Hot Model Experiments on Electromagnetic Stirring at About Crater End of Continuously Cast Bloom*

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Synopsis

For the improvement of centerline segregation and center-porosities in continuously cast blooms, the favorable conditions for electromagnetic stirring near the crater end have been determined by hot model experiments in which the influence of rotational stirring on V-shaped streaks formed at the zone with accelerated downward flow of residual melt caused by solidification shrinkage was investigated. It has been found that by rather weak electromagnetic stirring against the melt core kept in a range from 30 to 50 mm in diameter, V-shaped segregations are quite improved together with control of solidification structure consisting mainly of non-columnar dendrites. It has been observed also that an excessively strong stirring in the core zone with non-columnar structure brings about rather detrimental influence on V-shaped streaks because of coagulation of a solute enriched residual melt in the slow movement of slurry consisting of equiaxed crystals and the residual melt.

The favorable conditions are discussed by taking a solidification sequence into account. They are the stability of non-columnar crystals, the movement of a mushy solid-liquid mixture by electromagnetic stirring, and a change in downward suction flow during solidification.

Based on these results obtained by the hot model experiments, test campaigns have been carried out by utilizing a newly designed electromagnetic stirring unit installed to bloom casters in Mizushima Works. Through-out the campaigns, favorable conditions for electromagnetic stirring at two locations, namely, in the spray cooling zone and near the crater end, have been established for the production of sound blooms with less centerline segregation and center-porosities.

I. Introduction

Studies on electromagnetic stirring of liquid steel core in continuously cast steel slabs and blooms have been actively carried out in order to minimize centerline segregation and centerline porosities. To 9) According to these studies, it is postulated that a flow of liquid steel in the solid-liquid coexisting zone brought about by electromagnetic force, shears off dendrite tips which result in accumulation of equiaxed crystals at about half thickness, and besides it washes out the solute-enriched liquid steel in the interdendritic area which results in so called "white band".

These hypotheses, however, could not be directly applied to the case just before the crater end where the solidification fronts, unidirectionally moving to the centerline, made contacts with each other at the centerline and hence the solidification rate was accelerated.

In this study, the suitable conditions of electromagnetic stirring near the crater end have been determined through hot model experiments and favorable effects of the stirring have been confirmed in test campaigns by use of bloom casters installed with electromagnetic stirring (EMS) units designed after experimental results obtained by the former.5-4)

II. Hot Model Experiments on Crater End EMS

In general, centerline segregation in continuously cast blooms is accompanied by "mini-ingot" formation10) or bridging, where V-shaped segregation streaks and cavities are observed. This fact means that centerline segregation is formed by downward movement of solute-enriched melt which is caused not by bulging, but by negative pressure accompanied by solidification shrinkage.11)

In order to determine the suitable conditions of rotational stirring at just before the crater end, hot model experiments have been carried out.

1. Formation of V-shaped Segregation in a Small Ingot

An experimental apparatus is shown in Fig. 1. A necked part of the sand mold made of MgO is pre-heated up to about 800 °C. Besides, the solidification rate of the lower part of a small ingot 3) is accelerated by a thick bottom plate made of plain carbon steel. As a result of the enhanced flow through the necked part 2) accompanied by the solidification shrinkage of the lower part, V-shaped centerline segregations are formed in the necked part 3).

In preliminary experiments, it was found that the number and distinctness of V-segregation in the necked part depends on the ratio of cross sectional area of the lower part to that of the necked part, namely, (Dn/4)/(Dl/4), as seen in Fig. 1 and Table I(a). Typical examples of V-shaped segregation observed in the case of a small ingot with diameter of the necked part of 40 mm are shown in Photo. 1. When electromagnetic stirring was not applied (the left one), three V-shaped segregations were observed in the necked part with diameter of 40 mm. Meanwhile, in cases of small ingots with diameter of the necked part of 60 mm, only one or two V-shaped segregations were observed. In addition, distinctness of V-shaped segregation diminished with lowering in heating temperature of the necked part.

These phenomena can be understood in terms of the downward flow velocity of residual melt in a core zone which presumably depends on the cross sectional area in the necked part 3) for the melt to move downward and the amount of melt to fill up shrinkage


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cavities in the lower part A. Values of the volume ratio of solidification shrinkage of the part A to the volume of part is given in Table 1(b) as S.R. (%) together with dimensions of small ingots, the ratio, \( \frac{D_0}{D_1} \), and the number of V-shaped segregations.

2. Experiments

Hot model experiments consist of two types. In type I, the suitable conditions of electromagnetic stirring for the improvement of centerline segregation have been determined through various examinations of stirring effects on solidified structure and centerline segregation. In type II, the influences of electromagnetic stirring and solidified structure on the formation of so-called white bands and the dispersion or coagulation of segregation streaks have been studied. Therefore, duration of electromagnetic stirring was strictly controlled, and solidified structure was controlled to be either columnar or equiaxed by controlling the superheat of liquid steel just before pouring into the mold.

An outline of experimental details are as follows.

1) Chemical composition (\%) of liquid steel: \( C = 0.50, \ Si = 0.25, \ Mn = 0.90, \ P = 0.050, \ S = 0.020, \ Al = 0.050 \)

2) Melting furnace: High frequency induction furnace with capacity of 50 kg

3) Casting: Top pouring

4) Superheat:
   - Type I: 150±10°C
   - Type II: about 10°C. Temperature of liquid steel is lowered by cooling indirectly through a water jacket attached to the bottom of refractory guide for liquid steel.

5) Electromagnetic stirring:
   - For ingot with round cross section:
     - Rotary stirring in the horizontal plane with maximum magnetic flux density of 300 Gauss at the midst of the mold.
   - For ingot with rectangular cross section:
     - Stiring in the vertical direction in one of solid-liquid interfaces by use of a stirrer attached to one of the wide faces of an ingot.

6) Timing of electromagnetic stirring:
   - Type I: a) Continuous stirring from 1 to 4 min after the end of pouring till the completion of solidification.
     - b) Intermittent stirring with a cycle of 15 sec or 30 sec for turn-on and turn-off of stirring.
   - Type II: Stirring only at the predetermined timing during 30 sec after the end of pouring, or continuous stirring from 1 min after the end of pouring to the completion of solidification.
7) Temperature measurement: At the midst and at a quarter of diameter in the necked part, \( \Phi \).

From these temperature measurements the solidification rate of liquidus \( (K_L) \) and solidus \( (K_S) \) were determined according to an equation as follows:

\[
d(1-2d/3R)^{1/2} = Kt^{1/2} \quad \ldots \ldots \ldots \ldots \ldots \ldots (1)
\]

where, 
- \( d \): solidified shell thickness (mm)
- \( R \): ingot radius (mm)
- \( t \): time for solidification (min).

In Eq. (1) the acceleration of solidification near the axis was taken into account through a heat balance equation at the solid–liquid interface.

The effects of electromagnetic stirring are evaluated in terms of the following parameters characterizing the solidification structure and centerline segregation:

Type I: Number, width \( (W_V) \), and length \( (L_V) \) of V-shaped segregation, and width of equiaxed zone \( (W_{EQ}) \) as is shown in Fig. 2. Degree of centerline segregation classified to three grades, large (L), medium (M), and small (S) by use of S-prints and solute distribution profiles measured by a mapping analyzer.12)

Type II: Downward flow velocity of residual melt in the necked part estimated from negative segregation profiles of carbon and sulfur together with changes in solidified structure in the radial direction.

III. Experimental Results and Discussions of Hot Model Experiments

1. Flow Velocity and Solidification Rate

Rotating velocity of liquid steel was measured optically by use of a corundum ball as a tracer which floated at the surface of liquid steel filled up to the upper end of the necked part. Chemical composition of liquid steel was controlled to be 4.5 % C, 1.0 % Si, 1.0 % Mn, and 0.1 % P to lower the melting point. The intensity of electromagnetic field to stir liquid steel was controlled to be 125 Gauss (for ingot with neck diameter of 40 mm) or 175 Gauss (for ingot with neck dia. of 60 mm) at the midst of the mold. The maximum rotating velocity estimated is given in Table 2.

In addition, the velocity of liquid steel with lower alloying elements is assumed higher by about 3 % than the values mentioned above by taking difference in electric conductivity of liquid steels into account.

Solidification rates for liquidus \( (K_L) \) and solidus \( (K_S) \) fronts were determined by use of Eq. (1) and measured cooling curves, in which liquidus and solidus temperatures were assumed to be, respectively, 1483 and 1350 °C.13) Values of \( K_L \) and \( K_S \) are listed in Table 3. The difference in average values of \( K_L \) and \( K_S \) between hot model experiments of types I and II could be explained from the difference in the heating conditions of the necked part. In case of type I, preheating of the necked part was continued by use of a nichrome wire wound around the part until the axis of a small ingot solidified completely. Meanwhile, in type II the winding was omitted and pre-heating was stopped several minutes before casting. In addition, solidification rate thus calculated were confirmed to be consistent with that estimated from locations of white bands and timings of electromagnetic stirring.

2. Hot Model Experiments, Type I (Columnar Solidification)

In case of an ingot without stirring, V-shaped segregations were distinctly observed in a zone of columnar structure growing to the axis. In electromagnetically stirred ingots the sedimentation of equiaxed or branched columnar dendrite crystals were observed (Photo. 2). The effects of rotary stirring on the solidification structure and the segregation profile are summarized in Figs. 2 and 3, where \( n, W_V, L_V \), and \( W_{EQ} \) denote the number, the width, the length of V-shaped segregation, and the width of equiaxed zone, respectively. From these figures, it is clear that the equiaxed crystals formed by rather weak stirring with rotational velocity lower than 8.5 cm/sec effectively prevent a V-shaped segregation from forming. In this case, however, a white band is formed at the structure boundary of the columnar and the equiaxed, as is expected.

As far as the influence of stirring force in terms of intensity of rotary stirring on V-shaped streaks is concerned, marked improvements are observed by an increase in stirring force and attain to the maximum at values of rotating magnetic field, namely, 125 and 175 Gauss, respectively, for ingots with diameters of 40 and 60 mm of the necked part, as is shown in Fig. 2. Through further experiments changing the timing and mode of stirring, it is suggested that in order to prevent the V-shaped segregation the diameter of residual melt should be kept within a range from 30 to 50 mm (Table 4 and Photo. 3). Besides, in case of rather weakened stirring with an interval of 15 to 30 sec, the V-shaped streak and a white band is simultaneously minimized as is
shown in Photo. 4 and Figs. 2 and 3. In these figures, values of the parameters to characterize segregation profiles for the small ingots with such intermittent stirring are very favorable.

3. Hot Model Experiments, Type II (Non-columnar Solidification)

As was mentioned before, the solidification structure was controlled to consist mainly of non-columnar crystals by chilling liquid steel. Besides, in some experiments the duration of electromagnetic stirring was strictly controlled to be 30 sec in the initial stage of solidification (after 1 to 2.5 min from the end of pouring) to find conditions in which a white band was formed in the case of non-columnar solidification.

Typical examples of solidified structures and sulfur prints are given in Photos. 5 and 6. For some of small ingots thus obtained, distribution profiles of solute (in terms of $C/C_0$, where $C$ is chemical analysis of carbon and $C_0$ is ladle analysis) in the direction of solidification at about an half height were determined by chemical analysis as were given in Fig. 4. Changes in solidified structure in the radial direction are shown in addition to the locations of white bands and liquidus fronts ($T_L$) going ahead during electromagnetic stirring in the figure. In spite of a variety of casting conditions, negative segregation is observed in all ingots at about 20 mm from ingot surface, which corresponds to the position just inside the V-streaks as is observed in typical examples of S-prints on longitudinal cross section of the small ingots (Photo. 1 and Fig. 4).

It is clear in Fig. 4 that a white band is observed only in two ingots, namely, those with higher casting temperature and electromagnetic stirring at initial stage of solidification (Run No. H-0.5 and 1). Location of a white band corresponds to a transition point of solidified structure from columnar to non-columnar (at about 10 mm from surface of the ingots cast with higher super heat). In case of an ingot with higher casting temperature and with stirring from 2 to 2.5 min after the end of casting (H-2), however, a white band cannot be observed in spite of a solidified structure change from columnar to branched columnar.

On the other hand, a clear white band cannot be

Table 4. Effect of diameter of liquid core in the necked part at the start of EMS on centerline segregation of the small ingot with neck diameter of 60 mm.

<table>
<thead>
<tr>
<th>Timing of EMS</th>
<th>$D_{D-1}$ (mm)</th>
<th>$D_s$ (mm)</th>
<th>Degree of segregation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Just after pouring</td>
<td>2.4</td>
<td>1.0</td>
<td>53 Good</td>
</tr>
<tr>
<td>1 min after pouring</td>
<td>5.3</td>
<td>2.5</td>
<td>45 Better</td>
</tr>
<tr>
<td>2 min after pouring</td>
<td>7.4</td>
<td>3.7</td>
<td>38 Better</td>
</tr>
<tr>
<td>3 min after pouring</td>
<td>9.2</td>
<td>4.9</td>
<td>32 Not changed</td>
</tr>
<tr>
<td>4 min after pouring</td>
<td>10.5</td>
<td>6.2</td>
<td>26 Not changed</td>
</tr>
</tbody>
</table>

$D_s$ : thickness of completely solidified shell when EMS is turned on
$D_{D-1}$ : thickness of solid-liquid coexisting zone when EMS is turned on
$D_L$ : diameter of bulk liquid core in the axis of the necked part when EMS is turned on

Fig. 2. Effect of EMS on number ($n$), width ($W_y$), and length ($L_y$) of V-shaped segregation, and degree of centerline segregation.

Fig. 3. Relations between width of equiaxed zone ($W_{eq}$), intensity of magnetic field ($B$), and width of V-shaped segregation ($W_y$).
formed in case of ingot with lower casting temperature (L-0.5, 1 and 2) with similar stirring condition as ingots with higher casting temperature.

Accordingly, it is supposed that in case of non-columnar structure a clear white band cannot be formed by electromagnetic stirring.

Another important finding in the hot model experiments for ingots cast with liquid steel with lower super heat is that strong electromagnetic stirring (300 Gauss) continuing from just after the end of pouring till the end of solidification is not favorable for dispersing segregated grains as is shown in Photo. 7.

**4. Discussions on Hot Model Experiments**

Solidification structures and segregation profiles of most favorable ingots obtained by controlled electromagnetic stirring in the hot model experiments are shown in Photo. 8 in comparison with those obtained without stirring. V-shaped streaks observed in a small ingot without electromagnetic stirring is finely dispersed in the inter-equiaxed grains by applying EMS. The assumption mentioned above can be supported by Fig. 5 in which a concentration profile of phosphorus (measured by a mapping analyzer)
near a V-streak is compared with that for the necked part free from a V-streak. In Fig. 5, difference between the profiles is quite small. As is shown in Photo. 8, solidification structure can be controlled even in case of an ingot with rectangular cross section by intermittent stirring. A half of V-shaped streaks is observed in the left ingot of the figure and meanwhile growth direction of another half is changed to inverse V-shape by upward movement of liquid steel driven by a linear motor type stirrer. By altering stirring mode from continuous to intermittent, a segregation streak loses its continuity and disperses in the necked part.

As mentioned previously, there exist a suitable condition too in controlling V-shaped streaks in non-columnar solidification. In case of strong stirring continuing to the completion of solidification, a more distinct V-shaped streak was observed, as was shown in Photo. 7. On the other hand, when electromagnetic stirring was limited in the initial stage of solidification (1.5 min after the end of pouring) the streak was minimized. Concerning the phenomena the additional following experiments have been carried out: liquid steel with similar chemical composition was poured into a mold without a necked part (100 mm in dia.), and melt in the mold was continuously stirred during pouring to the end of solidification. As is shown in Photo. 9, distinct radial streaks were observed in a core zone where fine grained equiaxed crystals were accumulated as a result of strong stirring (300 Gauss). Meanwhile, a distinct V-shaped streak was not observed in the vertical cross section of the ingot. When one assumes that the streak is formed in a direction of the vector made by solidification rate and the rotational velocity, the latter can be estimated from angle of the streak to tangential direction: By use of measured angle (18+2 deg) and solidification rate (3.4 mm/min), one obtain a value of 0.2 mm/sec as the rotational flow velocity. A mapping analysis of the streak shows that the phosphorus content of the streak is about 0.20% which corresponds to the content expected for residual melt with solid fraction of
0.7 by use of Pfann’s equation.\textsuperscript{14} Besides, solidus temperature in solute enriched melt (with fraction of solid larger than 0.7) is lowered by about 200 °C,\textsuperscript{13} if components other than phosphorus are enriched also to those expected from the Pfann’s equation and carbon to those from the lever rule.

Accordingly, the radial streaks shown in Photo. 9 was supposedly formed by coagulation of solute enriched residual melt in slow movement of slurry consisting of residual melt and equiaxed crystals driven electromagnetically. The streaks observed in Photo. 9 may change its form to V-shape as is observed in Photo. 7 under a condition where downward movement of the slurry is enhanced as in the case of the ingot with a necked part.

The driving force of V-shaped streaks is downward flow of residual melt through a narrow channel as is shown by Tomono et al. in the cold model experiment.\textsuperscript{7} The mechanism of V-shaped streaks formation in the small ingot with a necked part is discussed by taking shell growth in the various part into account Fig. 6 is an example. The growth rate of a shell in the necked part is estimated at the critical condition at which any melt in the interdendritic space cannot move by electromagnetic force, namely, at the solid fraction of 0.67.\textsuperscript{22} By use of area in the necked part available for residual melt to flow together with shrinkage in the lower part of the small ingot, the downward flow velocity is estimated as is shown in Fig. 7, in which shrinkage by solidification is assumed to be 4.0 %.\textsuperscript{16} Besides, location of the line with solid fraction of 0.67 in the solid–liquid coexisting zone is determined by using measured temperature and by assuming the following equation.\textsuperscript{17}

\[
T = T_M - (T_M - T_L)/(1 - f_s(T_M - T_S)/(T_M - T_S))
\]

where, \(T_M\): the melting point of pure iron
\(T_L\): liquidus temperature

\(T_S\): solidus temperature.

Meanwhile, the flow velocity in the necked part can be estimated from negative segregation, which is derived by chemical analysis of specimen taken from the necked part with a pitch of 1 mm by use of a turner. In deriving the flow velocity near a white band, an equation by Sugitani et al. for 0.5–0.6 % C steel is used.\textsuperscript{18} As is shown in Fig. 7, the flow velocity, \(U\) thus obtained takes the maximum values of about 2 cm/sec at about 2 cm from the surface.

Velocity of liquid steel in the interdendritic space was estimated by use of the equation by Nomura et al.\textsuperscript{19}:
\[ \frac{\partial f_L}{\partial C_L} = \frac{k + (1 - \beta - k + 9(1 - \beta)V \Delta T \varepsilon)}{(1 - \kappa)C_L} f_L \quad \ldots(3) \]

where, \( f_L \): the fraction of liquid
\( k \): the distribution coefficient
\( \beta \): \((\rho_L - \rho_S)/\rho_S\) by taking \( \rho_L \) and \( \rho_S \) respectively, as density of liquid and solid steels
\( V \): the interdendritic flow velocity of liquid steel
\( \Delta T \): the temperature gradient
\( \varepsilon \): the cooling rate
\( C_L \): the solute concentration in liquid.

In Eq. (3), the term of \( \Delta T \varepsilon \) is equal to reciprocal of solidification rate, \( R \) and can be estimated from temperature measurement mentioned before. By integration of Eq. (3) from \( f_L \) = 1 to \( f_L \) and \( C_L \) to \( C_S \), one obtain \( C_L \) as a function of \( V/R \) and \( f_L \). In addition, the solute concentration after solidification, \( C_S \) is given by following equation.

\[ C_S = \alpha C_L(f_L = \alpha) + (1 - \alpha)C_S(f_L = \alpha) \quad \ldots\ldots(4) \]

where, \( \alpha \): fraction of liquid at the point where interdendritic flow velocity comes to zero
\( C_L \), \( C_S \): the solute concentration in liquid and solid phases at that point, respectively.

For calculation by use of Eqs. (3) and (4), value of 0.33 is assumed for the critical fraction.\(^{19}\)

Typical examples of flow velocity profiles obtained in a manner mentioned above is shown in Fig. 7. In the last stage of solidification flow velocity agrees well with those evaluated from solidification shrinkage and cross sectional area for fluid flow. In a region where solidification front with \( f_L \) of 0.33 does not attain 15 mm, however, flow velocities thus estimated differ each other. It means that in a region of \( x \) from 0 to 15, negative segregation of carbon is higher than those expected from downward suction flow of residual melt. Such a difference is supposed to take place, assuming that residual melt with higher solute concentration floats upward by gravitational force until solidification front with \( f_L \) of about 0.2 reaches the axis.

Umeda \textit{et al}.\(^{30}\) suggested the condition for an equiaxed crystal to survive as shown in Fig. 8 in the temperature gradient \( \varepsilon \), flow velocity plane. Numbers in this figure denote the ratio of heat flux along a primary arm of a columnar dendrite to that at the root of it (perpendicular to the axis). From the figure it is understood that larger the ratio, more stable columnar dendrites become. Changes of solidified structure in the core zone of the small ingots are shown in the plane by use of temperature gradient and flow velocity estimated previously. In the figure several tendencies are observed. In an ingot without stirring plots moves gradually to the right-lower corner, but columnar crystals survive till the last stage of solidification. On the other hand, in an ingot (L-2), non-columnar crystals once introduced by chilling and/or stirring changes to columnar in a region with a larger temperature gradient. In addition, in cases of ingot with higher pouring temperature and with EMS (H-0.5, H-1, and H-2), non-columnar crystals brought about by shearing of dendrite tips during electromagnetic stirring survive till the end of solidification. These facts suggest that an equiaxed crystal is stabilized in the lower, right-hand-side area of the figure, in other words, by decreasing the constitutional super cooling in front of growing crystals with the aid of electromagnetic stirring.

From hot model experiments, favorable conditions for electromagnetic stirring to minimize centerline segregation has been established as follows:

(a) The radius of residual melt must be controlled in the range from 30 to 50 mm in a case of columnar structure.

(b) Stirring force required is in a range from 100 to 200 Gauss in terms of magnetic field strength.

(c) In non-columnar structure, stirring continuing till the end of solidification is unfavorable. Intermittent stirring or stirring before the liquidus front approaches to the axis is rather better.

\textbf{IV. Experiments on Bloom Casters}

\textit{I. Experimental Conditions}

Test campaigns on electromagnetic stirring near the crater end of a bloom caster have been carried out by use of No. 1 caster of Mizushima Works. In the experiments one or both of the stirring units installed in the spray cooling zone and near the crater end were used.

A stirring unit to induce rotational flow of liquid steel in the plane vertical to casting direction have been newly designed for No. 1 bloom caster by use of results obtained in the hot model experiments. Maximum stirring force in terms of intensity of magnetic field was set to be 350 Gauss at the axis of the cast bloom by taking some current loss by solidified shell into account.

Conditions for electromagnetic stirring and continuous casting are as follows:

Maximum electric power supply for the stirring unit: 5–50 Hz, 60 kVA. In addition, residual melt was electromagnetically stirred by the unit at the
secondary cooling zone with constant power supply.

Steel grades:

Mainly low carbon steel for cold heading use and high carbon steel for wire use. More than ten heats were examined for every set of testing conditions.

Size of cast blooms:

250 x 300 mm (No. 1 bloom caster).

Casting speed:

0.6 to 1.1 m/min, solidified shell thickness at the location of electromagnetic stirring was varied by controlling casting speed in addition to reset location of a stirring unit.

Super heat: 20 to 45 °C.

Effects of electromagnetic stirring were mainly evaluated on cast blooms in terms of the following characteristic values: area fraction of equiaxed crystals on the upper side, degree of centerline segregation classified into five grades by use of S-prints on the longitudinal cross section, segregation ratio of the carbon content determined by chemical analysis of specimens taken by use of a drill with diameters of 3 mm or 5 mm from axis of cast bloom to that by ladle analysis.

2. Experimental Results and Discussions

1. Change in Solidification Structure by Crater End EMS

In order to estimate the flow velocity of liquid core driven by a crater end EMS unit, casting speed was raised by about 10% to the standard to control solidification structure at the stirring point to be columnar: Solidified structure cast under the conditions mentioned above is shown in Photo. 10 in comparison with those observed in blooms stirred in the spray cooling zone. It is noted that a change in solidified structure takes place in a strictly controlled manner in case of crater end EMS. Flow velocity of residual melt near the boundary in solidification structure in Photo. 10 is evaluated to be in a range from 0.5 to 5 cm/sec by use of negative segregation in carbon content (chemical analysis with a pitch of 1 mm). Accordingly, it is supposed that for controlling solidified structure the crater end EMS with rather weak stirring force is superior than EMS at spray cooling zone.

In addition it is confirmed in test campaigns that white band cannot be formed in an equiaxed zone, agreeing well with the fact observed in the hot model experiments.

2. Effect of Crater End EMS to Stabilize Equiaxed Crystals

Area fraction of equiaxed crystals in the upper side of cast blooms stirred near the crater end was compared with that obtained for EMS in spray cooling zone in Fig. 9. Casting conditions of the former were kept as similar as possible to the latter. The area fraction rather increases by applying crater end EMS especially in case of high carbon steel blooms.

This fact can be attributed to the effect of crater end EMS to stabilize equiaxed crystals as is pointed out before in Sec. III. 3. In this case multiplication of equiaxed crystals by crater end EMS may not occur because flow velocity induced by electromagnetic stirring is not so large. However, if gradients in temperature and solute content develop in the mushy zone under the condition without any artificial movement of residual melt, a columnar dendrite starts to appear as is shown in Photo. 5. The effect of crater end EMS to suppress appearance of columnar dendrites is supposed to be become larger with an increase in carbon content as is shown in Fig. 9.

Values of segregation index in terms of C/C₀ (C: average carbon content of specimen taken by use of a 5 mm drill by a pitch of 30 mm from specimen with length of 300 mm taken from central axis of cast bloom, C₀: ladle analysis of carbon) vary with stirring intensity, \( I^{1/2} \) (I is current in A and f is frequency in Hz of an electric power supply to the stirring unit) and diameter of residual melt in cast bloom which is electromagnetically stirred. As is shown in Fig. 10, the value of segregation index is lowered from about
1.3 to about 1.2 with increase in stirring force as a sum of both of the electric power supplied to stirring units. Besides, casting conditions to maintain the diameter of residual melt at about 40 mm were chosen so that segregation in high carbon blooms could be suppressed to the minimum.

The tendency on the suitable diameter of residual melt is quite similar to that observed in the hot model experiments.

Index of frequency of cuppy fracture tested on specimens taken from a coil of hard wire is shown in Fig. 11. By applying crater end EMS in addition to EMS at spray cooling zone, the index was markedly reduced to the lower level and hard wire free from breakage during drawing can be produced even if superheat of liquid steel is higher than 25 °C.

V. Summary

The suitable conditions for electromagnetic stirring were found:

1. Diameter of residual melt at the stirring should be kept in a range from 30 to 50 mm.
2. Stirring force should be kept in a rather weak range lower than 300 Gauss in terms of strength of magnetic field.
3. An intermittent stirring with a short interval is better for dispersion of V-shaped streaks.

The favorable conditions are discussed by taking of following solidification phenomena into account: shearing of dendrite tips; and movement of mushy solid-liquid mixture by electromagnetic stirring and change in downward suction flow during solidification.

Based on these results obtained by the hot model experiments, test campaigns have been carried out by use of newly designed electromagnetic stirring unit installed to bloom casters in Mizushima Works. Throughout the campaigns favorable conditions to produce sound blooms by electromagnetic stirring near the crater end have been established.

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17) J. Matsuno: Private communication.