Freezing Rate and Internal Structure of Heavy Carbon Steel Ingot*

By Kiichi NARITA** and Takasuke MORI**

Synopsis

The authors have examined the freezing process of heavy ingots with the aid of an electronic computer and have conducted a few analyses on the relationship of the equi-time solidus line, the freezing rate (the velocity of averaged advancing solidus line), the acceleration of the freezing rate, and the staying time with the internal structure. The results obtained are as follows.

(1) There is very close relations among the freezing rate, its distribution, and the solidification structure.

(2) Inverse V segregation appears in the region where the acceleration of the freezing rate is positive, and if this condition is satisfied it can be observed not only in the equi-axial crystal region, but also in the granular crystal region.

(3) Since the pouring temperature has a significant influence on the internal structure, it is necessary to consider the difference between the pouring temperature and the solidus temperature when one refers to the internal solidification structure.

(4) The solidification structure along the equi-time solidus lines at the top part of the ingot much differs from the bottom parts of the ingot. For example, the internal structure of a 20 t ingot 2 hr after the pouring is consisted of branched columnar crystals at the top, equi-axial crystals in the middle, and fine equi-axial or granular crystals at the bottom.

(5) The electric arc hot topping of the ingot riser gives some influences on the last solidifying zone to form the fine equi-axial crystal or granular crystal zone at the lower end and the near-by region.

I. Foreword

Various kinds of defects are often found in heavy steel ingots. For instance, a large amount of oxide inclusions in the negative segregation zone, the aggregation of sulfide inclusions and micro-cavities in the inverse V segregation zone, the occasional sand marks*** at the top and bottom of the ingot, and the various segregation phenomena such as negative segregation, inverse V segregation, V segregation, etc. will often cause some troubles. Among these defects, except the sand mark which seems to be due to a macroscopic foreign inclusion, negative segregation, inverse V segregation, V segregation, as well as the defects to be found in these segregation zones, are formed during the freezing process of the molten steel. It is also considered that they are closely related to the mass transfer during the freezing process of remaining molten steel, and also to the freezing mechanism. Although a great number of researches have been carried out and a variety of interpretations have so far been reported on the causes of these defects,¹⁻¹⁰⁾ it is rather hard to say that the phenomena occurred during the freezing process of ingot have been studied objectively and understood thoroughly.

The authors have been much interested in these problems, and have so far achieved successfully the examination and comparative investigation of the internal properties of a number of ingots.¹¹⁻¹⁴⁾ For this purpose, by cutting the atmospherically cast ingot of the basic electric arc furnace, the atmospherically cast ingot of the acid open hearth furnace and the vacuum cast ingot of the basic electric arc furnace, sections of these ingots were examined by the following ways; observations of the macrostructure and the sulfur print, the dye mark test, the magnetic flow detecting test, the auto-radiography, optical and electron microscopies, X-ray diffraction analysis, EPMA, chemical analysis, etc. Like many other studies of this field, however, previous works made by the authors were insufficient for discovering the generation mechanism of the various segregations in the ingot, the relationship between the freezing phenomena and freezing structure, and so on.

The results of the freezing process as well as the results on the relationship of the freezing rate and its acceleration with the internal solidification structure of the ingots are presented in this report.

II. Experimental Procedure

1. Experiment Specimens

In the present research, three different ingots were used: a 20 t 16-angle fluted ingot melted by a nominal 25 t Heroult basic electric arc furnace and cast in an air atmosphere (hereinafter to be referred to as the BEAC ingot); a 20 t 16-angle fluted ingot melted by the same basic electric arc furnace and cast in a vacuum (hereinafter to be referred to as the BEVC ingot); and a 20 t 16-angle fluted ingot melted by a nominal 60 t Merz acid open hearth furnace and cast in an air atmosphere (hereinafter to be referred to as the AOAC ingot).

Each test ingot was divided into six equal sections after removing the feeder head, and then plates of about 30 mm in thickness were cut out from these sections both in the lateral and the longitudinal planes along the central axis. Figures 1 and 2 briefly show the shape and the cutting procedure of a test ingot, and Tables 1 and 2 show the chemical compositions and the principal casting conditions of these ingots.

2. Auto-radiography

When a substance is exposed to thermal neutron

* Presented at the 75th ISIJ Meeting, April, 1968, in Tokyo. Manuscript received December 25, 1970.

** Central Research Laboratory, Kobe Steel, Ltd., Wakinohama-cho, Fukiai-ku, Kobe 651.

*** "Sand mark" means one of the defects found in semifinished and finished steels, which is caused by the existence of macroscopic indigenous and exogenous non-metallic inclusions in steel ingot.

Table 1. Chemical composition of test ingot (wt%)

Ingot	Design	C	Mn	Si	P	S	O	N
BEAC	S 45 C	0.47	0.62	0.27	0.048	0.021	0.0067	0.0076
BEVC	S 45 C	0.42	0.58	0.29	0.021	0.012	0.0030	0.0060
AOAC	S 45 C	0.43	0.62	0.26	0.022	0.019	0.0089	0.0054

BEAC : Basic electric arc furnace, air cast

BEVC : Basic electric arc furnace, vacuum cast

AOAC : Acidic open hearth furnace, air cast

Table 2. Casting conditions

Ingot	Design	Teeming condition	Ingot weight (t)	Tapping temp. (°C)	Teeming temp. (°C)	Teeming time
BEAC	S 45 C	air	20	1 605	1 524— 1 515	15'15"
BEVC	S 45 C	vacuum	20	1 642	1 516— 1 515	7'07"
AOAC	S 45 C	air	20	1 580	1 502— 1 490	15'12"

Ingot for vacuum cast

Ingot for air cast

Fig. 1. Shape of air and vacuum cast ingots

Fig. 3. Radiation decrease of irradiated isotopes

$$N = 6.02 \times 10^{23} \times \theta \cdot W_a / M, \quad \lambda = 0.693 / T_{1/2}$$

Consequently, by substituting the content and the nuclear characteristics of each element in a specimen obtained from the test ingot into Eq. (1) one can calculate the radioactive intensities to be caused by the various radioactive nuclides generated in the specimen. In Fig. 3, the generation and the decrement of the nuclides generated by the thermal neutron irradiation in the S45 C test ingot are shown as a function of time. As clearly indicated in this figure, the radioactivity of ^{64}Cu is strongest for the period of 20 to 70 hr after the irradiation. Therefore, it is possible to know the distribution of copper or copper and manganese in the specimen if the autoradiography is taken in this period. Furthermore, the detail observation and the identification of the internal structure of the ingot can also be made from the difference of the distribution coefficients of such elements between the liquid and solid phases.

rays, the elements composed of the substance are radioactivated mainly by the (n, γ) reaction and the intensity of radioactivity of a generated radio-isotope is expressed by Eq. (1):

$$A = N \cdot F \cdot \sigma \cdot (1 - e^{-\lambda t}) \cdot e^{-\lambda' t} \quad \dots \dots \dots (1)$$

where,

* These symbols are common to the paper, "A Study of the Solidification of Heavy Carbon Steel Ingot", *Trans. ISIJ*, **12** (1972), 83, in this issue.

Fig. 4. Segregation and distribution of equi-liquidus and equi-solidus line, and their differentials of heavy steel ingot of BEVC (20 t)
 (a) Distribution of equi-solidus line and equi-velocity line of solidification in radial direction
 (b) Distribution of liquidus and solidus line, and their differential on the axis
 (c) Segregation of sulphur

III. Experimental Results

1. Calculated Results and the Segregation of Heavy Steel Ingot

For BEVC ingot, the equi-time solidus line and the equi-freezing rate distribution in the radial direction, the solidus line and the freezing rate on the central axis of the ingot, and the distribution of sulfide inclusions are shown in Fig. 4 in comparison with each others. It has become clear that there is a very close relationship between the calculated results and the tendency of sulfide segregation found in the freezing process.

2. Freezing Rate and the Solidification Structure of the Ingot

The chemical components of molten steel, the melting temperature, and the pouring conditions have some influence on the solidification structure of the ingot. The effects of the freezing rate which gives the principal influence on them are shown in Figs. 5 to 8 by referring the BEVC ingot as an example.

Figure 5 shows the relation between the freezing rate and the solidification structure at the Y_6 level of the ingot top, which is the position just under the ingot shoulder. The chill crystal~columnar crystal zone is slightly thinner than that of the ingot bottom and the structure of the branched columnar crystal zone clearly indicates the direction of thermal flow. In the zone where the freezing rate is minimum, branched columnar crystals and equi-axial crystals co-exist broadly in mixture and it is considered that such structures were formed in the period at least 4 hr after the pouring: A nearly perfect equi-axial crystal zone is observed from this zone to the center of ingot. The

freezing rate increases again as approaches to the center, which results in the formation of a finer structure, and the finest structure is seen at the central part of the last solidifying zone.

Inverse V segregation is observed much over the branched columnar crystal~equi-axial crystal co-existing zone and the equi-axial crystal zone.

Figure 6 (p. 96) shows the structure near the Y_5 level of the ingot top. While the chill crystal~columnar crystal zone has almost the same width as that of the Y_6 level, the branched columnar crystal zone is much narrower. Comparing with the Y_6 level, the equi-axial crystal zone generates at a region closer to the ingot surface where the freezing rate is comparably high, and the structure becomes finer. As the solidification proceeds to the center of the radial direction, the freezing rate decreases and the structure becomes coarser. The freezing rate increases again near the center of the ingot and, accordingly, the equi-axial crystal structure becomes finer. A granular crystal zone is observed in the center part where the solidification proceeds rapidly, due to the termination of the electric arc heating at the feeding riser which caused a rapid temperature decrease there. Inverse V segregation is mainly observed in the equi-axial crystal zone.

Figure 7 (p. 97) shows the structure near the Y_4 level of the middle part of the ingot. The freezing rate is generally higher than that at the ingot top. While there is only a little difference in the growth of the chill crystal~columnar crystal zone from that of the Y_5 level, both the branched columnar crystal zone and the equi-axial crystal zone are much narrower. In the transit region from the branched columnar crystal zone to the equi-axial crystal zone, granular crystals are formed

Fig. 5.
Rate of freezing, internal macro-structure of radial direction by auto-radiography and equi-solidus line (A, B, C, D) at 120, 300, 420, and 540 min after pouring for the level Y_6 (2 360 mm high) of heavy steel ingot of BEVC (20 t)

separately here and there. The equi-axial crystals becomes finer at the region near the ingot center, being followed by the co-existing region of equiaxed and granular crystals. Granular crystals occupy mostly the central part where the freezing rate is high. As shown in Fig. 7, it is very interesting that ^{64}Cu is condensed between the granular crystals and that inverse V segregation can be observed in such a comparatively coarse granular crystal zone. The latter phenomenon especially indicates that inverse V segregation can occur in such zones of high freezing rate.

Figure 8 (p. 98) shows the solidification structure of the Y_2 level of the ingot bottom, *i.e.* the section which traverses near the center of the negative segregation zone, where the influence of solidification from the ingot bottom is clearly observed. The branched columnar crystal zone is still narrower than that of the Y_4 level and the following equi-axial crystal zone is also narrow and has a fine structure. A fine granular crystal zone appears from this region to the center and an equi-axial crystal zone disappears. In this granular crystal

structure, there is no directivity corresponding to the freezing rate obtained from the calculation. However, in the auto-radiography, a segregation line suggesting the birth of inverse V segregation is observed in the outskirts region where the freezing rate is supposed to be comparatively low.

The above was a brief explanation for the relation of the freezing rate with the solidification structure in the radial plane of the ingot. On the other hand, the relation between the equi-time solidus line and the solidification structure in the longitudinal plane may be explained as follows. There is a chill crystal zone followed by a columnar crystal zone around the whole circumference of the ingot. Generally there is no remarkable difference in these regions between the top and the bottom of the ingot, excepting that the thickness at the ingot top, especially near the Y_6 level, is slightly less than that at the ingot bottom. The internal structure, however, shows a considerable difference among the top, the middle, and the bottom parts of the ingot. In order to make a detail observation of this,

Fig. 6.

Rate of freezing, internal macro-structure of radial direction by auto-radiography and equi-solidus line (*A*, *B*, *C*, *D*) at 120, 300, 420, and 540 min after pouring for the level Y_5 (1 800 mm high) of heavy steel ingot of BEVC (20 t)

the loci of the equi-time solidus lines at 120 min, 300 min, 420 min, and 540 min after the pouring were drawn on the solidification structure of each position in the ingot shown in Figs. 5 to 8, and are marked with *A*, *B*, *C*, and *D*, respectively. In Fig. 5, the line *A* is deep in the ingot, because of a high freezing rate at the ingot top caused by the projection of the mold shoulder. Due to this, the line *D* is also shifted to the central part in order to form the equi-axial crystal zone there. Near the Y_5 level of the ingot top, as shown in Fig. 6, the line *D* is located at the region closer to the ingot outskirts than at the Y_6 level. It clearly indicates the influence of the electric arc heating of the feeding riser. As shown in Fig. 7, there is no remarkable influence of the electric arc heating of the feeding riser at the middle part of ingot. However, the line *D* is shifted again to

the central part because the solidification from the ingot bottom tends to make the remaining molten steel zone narrow in the last solidifying zone. At the region near the Y_2 level of the ingot bottom, as shown by Figs. 5 to 8, the lines *B*, *C*, and *D* do not exist and the solidification is completed within 4 hr after the pouring since the solidification progresses fairly rapidly. It is known that in the bottom part fairly fine granular crystals are already produced at about 60 min after the pouring.

IV. Discussion

1. Chill Crystal and Granular Crystal Zones

When a molten steel is poured into a mold, it begins to solidify from the place contacted with the inner wall of the mold and forms a chill crystal zone, and then a

Fig. 7.
Rate of freezing, internal macro-
structure of radial direction by
auto-radiography and equi-solidus
line (A, B, C, D) at 120, 300,
420, and 540 min after pouring for
the level Y_4 (1 300 mm high) of
heavy steel ingot of BEVC (20 t)

columnar crystal zone. Generally the thickness of the solidification zone, *i.e.* the sum of the thicknesses of the chill crystal and the columnar crystal zones, will gradually increase from the top to the bottom of the ingot, though there are some differences in the gradient among the test ingots, and finally reaches to the solidification zone of the ingot bottom. These facts also indicate that there are some differences in the progress of the freezing process in this region, depending on the height of the ingot. This is caused by the fact that when a molten steel is poured into a mold, there is a considerable difference in the pattern whereby the heat

of molten steel is transferred to the mold and in the influence of convection in the molten steel, depending on its depth, or in other words, the distance between the top and the bottom of the ingot.

The volume of the ingot is increased by the phase change of liquid-to-solid and the temperature decreases in the solid phase, when a molten steel heated at a temperature above the liquid phase line is poured into a cold mold. In this case, a chill crystal zone is firstly formed on the surface contacted with the mold and then a columnar crystal zone and the outer solidification zone of the ingot becomes to increase its thickness.

Fig. 8.
Rate of freezing, internal macro-structure of radial direction by auto-radiography and equi-solidus line (A , E) at 120 and 60 min after pouring for the level Y_2 (560 mm high) of heavy steel ingot of BEVC (20 t)

On the other hand, the mold expands due to the heat transferred from the molten steel. Such volume changes of the mold and the ingot due to the heat transfer make them separate and result in the formation of air gaps. Though there are some reports stating that such air gaps are formed in 2 to 3 min after the pouring,¹⁸⁻²⁰⁾ it is hard to believe that the formation of air gap is completed within several minutes in the case of heavy ingots which need more than 10 hr to solidify. At least, the ingot bottom must always contact with the mold bottom (surface plate) to support the weight of ingot itself, and the lower sides of ingot are supposed to contact broadly with the mold inner wall because of the hydraulic pressure of molten steel. Such conditions are not likely to change so much through the whole freezing process of the ingot.

2. Branched Columnar Crystal Zone

Branched columnar crystals are the structures formed at such zones of the ingot as the freezing rate is extremely low and the acceleration of the freezing rate is negative. Therefore in these zones it is hardly considered that the condensation layer of solute element to be formed ahead of the solidus line will be involved in the crystal and solidified. In other words, if the condensed molten steel happens to be involved and solidified in the crystal, the segregation having a considerable concentration difference will be caused.

While the branched columnar crystal zone in the heavy ingot is fairly thick from the top to the middle

part of the ingot, it is so thin as to barely cover the negative segregation zone at the ingot bottom. (Refer to Figs. 5 to 8). Now, let us consider the conditions of the generation of the branched columnar crystal zone. When the columnar crystal zone grows from the chill crystal zone, it is supposed that there are considerable temperature differences between the inside and outside of the ingot and, that there is a relatively large flow of molten steel descending in front of the solidus line. However, when the branched columnar crystal zone is formed, it is supposed that the flow of molten steel is comparatively less and the uni-directional thermal flow is gradually diminished, and that there is only a little effect of the initial cooling by the mold.

This can readily be understood from the direction of the development of branched columnar crystal shown in Figs. 5 to 8. At the bottom of the ingot, however, the mold contacts with the surface plate having a large thermal absorption capacity, and the initial cooling effect by the mold and the surface plate lasts longer than at the ingot top. Accordingly the generation of a branched columnar crystal during the freezing process of a molten steel should be comparatively less.

3. Equi-Axial Crystal Zone

Equi-axial crystals appear from the top to the middle part of the ingot. They begin to appear in the region where the radial freezing rate is lowest and the acceleration of the freezing rate slowly changes from negative to positive, and broadly prevail in the region

near the last solidifying zone where the freezing rate is relatively high. In the negative segregation zone at the ingot bottom, however, its growth is fairly limited and such well-developed equi-axial crystals as found in the ingot top can hardly be observed, as shown in Photo. 1. The ingot bottom comprises comparatively fine equi-axial or granular crystals. There is a tendency that the equi-axial crystals are coarse where the freezing rate is comparatively low and fine where it is high. Thus it is realized that there is a close relationship between the macroscopic freezing rate or the average advancing velocity of the solidus line and the growth of the crystals.

It is well known that the inverse V segregation is likely to appear in the equi-axial crystal zone. From the view point of the freezing rate acceleration, it can be said that the inverse V segregation appears in the equi-axial crystal zone because the freezing rate is low and the freezing rate acceleration is mostly positive in this zone. In such zones it is thought that the velocity of crystallization is larger than the rate that the solute elements condensed in front of the solidus line can disperse into the bulk, and as a result such elements will be solidified in the crystals.

4. Negative Segregation Zone

As shown in Fig. 4, negative segregation will appear in the zone where the radial distribution of the equi-freezing rate acceleration has the shape of a bulb at the ingot bottom, or in the zone where the solidus line at the ingot center axis is slightly inclined and the freezing rate shows a minimum with the freezing rate acceleration changing from negative to positive. The radial freezing rate of the ingot is distributed in the shape of U and is fairly high at the center.

In such zones at the ingot bottom, the freezing rate of the ingot is influenced by the solidification from both the sides and the bottom of the ingot and the solidification proceeds in a concave pattern.

Observing the structure of negative segregation more in detail, it is found that the structure is generally consisted of comparatively fine equi-axial or granular crystals, having a relatively coarser structure at the bottom and finer at the top of the negative segregation zone, respectively. As mentioned above, the freezing rate in this zone is influenced by the overlapping of the solidification from the sides and the bottom of the ingot, and it is presumed, from the result of a further examination that the longitudinal distribution of the freezing rate has a considerable influence on the rate of

crystal development. On the other hand, such relationships cannot clearly be realized in the radial direction, which mostly justifies the influence of the crystal sedimentation.

5. Last Solidifying Zone at the Ingot Top

Excepting the feeding riser, the last zone of the ingot itself to solidify is, as shown in Fig. 4, the gourd-shaped portion at the upper middle of the ingot, which is nearly corresponding to the so-called V segregation zone.

As shown in Photos. 2 (a), and (1), the structure observed under this zone much differs from the surrounding structure and contains a lot of granular crystals. From the fact that the solidification of this zone is completed at about the same time when the electric arc heating is stopped, the above phenomenon is supposed to be taken place because the granular crystals generated around the feeding riser have descended and at the same time the remaining molten steel has comparatively slowly solidified to produce the coarse equi-axial crystals.

6. Inverse V Segregation Zone

As already explained in Section 3, in the zone where equi-axial crystals appear, the freezing rate is low and the freezing rate acceleration changes from negative to positive. Especially in the zone of positive freezing acceleration, the inverse V segregation due to the condensation of solute elements is very likely to appear. As shown in Photos. 2 (a) and (b), the inverse V segregation does not always exist in such zones as have a nearly uniform freezing rate. It is also shown that the inverse V segregation is observed not only in the equi-axial crystal zone but also sometimes in the branched columnar crystal zone. (Refer to Photos. 2 (a) and (2)).

Further examining the relation between the freezing rate acceleration and the inverse V segregation zone, it is found that such a segregation is most likely to appear in the equi-axial crystal zone where the freezing rate acceleration is positive and the freezing rate increases gradually. A small inverse V segregation is also locally observed in the branched columnar crystal zone of a positive freezing rate acceleration. Furthermore, Photo. 2 (a) shows the existence of such a segregation in the granular crystal zone at the ingot center. As a summary, the appearance of inverse V segregation is not limited to any specific structure in the ingot, but its generation is influenced by the freezing rate, and the

Photo. 1.
Macrostructure of the
bottom of BEAC ingot
(Y₂)

Photo. 2. (a) Macrostructure of BEAC ingot level middle between (Y_4) and (Y_5)
 (1) Near the central axis (2) Outside ——— columnar zone
 (3) Middle ——— equiaxed zone
 (b) Macrostructure of AOAC ingot level under (Y_5)

macroscopic developing process is controlled by the freezing rate acceleration.

Negative freezing rate acceleration means that the advancing of the solidus line will be slowing gradually and that the solute elements condensed ahead of the solidus line can comparatively easily disperse into the bulk. On the contrary, a positive freezing rate acceleration means that there is not enough time for the solute elements condensed ahead of the solidus line to disperse into the bulk and that they will be caught by advancing solidus line.

With regard to the freezing rate, the staying time (ST), or the time when the newly solidified structure stays in the advancing process, is long in such zones as the freezing rate is low, and accordingly the concentration of solute elements in the interdendritic condensed molten steel is supposed to be high in the zones of a high solidus rate. Such an interdendritic condensed molten steel will gradually become concentrated and begin to float.¹⁷⁾ If the advancing solidus line encounters the condensed molten steel thus floating, it will be caught in the dendritic structure and solidified there, or it will ascend while being successively caught by the dendritic structure and solidified leaving its ascending locus. This is clearly indicated by the following fact: from a careful observation of inverse V segregation, it is obvious that the structural boundary is very definite in the direction facing to the advancing solidus line, but very obscure in the direction passed by the solidus line or at the ingot center, and the auto-radiography shows an exponentially small blackness degree. In short, such a solidification is considered to be taken place by the reason that the velocity of the advancing solidification is faster than the velocity at which the condensed molten steel is dispersed into the bulk.

The fact that the direction of the development of a well grown inverse V segregation coincides rather well with the equi-time solidus line indicates that the condensed molten steel floats by moving selectively in a layer (plane) where the solidus rate is most suitable to rise. Therefore it is concluded that the locus of the inverse V segregation is decided by the degree of mol-

ten steel condensation, the rate of its ascension, and the rate of the advance of the layer (plane) having the most suitable solidus rate for such ascending movement.

7. Pouring Temperature and the Solidification Structure

In order to clarify the relation between the solidification structure and the pouring temperature of ingots, a comparison of the auto-radiographs has been made by using ^{64}Cu for the BEAC and AOAC ingots, which differ fairly in pouring temperature, at nearly corresponding locations, and the results obtained are shown in Photos. 2 (a) and (b). In the BEAC ingot, of a relatively high pouring temperature (1 524° to 1 515°C), the chill crystals, the columnar crystals, the branched columnar crystals, the equi-axial crystals, and the last solidifying zones were very clearly observed. On the other hand in the AOAC ingot, of a low pouring temperature (1 502° to 1 490°C), the chill crystal and the columnar crystal zones were much narrower and the equi-axial crystal zone broader than the BEAC ingot, and the central part of the ingot had a comparatively fine equi-axial crystal or granular crystal structure.

When the pouring temperature is high, columnar crystals develop fairly well because the temperature difference between the solidus line at the ingot outskirts and the bulk is high, and this temperature difference lasts for a comparatively long time. Conversely, when the pouring temperature is low, such temperature differences are small and the development of columnar crystals is much restricted. This tendency is also found in the case of the branched columnar crystal zone. It develops well when the pouring temperature is high as seen in the BEAC ingot structure and hardly develops when the temperature is low as seen in the AOAC ingot structure. The development of equi-axial crystals, however, is remarkable in the low pouring temperature ingot and the internal structure of the AOAC ingot is mostly composed of equi-axial crystals. On the other hand in the BEAC ingot, the equi-axial crystals appear only in a region surrounded by the branched columnar crystals and the last solidifying zones. It is very interesting that the solidifica-

tion structure has such remarkable differences depending on the pouring temperature even in the ingots of the same material, shape, and size.

8. Solidification Structure along the Equi-time Solidus Line

The solidification structure has a thin chill crystal zone at the outskirts with a columnar crystal zone inside it. What is important here is the structure further inside, its precipitation time, and its precipitation mechanism.

From all the explanations mentioned above, it is realized regarding the structure on the equi-time solidus line inside the columnar crystal zone, that when the ingot top has an equi-axial crystal zone, the middle and the bottom parts still have a comparatively fine equi-axial or granular crystal zone. While the typical inverse V segregation appears in the equi-axial crystal zone, small ones or such segregations as can be deemed to be the sign of its birth will also appear in the fine equi-axial or granular crystal zone. Such small segregations are caused by the lack of condensed molten steel in front of the solidification phase. That is, if the equi-axial or granular crystals to be found in this zone were originally crystallized in some other zone and moved to the ingot bottom, the condensed molten steel is replaced by such crystals of comparatively low concentration of solute element, which results in the relative lack of molten steel. Additionally, the sedimentation of such crystals substantially leads the zone to the freezing temperature and the growth of inverse V segregation is hindered, only leaving the signs of its birth.

The distribution of inverse V segregation which appears in the fine equi-axial crystal zone just above the columnar crystal zone at the ingot bottom is not parallel to the solidus line but nearly parallel to the radial equi-freezing-rate distribution, appearing in the zone of a positive freezing rate acceleration. Judging from these observed results, it is concluded that the birth and growth of inverse V segregation is very closely related to the freezing rate and its acceleration.

It is also realized that the change from the equi-axial to the granular crystals in the structure between solidus lines (B) and (C) at 300 min and 420 min after the pouring, respectively, shown in Fig. 7, and also the existence of abnormal structures between the solidus lines (C) and (D) at 420 min and 540 min after the pouring respectively, shown in Fig. 6, are caused by the migration of fine equi-axial or granular crystals generated in some other zone, from the viewpoint of the distribution of freezing rate and its acceleration.

V. Conclusion

By solving the partial differential equations of heat transfer with the aid of an electronic computer and by comparing the observed results of solidification structure, analyses have been made on a few phenomena of the freezing process of heavy steel ingots. The results

obtained are summarized as follows.

- (1) There is a very close relation of the freezing rate and its distribution with the solidification structure.
- (2) Inverse V segregation can be observed only when the acceleration of the freezing rate is positive. Under such a condition, it appears not only in the equi-axial crystal zone but also in the granular crystal zone.
- (3) The pouring temperature has a significant influence on the internal structure. Thus it is necessary to consider the difference between the pouring temperature and the solidus temperature when one refers to the internal solidification structure.
- (4) The solidification structure along the equi-time solidus lines at the top of ingot much differs from that of the bottom of ingot. For example, the internal structure of a 20 t ingot at 2 hr after the pouring is of branched columnar crystals at the top, equi-axial crystals in the middle part, and fine equi-axial or granular crystals at the bottom.
- (5) The electric arc heating of the ingot feeding riser greatly influences the last solidifying zone to produce a fine equi-axial or granular crystal zone at the lower end and the near-by region.

The above points have been revealed through the current investigation.

REFERENCES

- 1) Report on Heterogeneity of Steel Ingot, 7th Report, (1937), p. 12, J. Iron and Steel Inst., London.
- 2) Y. Nakagawa and A. Momose: *Tetsu-to-Hagané*, **53** (1967), 1477.
- 3) H. Kosmider and H. Neuhaus: *Stahl u. Eisen*, **77** (1957), 133.
- 4) G. S. Cole and K. A. Jackson: *J. Inst. Metals*, **93** (1964-65), 153.
- 5) C. Benedicks: *JISI*, **135** (1937), 363.
- 6) B. Gray: *JISI*, **183** (1956), 366.
- 7) H. Mori, M. Matuo, K. Kamizawa, and M. Yamate: *Tetsu-to-Hagané*, **52** (1966), 419.
- 8) H. Iijima and K. Inamoto: *Tetsu-to-Hagané*, **45** (1959), 425.
- 9) E. Morburg: *J. Metals*, **5** (1953), 152.
- 10) S. Onodera and Y. Arakida: *Tetsu-to-Hagané*, **45** (1954), 154.
- 11) G. Sugano, K. Narita, T. Miyamoto, and S. Koyama: *Tetsu-to-Hagané*, **50** (1964), 1770.
- 12) K. Narita, T. Ito, T. Tanaka, and S. Matumoto: *Tetsu-to-Hagané*, **53** (1967), 1199.
- 13) K. Narita, S. Koyama, T. Miyamoto, and C. Saitoh: *Tetsu-to-Hagané*, **53** (1967), 1202.
- 14) K. Narita, T. Mori, and C. Saitoh: *Tetsu-to-Hagané*, **54** (1968), 63.
- 15) A. Ohno: *Tetsu-to-Hagané*, **54** (1968), 401.
- 16) T. Takahashi: *Tetsu-to-Hagané*, **54** (1968), 1024.
- 17) R. J. McDonald and J. D. Hunt: *Trans. AIME*, **245** (1969), Sept., 1993.
- 18) G. A. Fisher: *Proc. ASTM*, **62** (1962), 1137.
- 19) R. J. Sarjant and M. R. S. Lack: *JISI*, **177** (1954), 428.
- 20) K. Chihara and M. Kunioka: *Nihonkokiho*, No. 22, (1964), p. 10.