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# Microstructural Features and Formation Processes of As-cast Austenite Grain Structures in Hypoperitectic Carbon Steels

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Formation processes of as-cast austenite grain structures in hypoperitectic carbon steels have been investigated by means of a rapid directional solidification method, the cooling conditions of which are similar to those in the vicinity of slab surfaces in continuous casting processes. Coarse Columnar austenite Grain (CCG) structure was observed in all the hypoperitectic carbon steels employed in this study. It was demonstrated that its formation mechanism is ascribable to the discontinuous grain growth from Fine Columnar austenite Grain (FCG) formed in the delta phase, in which both the delta phase and residual liquid phase act as the pinning phase in the grain growth process. Then, a summary of the findings was provided regarding the microstructural features and the formation mechanisms of as-cast austenite grain structures formed in the rapid directional solidification in carbon steels with the carbon composition ranging from 0.05 to 0.45 mass%.

KEY WORDS: austenite grain structure; hypoperitectic carbon steel; solidification; casting; grain growth.

## 1. Introduction

Formation of Coarse Columnar austenite ( $\gamma$ ) Grain (hereafter abbreviated as CCG) structure in the vicinity of slab surfaces is one of the serious problems in continuous casting processes of peritectic solidified carbon steels, because the CCG structure causes deterioration of hot ductility of the slabs.<sup>1,2)</sup> Elucidation of the formation mechanism and kinetics of the CCG structure is an issue of great importance for avoidance of such a problem. The solidification of peritectic solidified carbon steels starts with the primary crystallization of  $\delta$  phase and it is followed by the peritectic reaction/transformation to produce  $\gamma$  phase. Depending on the steel compositions, the  $\gamma$  phase coexists with the  $\delta$  or liquid phase in the temperature range below the peritectic reaction temperature,  $T_p$ . In this range, the  $\delta$  or liquid phase generally surrounds the  $\gamma$  phase and the  $\gamma$  grain growth is thereby suppressed by the pinning force due to the presence of  $\delta$  or liquid phase.<sup>2–6)</sup> However, a rapid  $\gamma$  grain growth takes place immediately after the  $\delta$  or liquid phase disappears below  $T_\gamma$  which is a temperature of completion of the transformation to  $\gamma$  single phase. This behavior is well substantiated for the formation of equiaxed  $\gamma$  grain structures in slow cooling processes with small temperature gradients.<sup>2–4)</sup>

We recently investigated the formation mechanism of CCG structure in hyperperitectic carbon steels by using rapid directional solidification equipment.<sup>7,8)</sup> The cooling conditions in this equipment are quite similar to those near

the slab surface in the practical continuous casting.<sup>7)</sup> The important findings are briefly summarized below. The typical microstructure during the formation of CCG structure is schematically illustrated in Fig. 1(a). During the formation of CCGs, Fine Columnar  $\gamma$  Grains (FCGs) always exist ahead of the CCGs growing in the direction of temperature gradient (vertical direction of the figure). The change from the FCG to CCG structure is discontinuous and the boundary between these two regions is clearly identified. In this paper, this boundary is called FCG/CCG Region Boundary (FCRB). The temperature at FCRB is always around  $T_\gamma$  during the solidification process. Hence, the FCG region corresponds to the liquid +  $\gamma$  two-phase field, while the CCG

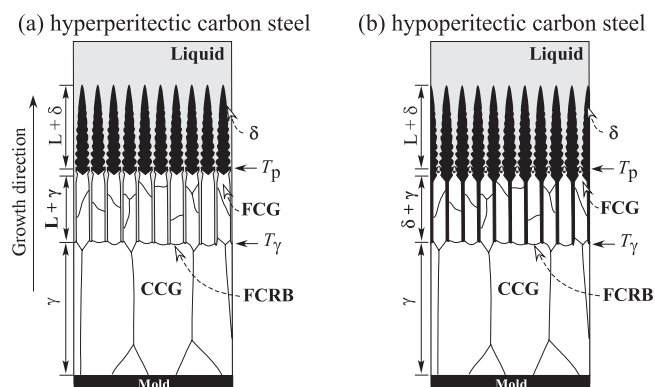


Fig. 1. Schematic illustration of solidifying microstructures during formation of as-cast coarse columnar  $\gamma$  grain (CCG) structure in (a) hyperperitectic and (b) hypoperitectic carbon steels by discontinuous grain growth.

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region is located in the  $\gamma$  single-phase field. The short-axis diameter of FCGs is comparable to the primary arm spacing of  $\delta$  dendrite,  $\lambda_1$ . This fact can be explained by inhibition of the growth of FCG in the short-axis direction by the surrounding liquid phase. The liquid phase also pins the migration of FCRB in the direction of temperature gradient. As the cooling proceeds, the position of  $T_\gamma$  moves away from the mold side and the liquid phase near FCRB accordingly disappears. FCRB then moves away from the mold side, which corresponds to the growth of CCGs and the shrinkage of FCGs. This process is classified into the discontinuous grain growth. The microstructure illustrated in Fig. 1(a) is essentially identical to that observed in a Bridgman-type directional solidification experiment.<sup>9)</sup>

The kinetics of the discontinuous grain growth responsible for the formation of CCGs was analyzed by means of phase-field simulations of grain growth.<sup>10)</sup> Based on the results of the simulations and theories of grain growth, we derived the critical condition for the discontinuous grain growth to start and continue, which is given by,<sup>10)</sup>

$$V_T \leq M(T_\gamma) \frac{1}{\xi d_{FCG}} \quad \text{..... (1)}$$

where  $V_T$  is migration velocity of a position at which the temperature is equal to  $T_\gamma$ ,  $M(T_\gamma)$  is a kinetic constant for the grain growth at  $T_\gamma$ ,  $d_{FCG}$  is the short-axis diameter of FCG which is comparable to  $\lambda_1$  and  $\xi$  is a parameter determined by the local shape of FCRB.<sup>10)</sup> Here it should be mentioned that the velocity given on the right-hand side of Eq. (1) represents the migration velocity of FCRB without the pinning phase, which is denoted by  $V_{CCG}$ . When  $V_T$  is lower than  $V_{CCG}$ , FCRB can move in the direction of temperature gradient immediately after the pinning phase disappears. In other words, the FCGs always shrink in this condition and, therefore, the discontinuous grain growth occurs. However, if  $V_T$  is higher than  $V_{CCG}$ , FCRB cannot follow the migration of the position of  $T_\gamma$ . Then, the FCGs located between the position of  $T_\gamma$  and FCRB can grow to be coarse grains due to depinning in this region. It results in the formation of Equiaxed  $\gamma$  Grain (EG) structure, terminating the discontinuous grain growth.<sup>10)</sup> The validity of Eq. (1) was recently demonstrated by means of permanent mold casting experiments<sup>11)</sup> and a Bridgman-type directional solidification experiment for a 0.2 mass% carbon steel.<sup>12)</sup>

It should be pointed out that the findings thus described were obtained only for hyperperitectic carbon steels. Therefore, the formation mechanism of the CCG structure in hypoperitectic carbon steels remains to be clarified. As mentioned above, the pinning phase plays an important role in the discontinuous grain growth of CCGs. According to the equilibrium phase diagram, it is expected that the pinning phase should be  $\delta$  phase in hypoperitectic carbon steels, provided that the similar discontinuous grain growth takes place. The schematic illustration of the expected microstructure in the solidifying sample is shown in Fig. 1(b), in which the  $\delta$  phase exerts the pinning force on the migration of FCRB. In the Bridgman-type directional solidification experiment of hypoperitectic carbon steels, it was observed that the FCGs exist ahead of the growing CCGs and they coexist with  $\delta$  phase during the slow directional solidification processes.<sup>13)</sup> This observation supports the validity of

the prediction shown in Fig. 1(b) in the case of the slow cooling process. In this study, we focus on the CCG structure in the rapid directional solidification process.

The main objective of the present study is to clarify the formation mechanism of the CCG structure in hypoperitectic carbon steels by carrying out the rapid directional solidification experiment. It will be demonstrated that the formation mechanism of CCGs in hypoperitectic carbon steels can be attributed to the discontinuous grain growth. The pinning phases involved in this process are both  $\delta$  and liquid phases. In this paper, moreover, a summary of the findings including those in our previous studies<sup>7,8)</sup> will be provided regarding the microstructural features and the formation mechanism of  $\gamma$  grain structures appearing during the rapid directional solidification of steels with the carbon composition ranging from 0.05 mass% to 0.45 mass%.

## 2. Experimental Procedures

We focused on carbon steels with the carbon composition ranging from 0.05 mass% to 0.135 mass%. A forged 0.2 mass% carbon steel bar, electrolytic pure iron, Fe–Mn, Fe–P alloys and pure Si were used to fabricate the samples. The chemical composition of the samples employed in this study is shown in **Table 1**. For the sake of convenience, the sample name given in Table 1 is used hereafter such as 0.05C sample instead of 0.05 mass% carbon steel. According to the thermodynamic calculation using Pandat and the thermodynamic database, PanIron version 8,<sup>14)</sup> all the samples except for 0.05C and 0.08C samples are the hypoperitectic carbon steels, while the 0.05C and 0.08C samples do not undergo the peritectic reaction under the equilibrium cooling condition. As mentioned in the introduction, our main focus in this paper is the formation mechanism of CCG structure in hypoperitectic carbon steels. The 0.05C and 0.08C samples were investigated to clarify the range of carbon composition in which the CCG structure dominantly forms during the rapid directional solidification.

The sample of 180 g was put in a cylindrical MgO crucible with an inner diameter of 28 mm and a depth of 70 mm and melted at 1 570°C in an SiC furnace filled with Ar gas of five-nine purity, followed by holding at this temperature for an hour. Then, the melted sample was cast into the rapid directional solidification equipment.<sup>7)</sup> The equipment consists of a water-cooled copper mold and an MgO pipe put on the copper mold. The MgO pipe was preheated at

**Table 1.** Chemical composition of the samples employed in this study.

| Sample name | Chemical composition, in mass% |      |      |      |       |       |       |        |
|-------------|--------------------------------|------|------|------|-------|-------|-------|--------|
|             | C                              | Si   | Mn   | P    | S     | Al    | O     | N      |
| 0.05C       | 0.05                           | 0.20 | 0.80 | 0.02 | 0.013 | 0.01  | 0.007 | 0.0013 |
| 0.08C       | 0.08                           | 0.20 | 0.80 | 0.02 | 0.015 | 0.02  | 0.001 | 0.002  |
| 0.1C        | 0.1                            | 0.20 | 0.80 | 0.02 | 0.018 | 0.02  | 0.013 | 0.0025 |
| 0.11C       | 0.11                           | 0.20 | 0.80 | 0.02 | 0.02  | 0.022 | 0.015 | 0.0028 |
| 0.12C       | 0.12                           | 0.20 | 0.80 | 0.02 | 0.021 | 0.024 | 0.016 | 0.0030 |
| 0.135C      | 0.135                          | 0.20 | 0.80 | 0.02 | 0.023 | 0.027 | 0.018 | 0.0034 |

1 570°C and it served as a side wall of the cast. The sample solidifies directionally from the bottom (copper mold side) toward the top. The cooling conditions in this equipment and the resulting  $\gamma$  grain structure in the cast are similar to those observed in vicinity of the surface of continuously-cast slabs in the industry.<sup>7)</sup>

The ingot cooled to room temperature on the copper mold has a columnar shape with a height of 40 mm and a diameter of 28 mm. It was vertically sectioned along the center axis of the ingot. We focused on the microstructure in a region from the bottom to 20 mm height, because the upper part of the ingot was air-cooled and this part is not the focus of this study. The section was polished and etched with 3%-nital and Oberhöffer solutions to observe the as-cast  $\gamma$  grain and dendrite structures, respectively. In addition, the microstructure on the horizontal section at several heights from the bottom was observed to measure the  $\gamma$  grain size which corresponds to the circle equivalent diameter.

In addition to the ingots cooled to room temperature, we investigated microstructures in solidifying samples. In the rapid directional solidification equipment used in this study, the solidifying sample can be rapidly dropped into an intensely agitated iced water bath equipped with an automatic crucible crusher, which enables analyses of frozen microstructures in solidifying samples.<sup>7)</sup> When the solidifying sample was dropped into the water, the steel chains agitating the iced water immediately crushed the MgO pipe and removed the liquid phase from the solidifying sample,

which left only the solidified part of the sample. Hence, the height of the quenched sample is shorter than 40 mm. The microstructural observation of the quenched samples was carried out to investigate the formation process of the as-cast  $\gamma$  grain structure.

### 3. Results and Discussion

#### 3.1. Variation of the As-cast $\gamma$ Grain Structure in Samples Cooled to Room Temperature

The  $\delta$  dendrite and as-cast  $\gamma$  grain structures in 0.05C, 0.08C, 0.1C and 0.12C samples are shown in Fig. 2. In each set of the snapshots, the microstructures on the left-hand and right-hand sides represent the  $\delta$  dendrite and  $\gamma$  grain structures, respectively, in the same region on the cross-section of the sample. All the samples were cooled to room temperature on the water-cooled copper mold, except for the 0.05C sample. The  $\gamma$  grain structure in the 0.05C sample cooled to room temperature was not clearly observed due to a large amount of ferrite precipitation. Thus, this sample was quenched at 40 s after the casting in order to avoid the ferrite precipitation. In all the samples in Fig. 2, it is noted that the columnar  $\delta$  dendrites grew from the bottom (the copper mold side) toward the upper part. However, there are distinct differences in the  $\gamma$  grain structure between these samples as described below.

For convenience, let us discuss the  $\gamma$  grain structure in order from high (0.12C sample) to low carbon composition

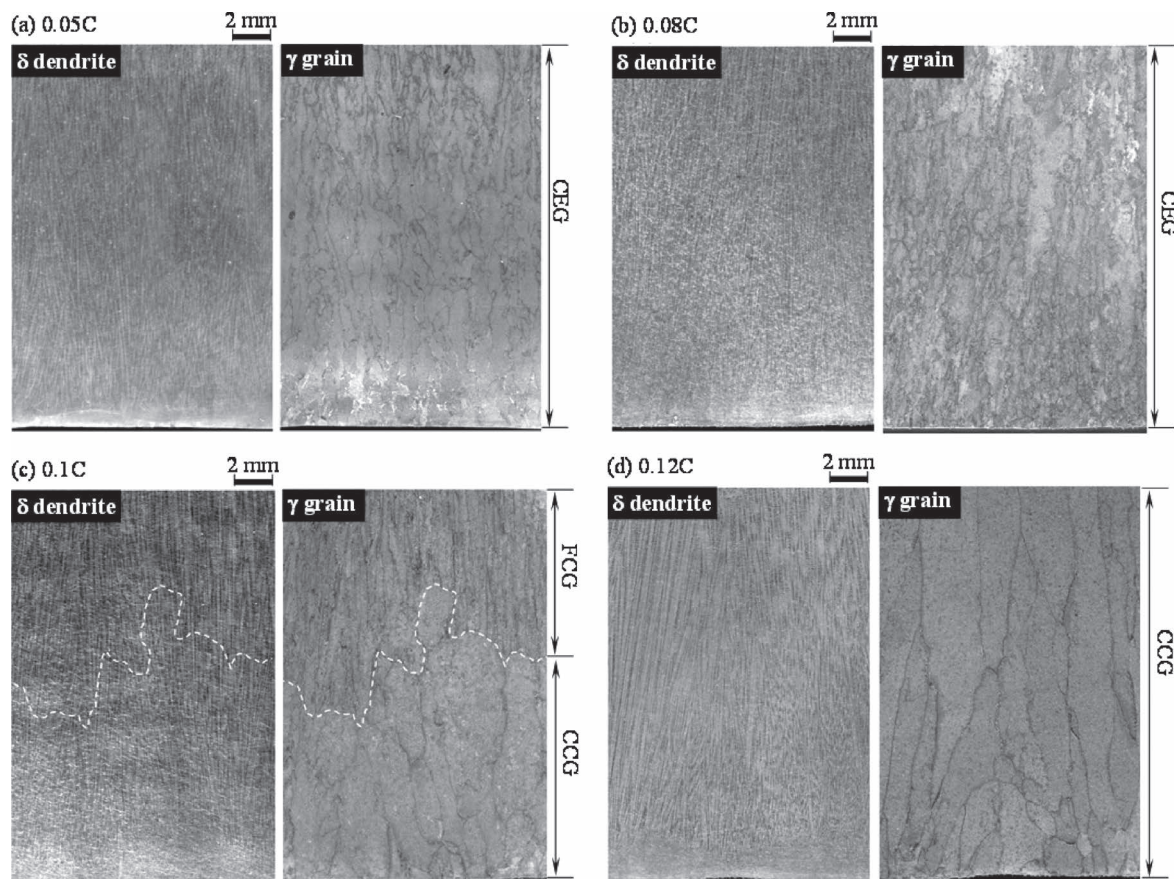


Fig. 2.  $\delta$  dendrite (left-hand side) and  $\gamma$  grain (right-hand side) structures in (a) 0.05C, (b) 0.08C, (c) 0.1C and (d) 0.12C. All the samples were naturally cooled to room temperature except for 0.05C sample which was quenched at 40 s after casting in order to avoid ferrite precipitation making it difficult to observe the as-cast  $\gamma$  grains.

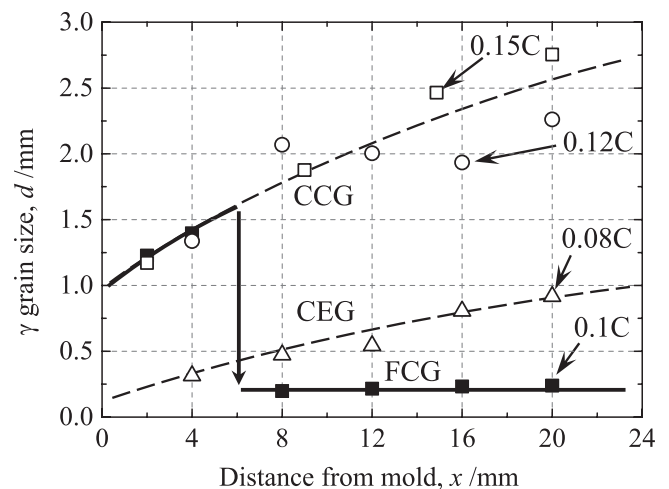
(0.05C sample). In 0.12C sample (Fig. 2(d)), very coarse columnar grains develop from the bottom to the upper part. These grains correspond to the CCG. Although not shown here, the CCGs also form in the whole observation area of 0.11C and 0.135 samples. Similarly, the CCGs form in the vicinity of the mold wall in 0.1C sample. However, the  $\gamma$  grain structure in this sample discontinuously changes from the CCG to very fine columnar grains, and this position is indicated by dashed lines in both the dendrite and  $\gamma$  grain structures in Fig. 2(c). The short-axis diameter of these fine columnar grains is comparable to the primary arm spacing of  $\delta$  dendrite,  $\lambda_1$ . These fine grains observed in Fig. 2(c) correspond to the FCGs. As explained later, the FCGs formed during the solidification process of this sample did not experience the significant grain growth during the cooling process. The  $\gamma$  grain structure drastically changes with a further decrease in the carbon composition,  $x_C$ . The as-cast  $\gamma$  grain structure in the 0.08C sample consists of both columnar and equiaxed  $\gamma$  grains. The appearance of the  $\gamma$  grain structure is similar to that in 0.05C sample. In this paper, this structure is called Columnar and Equiaxed  $\gamma$  Grain (CEG) structure. The CEGs are surrounded by saw-edged grain boundaries. In the CEG structure, moreover, particular relationships were not found between the position of  $\gamma$  grain boundaries and the boundaries in the dendrite structure such as interdendritic position, dendrite stem and boundaries of dendrite assemblages.

**Figure 3** shows the  $\gamma$  grain size measured on the horizontal cross-section at several heights from the mold wall. The CCG structures formed in the whole observation area of 0.15C and 0.12C samples and their short-axis diameters increase with increasing distance from the mold. In the 0.1C sample, the short-axis diameter of CCG near the mold wall is comparable to those in the 0.15C and 0.12C samples. However, the grain size suddenly decreases at the distance of 6 mm from the mold due to the discontinuous change of the grain structure from CCG to FCG. The short-axis diameter of FCG is as low as 200  $\mu\text{m}$ . In the 0.08C sample, CEG is coarser than FCG but much finer than CCG and the grain size increases with the increase in the distance from the mold wall.

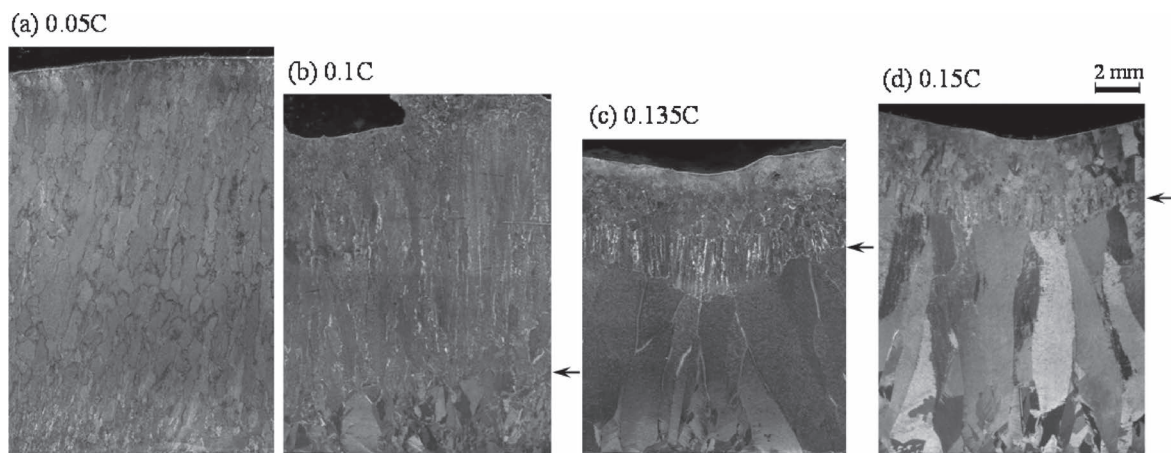
### 3.2. Formation Mechanism of As-cast $\gamma$ Grain Structures

Our focus is now directed at the formation mechanism of CCGs observed in the hypoperitectic carbon steels. As explained above, the CCG structure forms in all hypoperitectic carbon steels employed in this study ( $0.1 \text{ mass}\% \leq x_C \leq 0.135 \text{ mass}\%$ ). We examined the solidifying microstructures to reveal the formation mechanisms. The microstructures in the samples quenched at 30 s after casting are shown in **Fig. 4**, where the result for 0.15C sample obtained in our previous study<sup>8)</sup> is also shown for comparison. The CEG structure forms in the 0.05C sample. Importantly, FCGs exist ahead of growing CCGs in the 0.1C, 0.135C and 0.15C samples. This is essentially identical to the typical microstructure observed during the formation process of CCGs by the discontinuous grain growth mechanism in hyperperitectic carbon steels.<sup>7,8)</sup> Hence, the formation of CCG structure in the hypoperitectic carbon steels should be ascribed to the discontinuous grain growth from the FCG structure. This is also supported by the fact discussed below.

It is noted in Fig. 4 that the position of FCRB, indicated by the arrow on the right-hand side of each snapshot, decreases with the decrease in  $x_C$  from 0.15 to 0.1 mass%. As mentioned in the introduction, during the formation process of CCGs in hyperperitectic carbon steels, FCRB is

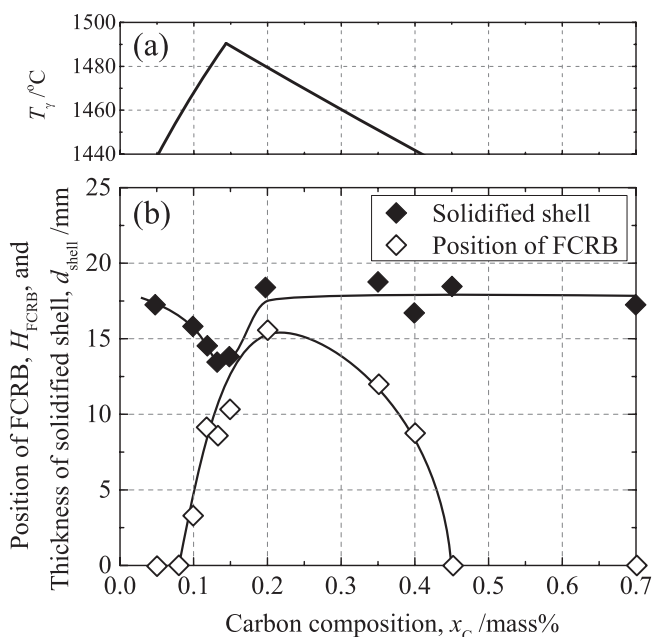


**Fig. 3.** Variation of the as-cast  $\gamma$  grain size in cast samples.



**Fig. 4.** As-cast  $\gamma$  grain structures in samples quenched at 30 s after casting. The arrow on the right-hand side of the snapshots (b), (c) and (d) indicates the position of FCRB.

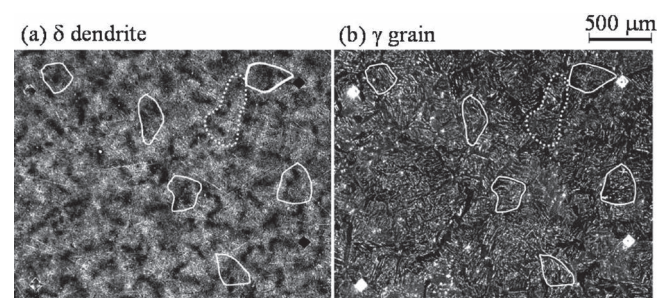
pinned by the liquid phase and the position of FCRB thereby coincides with the position of  $T_\gamma$ . If the similar growth mechanism occurs in the hypoperitectic carbon steels, the pinning phase corresponds to the  $\delta$  phase as illustrated in Fig. 1(b). Then, the variation of the position of FCRB with  $x_C$  observed in Fig. 4 should accord with the variation of  $T_\gamma$  with  $x_C$ , provided that the cooling condition does not significantly depend on  $x_C$ . **Figure 5** shows the variation of  $T_\gamma$  obtained from the thermodynamic calculation (Fig. 5(a)) and the position of FCRB (Fig. 5(b)) with  $x_C$ . The data of samples with  $x_C \geq 0.15$  mass% obtained in the previous study<sup>8)</sup> are also plotted in Fig. 5(b) for comparison. All the samples were quenched at 30 s after casting. In the 0.05C and 0.08C samples, CCGs do not form and therefore the positions of FCRB in these samples are plotted at zero. As  $x_C$  increases from 0.08 mass%, the position of FCRB moves upward and then it moves downward, exhibiting a peak at around 0.2 mass% C. This behavior can be explained on the basis of the discontinuous grain growth mechanism. When  $T_\gamma$  is high, the pinning phase disappears at a high temperature and the position of FCRB should be thereby located at the upper position of the cast. In fact, the variation of the position of FCRB is roughly the same as the variation of  $T_\gamma$ . It supports the fact that the CCG structure in the hypoperitectic carbon steels originates from the discontinuous grain growth in which the pinning phase is  $\delta$  phase. Having a closer look at Fig. 5, however, one can find a difference between the peak positions of  $T_\gamma$  and FCRB. To be more specific,  $T_\gamma$  takes the highest value at around  $x_C = 0.15$  mass%, while the peak of FCRB appears at around  $x_C = 0.2$  mass%. This difference may originate from uneven solidification in the hypoperitectic carbon steels. As observed in Fig. 4, the total height of the quenched samples, which is called the thickness of solidified shell in this paper, considerably changes with  $x_C$ . It indicates that the solidification velocity depends on  $x_C$ .



**Fig. 5.** (a) Variation of  $T_\gamma$  in Fe- $x_C$ -0.2mass%Si-0.8mass%Mn system obtained from the thermodynamic calculation. (b) Variation of the position of FCRB (open symbol) and the thickness of the solidified shell (filled symbol) measured in the samples quenched at 30 s after casting.

The measured thickness of the solidified shell is shown by the filled plot in Fig. 5(b). The thickness exhibits the trough near  $x_C = 0.13$  mass%. It is known that the uneven solidification is salient in steels near the peritectic point due to the shrinkage of solidified shell during the  $\delta/\gamma$  transformation.<sup>15,16)</sup> Although quantitative data are not shown here, the bottom surface of 0.11C, 0.12C and 0.135C samples exhibits large concave shape as compared with the flat surface of the other samples. Hence, the center region of the bottom surface did not contact with the mold and the thickness of solidified shell was accordingly decreased in the center region of these samples. It is noted that the ingot size of the present experiment is relatively small compared with the spatial scale of unevenness of the solidified shell observed in early works.<sup>15,16)</sup> However, it was recently demonstrated by means of elasto-plastic analysis of the solidified shell of carbon steels that unevenness of the shell develops due to volume contraction during the  $\delta/\gamma$  transformation even in small shell having disk shape with 30 mm diameter.<sup>17)</sup> It indicates that the uneven solidification can occur in our samples. Hence, the solidification in the present samples should be retarded due to the volume contraction of  $\delta/\gamma$  transformation and the position of FCRB was accordingly lowered, which results in the difference between the peak position of  $T_\gamma$  and FCRB as shown in Fig. 5. In addition, this difference may be related to the pinning phase involved in the discontinuous grain growth as discussed below.

The important observation in Figs. 4 and 5 is that the formation of CCG structure in the hypoperitectic carbon steels can be attributed to the discontinuous grain growth. This mechanism should be essentially identical to that found in hyperperitectic carbon steels. However, there is a difference in the pinning process of FCRB between the hyperperitectic and hypoperitectic carbon steels. The pinning phase is the liquid phase in the former case,<sup>7)</sup> while it should be the  $\delta$  phase in the latter case according to the equilibrium phase diagram. In fact, the variation of the position of FCRB is roughly the same as the variation of  $T_\gamma$  as shown in Fig. 5. **Figure 6** shows the  $\delta$  dendrite and  $\gamma$  grain structures observed on the horizontal section at 20 mm height of 0.1C sample cooled to room temperature. The  $\gamma$  grain structure at this height is the FCG structure as shown in Fig. 2(c). In the dendrite structure (Fig. 6(a)), the bright and dark regions correspond to the dendrite stem and interdendritic regions, respectively. Some of  $\gamma$  grain boundaries are indicated by solid and dashed lines in the  $\gamma$  grain structure (Fig. 6(b)), since some parts of the structure are not clearly visible in this printed version. These lines are also shown in the den-

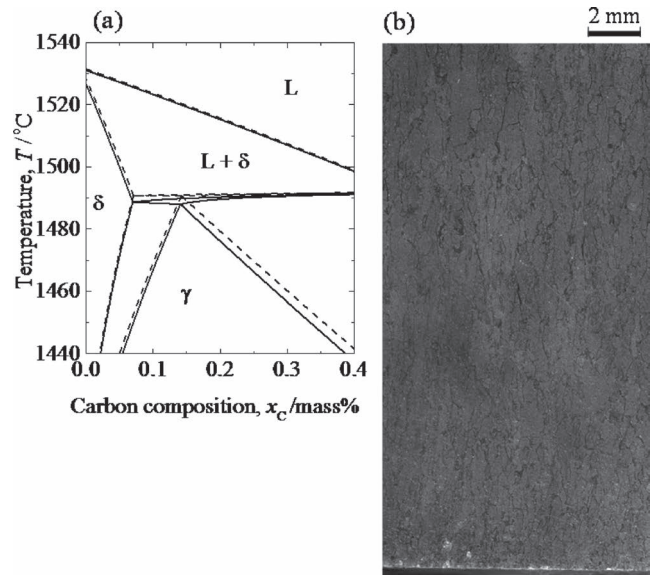


**Fig. 6.** (a)  $\delta$  dendrite and (b)  $\gamma$  grain structures observed on the horizontal section of FCG region in 0.1C sample.

drate structure. It is seen that the  $\gamma$  grain boundaries specified by the solid lines are often located on the dendrite stems, which indicates that the  $\delta$  phase coexists with  $\gamma$  phase in the FCG region during the cooling process. This is consistent with the result of the Bridgman-type directional solidification experiment.<sup>13)</sup> Therefore, the  $\delta$  phase is the pinning phase during the migration of FCRB. On the other hand, some of  $\gamma$  grain boundaries are located on the interdendritic region as exemplified by the dashed line. Hence, the FCRB should be partly pinned by the liquid phase which may exist at low temperatures due to microsegregation (most likely P segregation<sup>18)</sup>). Such an additional pinning force by the liquid phase, if exists, should have contributed to the lowering of the position of FCRB in the quenched sample, thus resulting in the difference between the peak position of  $T_\gamma$  and FCRB in Fig. 5. In order to elucidate the pinning phase in the hypoperitectic carbon steels more clearly, we investigated effects of addition of a ferrite-stabilizing element, Nb, and austenite-stabilizing element, Mn, as explained in detail below.

As shown in Fig. 2(c), the FCG structure remains in the 0.1C sample cooled to room temperature. The existence of the FCG structure indicates that the pinning phase(s) remains until very low temperatures during the cooling process, thus preventing the discontinuous grain growth from continuing and also suppressing the growth of FCGs in this sample. If  $\delta$  phase is the pinning phase, the length of FCG region in the sample cooled to room temperature should be increased by adding a ferrite-stabilizing element because the  $\delta$  phase should be stabilized down to low temperatures. The validity of this expectation is investigated. We focused on the addition of Nb which is known as the ferrite-stabilizing element. In the Bridgman-type directional solidification experiment,<sup>13)</sup> it was found that the length of FCG region in a solidifying microstructure of 0.13 mass%C steel increases by an addition of 0.15 mass%Nb. Since NbC and NbN phases were not observed in the TEM examinations, such a microstructural change can be attributed to the stabilization of  $\delta$  phase. In the present study, 0.05 mass% Nb was added to 0.1C sample. **Figure 7(a)** shows the equilibrium phase diagram of Fe- $x_C$ -0.2Si-0.8Mn-0.025N (in mass%) with 0.05 mass%Nb, obtained from the thermodynamic calculation. The addition of 0.05 mass% Nb does not considerably change the phase equilibria in this system. Importantly, it does not lead to the formation of NbN or NbC. Therefore, we can focus only on the effect of the stabilization of  $\delta$  phase during the cooling process.

Figure 7(b) represents the as-cast  $\gamma$  grain structure in the 0.1C sample with the addition of 0.05 mass%Nb cooled to room temperature. It is seen that CCGs do not exist and the whole structure consists of FCGs. The CCG region completely disappears by the addition of Nb. This is consistent with the above-mentioned expectation that the discontinuous grain growth should be prevented by adding the ferrite-stabilizing element because  $\delta$  phase is the pinning phase. It is noted that addition of 0.05 mass%Nb decreases  $T_\gamma$  in 0.1C sample as shown in Fig. 7(a). However, this decrement is quite small. Hence, it is considered that the refinement of  $\gamma$  grain structure in Fig. 7(b) originates from pinning of  $\delta$  phase which was stabilized in low temperature region due to segregation of Nb. Considering the small



**Fig. 7.** (a) Calculated phase diagram for Fe- $x_C$ -0.2mass%Si-0.8mass%Mn-0.0025mass%N (dashed line) with addition of 0.05 mass%Nb (solid line). (b) As-cast  $\gamma$  grain structure in 0.1C sample with addition of 0.05 mass Nb.

amount of Nb, this element provides the significant effect in suppressing the formation of CCG structure. However, it should be pointed out that the result shown in Fig. 7(b) does not deny a possibility of the liquid phase acting as the pinning phase, because the addition of Nb might lower the solidification temperature due to enhancement of the microsegregation developing during the solidification. To make it clear whether the liquid phase can act as the pinning phase, we investigated the effect of addition of Mn which is the austenite-stabilizing element.

In this study, 0.7 mass%Mn was added in the 0.1C sample. The calculated phase diagram is shown in **Fig. 8(a)**.  $T_\gamma$  increases by about 10 K due to the addition of 0.7 mass%Mn. This value is as high as that in the 0.12C sample in which the CCG structure forms in the entire observation area (Fig. 2(d)). Hence, if the  $\delta$  phase is the only pinning phase for the formation process of CCGs, the CCG region should be largely extended by the addition of 0.7 mass%Mn. On the other hand, the CCG region will be shortened if the liquid phase acts as the pinning phase.

Figure 8(b) shows the as-cast  $\gamma$  grains structure in 0.1C samples with the addition of 0.7 mass%Mn. Figure 8(c) is the enlargement of the structure in the vicinity of the mold wall. Although the CCGs form near the mold wall, the length of CCG region is obviously shortened. Hence, the addition of Mn is effective in suppressing the formation of CCG structure, which indicates that the liquid phase actually acts as the pinning phase for the migration of FCRB in the hypoperitectic carbon steels. **Figure 9** shows the  $\gamma$  grain size measured on the horizontal sections of each sample. As already shown in Fig. 3, the grain size in 0.1C sample discontinuously changes from about 1.4 mm to 200  $\mu$ m due to the change of the grain structure from CCG to FCG. However, the grain size in the 0.1C samples with the addition of Nb or Mn takes about 200  $\mu$ m, which is approximately equal to  $\lambda_1$ , in the whole observation area.

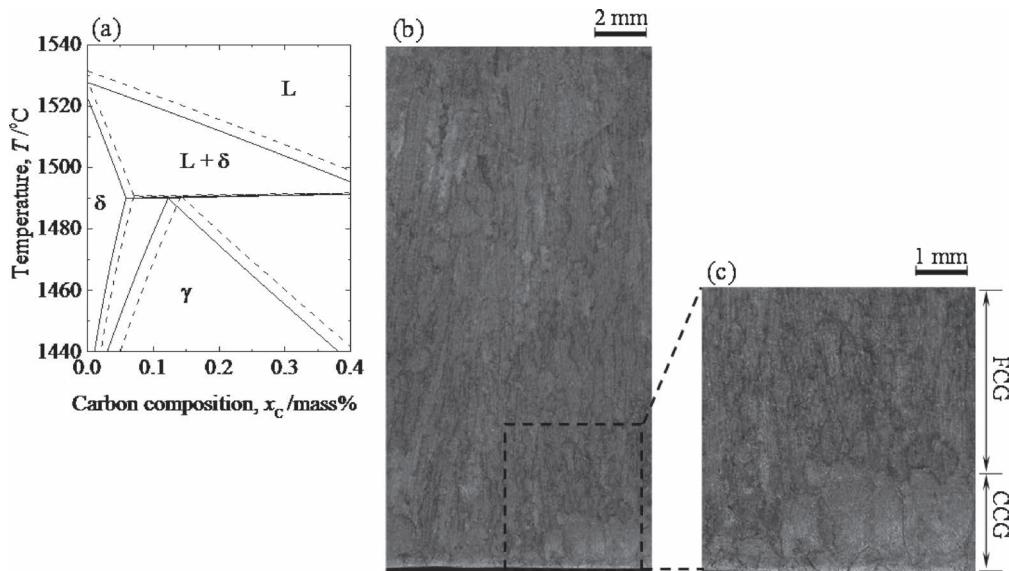


Fig. 8. (a) Calculated phase diagram for Fe- $x_C$  mass% C-0.2 mass% Si-0.8 mass% Mn-0.0025 mass% N (dashed line) with addition of 0.7 mass% Mn (solid line). (b) As-cast  $\gamma$  grain structure in 0.1C sample with addition of 0.7 mass% Mn. (c) Enlargement of the structure in the vicinity of the mold wall.

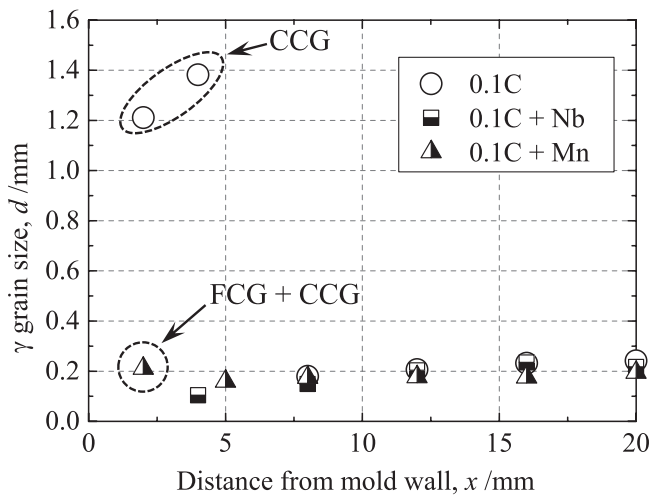


Fig. 9. Variation of  $\gamma$  grain size in 0.1C samples without and with Nb or Mn.

Although the data of 0.1C sample with Mn addition at 2 mm height from the mold wall, indicated by the dashed circle, is the averaged value of CCGs and FCGs, it is also as low as  $200\ \mu\text{m}$  because of the relatively small amount of CCGs in this region.

From the results discussed in this section, it is concluded that the formation of CCGs in hypoperitectic carbon steels is ascribable to the discontinuous grain growth in which the  $\delta$  and liquid phases exert the pinning force on the migration of FCRB. Hence, the prevention of formation of the CCG structure can be realized by stabilizing the  $\delta$  and/or liquid phase to low temperatures.

The main objective of this paper is the elucidation of the formation mechanism of the CCG structure in hypoperitectic carbon steels. As mentioned in Section 2, the microstructures in the 0.05C and 0.08C samples were also investigated to clarify the range of carbon composition in which the CCG structure dominantly develops. In the 0.05C and 0.08C samples that do not undergo the peritectic reac-

tion in the equilibrium solidification process, we observed the CEG structure instead of the CCG structure. The CEG structure has not been found in both the hypo- and hyperperitectic carbon steels in a series of our studies<sup>7,8)</sup> including the present one. The elucidation of the formation kinetics and mechanism of the CEG structure remains as an important future work.

### 3.3. Summary of As-cast $\gamma$ Grain Structures and the Formation Processes

The formation process of as-cast  $\gamma$  grain structures in hyperperitectic carbon steels with  $0.15\ \text{mass}\% \leq x_C \leq 0.45\ \text{mass}\%$  was investigated in the previous study.<sup>8)</sup> Now, it should be useful for controlling of the as-cast  $\gamma$  grain structure in casting processes to summarize the findings for a wide range of carbon compositions obtained in the present and previous studies.<sup>7,8,19)</sup> Figure 10 shows schematic illustrations of the typical as-cast  $\gamma$  grain structures observed in samples cooled to room temperature. The height of each region of the grain structure in the sample cooled to room temperature is shown in Fig. 11. Also, the  $\gamma$  grain sizes measured on the horizontal sections near the mold wall (4–6 mm heights) and in the upper region (14–16 mm heights) are shown in Fig. 12. Depending on  $x_C$  and the position of the cast, five types of  $\gamma$  grain structures such as CEG, FCG, CCG, EG and Columnar  $\gamma$  Grain (CG) structures appear in the rapid directional solidification. The type of  $\gamma$  grain structure observed especially near the mold wall and their formation mechanisms are summarized in Table 2. The features and the formation processes of the as-cast  $\gamma$  grain structures are discussed below. For the sake of completeness, we also explain the results obtained in the previous work<sup>7,8)</sup> for the hyperperitectic carbon steels ( $x_C \geq 0.15\ \text{mass}\%$ ).

When  $x_C$  is less than 0.1 mass%, the peritectic reaction does not take place according to the equilibrium phase diagram. The whole observation area in 0.05C and 0.08C samples consists of the CEG structure which is characterized by a mixture of columnar and equiaxed grains sur-

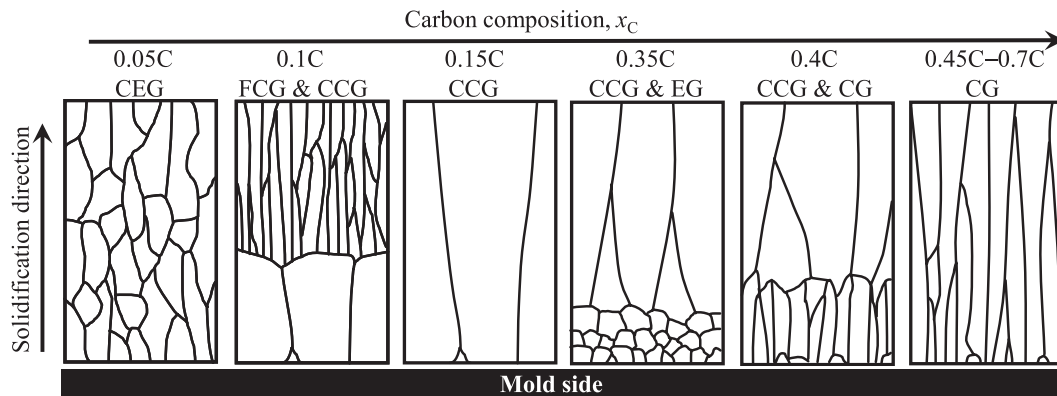


Fig. 10. Schematic illustrations of as-cast  $\gamma$  grain structures with different carbon compositions.

Table 2. Summary of as-cast  $\gamma$  grain structures and their formation mechanisms in carbon steels.

| Solidification mode in equilibrium                         | Carbon composition $x_C$ (mass%) | Type of $\gamma$ grains near mold (typical size)* <sup>1</sup> | Formation mechanism of $\gamma$ phase                                                               |
|------------------------------------------------------------|----------------------------------|----------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
| $\delta$ solidification (& $\delta/\gamma$ transformation) | $x_C < 0.1$                      | CEG (300–800 $\mu\text{m}$ )                                   | Not elucidated                                                                                      |
|                                                            | $0.1 \leq x_C \leq 0.2$          | CCG (~1 mm)                                                    | Discontinuous grain growth <sup>7)</sup>                                                            |
| Peritectic solidification                                  | $0.2 < x_C < 0.38$               | CCG (~1 mm) & EG (less than 1 mm)                              | CCG: Discontinuous grain growth <sup>7,8)</sup><br>EG: Continuous grain growth <sup>10,11,19)</sup> |
|                                                            | $0.38 \leq x_C \leq 0.51$        | CG (less than 500 $\mu\text{m}$ )                              | Preferential $\gamma$ solidification <sup>9)</sup>                                                  |
| $\gamma$ solidification                                    | $0.51 < x_C$                     |                                                                |                                                                                                     |

\*<sup>1</sup> Size of columnar grains represents the short-axis diameter.

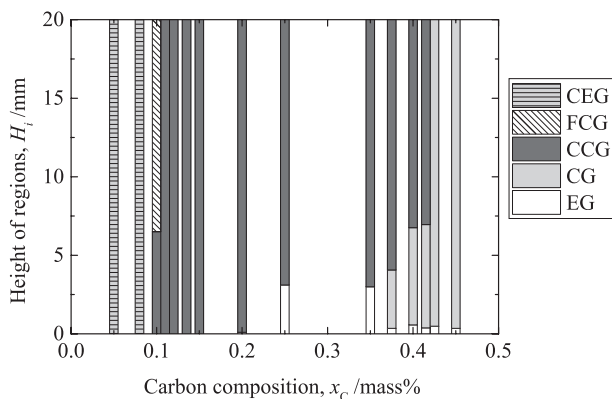


Fig. 11. Height of each grain region in steels with different carbon compositions.

rounded by saw-edged grain boundaries and the average grain size of about 300–800  $\mu\text{m}$ . This structure was not observed in the other samples ( $x_C \geq 0.1$  mass%) used in the present and previous studies.<sup>7,8)</sup> The details of the formation process and mechanism of the CEG structure have not been elucidated in this study.

At  $x_C = 0.1$  mass%, the CCGs form near the mold wall and the grain structure discontinuously changes from the CCG to FCG at around 6 mm height from the mold wall. The FCG structure was also found in the solidifying sample as shown in Fig. 4(b), which indicates that CCG in this sample develops by the discontinuous growth mechanism. The comparison between the  $\delta$  dendrite and FCG structures in Fig. 6 indicates that the pinning phase in this process corresponds to  $\delta$  and liquid phases. When  $\delta$  or liquid phase remains until low temperatures, the discontinuous grain

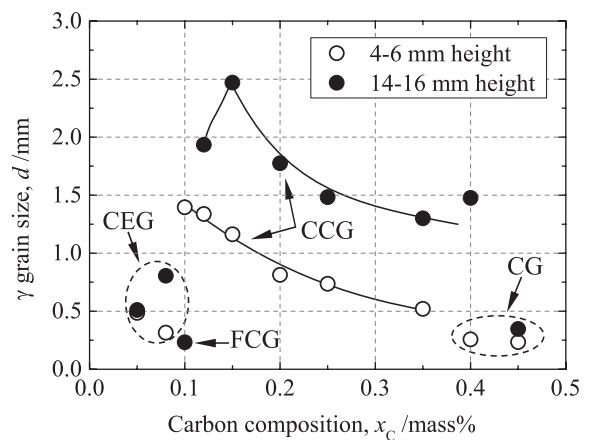


Fig. 12. Variation of  $\gamma$  grain sizes measured at 4–6 mm heights (open circle) and 14–16 mm heights (filled circle) with carbon compositions.

growth will stop and then FCGs will start to grow to be equiaxed grains. Furthermore, if the pinning phase remains until very low temperatures, the substantial growth of FCGs is suppressed during the cooling process. The existence of the FCG structure in 0.1C sample cooled to room temperature indicates that  $\delta$  and/or liquid phase remains until very low temperatures and they prevent the discontinuous grain growth from continuing and also suppress the growth of FCGs.

The CCG structure forms in the whole observation area of the samples with  $0.1 < x_C \leq 0.2$  mass%. As understood from Fig. 5(a),  $T_\gamma$  is high in these steels and hence  $V_{CCG}$  takes high values. Thus, the discontinuous grain growth can easily take place in these samples even near the mold

wall where  $V_T$  is generally high. As shown in Fig. 11, the increase of  $x_C$  from 0.2 to 0.25 mass% yields the formation of EG structure near the mold wall, which can be explained by the occurrence of the continuous grain growth<sup>10,11,20</sup> due to the reduction of  $T_\gamma$ . A further increase in  $x_C$  results in the formation of CG structure near the mold wall. As was found in our previous study,<sup>8)</sup> CG is generally coarser than FCG but much finer than CCG. The positions of grain boundaries of CGs exactly correspond to the positions of boundaries of dendrite assemblages. In addition, our numerical calculations of dendrite growth processes showed that preferential growth of  $\gamma$  dendrites takes place near the mold wall in these composition ranges. From these results, it was concluded that the CGs are the  $\gamma$  grains directly forming from the  $\gamma$  dendrite assemblages.<sup>8)</sup> Therefore, the size and morphology of CG structure is determined not by the grain growth but by the  $\gamma$  dendritic growth. When  $x_C > 0.43$  mass%, the whole observation area consists of the CG structure. It is noted that a range of  $x_C$  in which the preferential  $\gamma$  solidification takes place depends on the compositions of Mn and Si as reported elsewhere.<sup>21)</sup>

It is shown in Fig. 12 that the CCG structure is the coarsest structures among the five types of the grain structures. The short-axis diameter of CCG clearly depends on  $x_C$ . As reported in our previous study based on the phase-field simulation,<sup>20)</sup> the short-axis diameter of CCG increases with the increase of  $T_\gamma$  and with the decrease of the cooling rate. The carbon composition dependence of the short-axis diameter of CCG at the height of 14–16 mm basically coincides with the dependence of  $T_\gamma$  on  $x_C$ . This coincidence can be also observed in the data obtained for the height of 4–6 mm. However, the short-axis diameters of 0.1C and 0.12C samples at the height of 4–6 mm are larger than that of 0.15C sample. This should be attributed to the retardation of the cooling process in 0.1C and 0.12C samples due to the uneven solidification as discussed in Figs. 4 and 5.

#### 4. Conclusions

In this study, the formation process of Coarse Columnar  $\gamma$  Grain (CCG) structure in hypoperitectic carbon steels was investigated by means of the rapid directional solidification method. The important finding is that the formation of CCG in the hypoperitectic carbon steels with the carbon composition,  $x_C$ , ranging from 0.1 to 0.135 mass% is ascribable to

the discontinuous grain growth mechanism in which the  $\delta$  phase and also the liquid phase act as the pinning phase for the migration of Fine Columnar  $\gamma$  Grain (FCG)/CCG Region Boundary (FCRB). In the steels with  $x_C < 0.1$  mass%, the Columnar and Equiaxed  $\gamma$  Grain (CEG) structure was observed in the whole investigated region. The CEG is much finer than CCG and coarser than FCG. The summary of the findings obtained in the present and previous studies<sup>7,8)</sup> was given regarding the microstructural features and the formation mechanisms of as-cast  $\gamma$  grain structures in steels with  $0.05 \text{ mass\%} \leq x_C \leq 0.45 \text{ mass\%}$ .

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