creased as the fL is decreased. The semi-macro

segregates are formed by the transport, due to bulging, of the solute enriched liquid in the mushy zone to the small cells or the free spaces. The solute concentra-tion of the liquid transported is lowered by the mixing with the liquid which originally exists in the cells or the free spaces. Therefore, it is plausible that the degree of the semi-macro segregation is increased by EMS or the soft reduction because the lowering effect of the concentration of solutes is diminished by the decrease of the volume of the cells or the free spaces due to the application of EMS or the soft reduction.

3. Hydrogen Induced Cracking (HIC) in Plate
The index of HIC measured for the plate samples is plotted against ACR in Fig. 11 for the three casting modes. At a given value of ACR or a degree of sulfide shape control,5~ the index of HIC is largest for

Fig. 8. Typical examples of
of segregates (c).

macro analysis on Z-cross section, (a) and (b), and determination of diameter

Fig. 9. Size distribution of glob
with EMS.

ular segregates in slabs cast

Fig. 10. Areal fraction on the Z-cross section for the inter-vals of segregation ratio.

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the cast with the soft reduction and is a little larger for the cast with EMS than for the conventional

casting. This means that the decrease in AFCS by EMS or the soft reduction is not correlative to de-crease in the index of HIC. The index of HIC rather

has correlation with the areal ratio, shown in Fig. 10, of the semi-macro segregates.
The effect of the bulk concentration of phosphorus on the index of HIC is shown in Fig. 12. It is seen from the figure that the index of HIC is markedly decreased by decreasing the phosphorous content from 0.010 to 0.005 %. To interpret this effect of the phosphorous content, the maximum phosphorous content, Pmax, was measured in the slab samples by the method illustrated in Fig. 7(b) and the relation between Pmax and the index of HIC of the plates rolled from the slabs is examined in Fig. 13. Positive cor-relations are obvious in the figure between the two variables. This confirms the report8~ that the positive segregations of phosphorous and manganese in the centerline segregation causes the band structure which helps the propagation of HIC. The reduction of bulk phosphorous content is effective in minimizing the index of HIC because it decreases the maximum

concentration of phosphorus in the centerline seg-regation.
The positive correlation found in Fig. 13 is incon-sistent with the fact that the index of HIC is not

decreased by EMS although the maximum segrega-

tion ratio in the centerline segregation is decreased by EMS as shown in Table 2. This inconsistency can be resolved by considering as follows : For a particu-lar casting mode, e.g., the conventional casting without EMS nor the soft reduction, the decrease in the maxi-mum segregation ratio defined in Fig. 7(b) corre-sponds to the one in the degree of the semi-macro segregation and, therefore, results in decrease in the index of HIC as shown in Fig. 13. The relation be-tween the maximum segregation ratio and the degree of the semi-macro segregation for the conventional casting, however, is not valid for the casting with EMS. Consequently, the lowering of the maximum segregation ratio by EMS does not result in decreases in the index of HIC.

Another method for reducing degree of the semi-macro segregation is the heat treatment of slabs at high temperatures. The effect of the heat treatment is shown in Fig. 14 in which the maximum segrega-tion ratio in the semi-macro segregates is compared between the slabs as cast and heat-treated at 1 250 °C for 16 hr. Although the scatter of the data in the figure is very large, the comparison of the regression analysis for the as cast slab (solid line in the figure) and heat treated slab (broken line) clearly indicates the marked decrease in the degree of the semi-macro

Fig. 11. Relation between index
conventional, with EMS,
castings.

of HIC and ACR for
and with soft reduction

Fig. 12. Relation between index of HIC and ACR for plate with different phosphorous contents.

Fig. 13. Relation between
segregation zone.

index of HIC and P max

in

Fig. 14. Decrease of semi-macro segregation ratio of man-ganese by heat treatment of slab. (r: correlation coefficient)

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segregation by the heat treatment. The heat treat-ment resulted in the substantial decrease in the index of HIC. It again confirms that the degree of semi-macro segregation is the predominant factor in de-termining the index of HIC.

Iv. Summary

The effect of Electro Magnetic Stirring (EMS) and the soft reduction at near the crater end on the degree of the centerline segregation has been investigated in slab and plate. The degree of the centerline segrega-tion was evaluated by two methods; the macroscopic one by use of sulfur prints and the semi-macroscopic one by use of EPMA Macro Analyzer. The results of the investigation can be summarized as follows :
(1) Both EMS and the soft reduction are effective to diminish macroscopically evaluated degree of the centerline segregation or Areal Fraction of the Center-line Segregation (AFCS).
(2) The centerline segregation in the convention-ally cast slab is composed of the mutually connected semi-macro segregates. The soft reduction makes the segregates disperse in the narrow thickness and, there-fore, makes the centerline segregation narrow in thick-ness but the maximum segregation ratio high.

(3) The centerline segregation in the slab cast with EMS is composed of the isolated globular semi-macro segregates which are distributed in wide thick-ness. As a result, the centerline segregation becomes wide in thickness but low in maximum segregation ratio.

(4) The narrow centerline segregation for the case of the soft reduction and the morphology of the centerline segregation; isolated globular segregates, for the case of EMS explains the small values of AFCS for the slabs cast with these measures. It is estimated, however, by use of the thickness and the maximum segregation ratio that the volume of the solute enriched liquid transported due to bulging to form the center-line segregation is not significantly influenced by EMS or the soft reduction.

(5) The degree of the semi-macro segregation or the segregation ratio in the semi-macro segregates increases a little by EMS and substantially increases by the soft reduction. This can be qualitatively ex-

plained by the effect of EMS and the soft reduction to decrease the volume of the liquid steel which forms the segregates after mixed with the solute enriched

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liquid transported due to bulging.

(6) The frequency of the occurrence of the Hydro-gen Induced Cracking (HIC) is related not to the degree of macro segregation but to the degree of semi-macro segregation. Lowering the bulk concentra-tion of phosphorus and the heat treatment of slab decrease the maximum concentration of phosphorous in the segregates and, therefore, are effective to de-crease the occurrence of HIC.

It has been reported that EMS10~ and the soft reduction2~ improves the durability of the plates to the side bend test. This benificial outcome of EMS

or the soft reduction was also experienced by the authors. This inconsistency between the reports and the results of this work implies that the different prop-erties of the plates are influenced by the different aspects of the centerline segregation, e.g., the porosity, the degree of macro or semi-macro segregations, etc. Therefore, it has to be emphasized that the dis-advantageous effect of EMS or the soft reduction found for the index of HIC can not be generalized without further works, to the other properties of the

plate or the other products. It is required for the future works to reveal what property and to what extent a particular countermeasure for the centerline segregation can improve.

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