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Author(s)	Tsuchiya, Shingo; Ohno, Munekazu; Matsuura, Kiyotaka; Isobe, Kohichi
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Effects of Cr Addition on Coarse Columnar Austenite Structure in As-Cast 0.2 mass% Carbon Steel

Shingo TSUCHIYA,¹⁾ Munekazu OHNO,²⁾ Kiyotaka MATSUURA²⁾ and Kohichi ISOBE³⁾

1) Graduate Student, Graduate School of Engineering, Hokkaido University, Kita 13 Nishi 8, Sapporo, Hokkaido 060-8628 Japan. 2) Division of Materials Science and Engineering, Faculty of Engineering, Hokkaido University, Kita 13 Nishi 8, Sapporo, Hokkaido 060-8628 Japan. 3) Muroran R&D Lab., Nippon Steel Corp., 12 Nakamachi Muroran 050-8550 Japan.

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Effects of Cr addition on as-cast Coarse Columnar austenite Grain (CCG) structure were investigated for 0.2 mass% carbon steel by means of rapid unidirectional solidification method which realizes cooling conditions similar to those in the vicinity of continuous cast slab surface. Although the as-cast structure of the unidirectionally solidified samples always consisted of the CCGs regardless of Cr addition, the aspect ratio of the CCGs was remarkably reduced by the Cr addition. During solidification, Fine Columnar austenite Grains (FCGs) existed at the growing front of the CCG region and the migration velocity of the FCG/CCG boundary was reduced by the Cr addition. EPMA analysis revealed that the Cr addition enhances P segregation at interdendritic positions, which lowers a temperature for completion of γ transformation, T_γ . This lowered T_γ reduces the migration velocity of the FCG/CCG boundary and, as a result, induces the formation of CCGs having shorter major axis diameters.

KEY WORDS: carbon steel; solidification; peritectic transformation; austenite grain; columnar structure; chromium; phosphorous; segregation; grain growth.

1. Introduction

As-cast γ -austenite grain size in peritectic carbon steels is one of the important parameters which determine the ductility of Continuous Cast (C.C.) slabs. Surface cracking susceptibility of the C.C. slabs depends largely on the as-cast γ grain size. It was reported that the surface crack propagates on the boundary of Coarse Columnar γ Grain (CCG) formed from the surface toward the center of the thickness and, moreover, the depth of surface crack is affected by the major axis diameter of CCG.^{1–3)} Therefore, it is very important to prevent the formation of CCG structure in order to avoid the surface cracking. However, the formation process of CCG structure remains to be clarified.

The grain growth of γ phase in peritectic carbon steels immediately occurs after liquid or δ -ferrite phase disappears below a temperature for completion of γ transformation, T_γ , since the liquid or δ phase acts as a pinning phase for γ grain growth above T_γ .^{4–6)} Some members in our group investigated the formation process of CCG structure in a hyperperitectic carbon steel during slow cooling solidification by means of Bridgman type unidirectional solidification method.⁷⁾ It was observed that the CCG region develops along the direction of temperature gradient. Importantly, it was found that Fine Columnar γ Grain (FCG) always forms at the front of the CCG region and, moreover, the FCG region corresponds to the liquid+ γ two phase field. The minor axis diameter of FCG is comparable to the

primary dendrite arm spacing. Based on these observations, in the study on the γ grain growth of low carbon steels,^{8,9)} a classical grain growth model based on curvature driven growth was applied to the prediction of CCG size with the assumption that the grain growth continuously takes place from the FCG to CCG at temperatures below T_γ . Although it was demonstrated that such a classical model is quite useful in predicting the γ grain size, the assumption of the continuous grain growth from the FCG to CCG remains to be verified. In our recent report,¹⁰⁾ the formation process of CCG structure during metal mold casting of hyperperitectic carbon steels was investigated by means of a rapid unidirectional solidification method which realizes a cooling condition quite similar to that for a part near the slab surface of a practical continuous casting process. It was found that the FCG region forms at the front of CCG region also in case of the metal mold casting. The temperature at the boundary between the FCG and CCG regions corresponded to T_γ . Importantly, it was revealed that the continuous growth from the FCG to the CCG does not occur and, instead, the CCG region, which initially forms near the mold side, develops along the direction of temperature gradient by consuming the FCG region. Therefore, at a fixed point of the cast sample, the grain size discontinuously changes by about one order of magnitude from the FCG to the CCG when the temperature at the fixed point falls below T_γ , which is in marked contrast to the above-mentioned assumption in the continuous grain growth model.^{8,9)} It was concluded in our

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

Sample name	Steel composition, in Mass%									
	C	Si	Mn	P	S	Al	O	N	Cr	Fe
0.2C	0.20	0.21	0.79	0.02	0.003	0.04	0.0027	0.0051	-	bal.
0.2C+3Cr	0.19	0.20	0.76	0.02	0.003	0.04	0.0026	0.0051	3.0	bal.

recent report¹⁰⁾ that it is important to prevent the continuous development of CCG region along the direction of temperature gradient in order to realize the refinement of as-cast γ grain structure.

According to the studies on the effects of alloying elements on the as-cast γ structure, the addition of alloying element such as P and Al is quite effective in the refinement of as-cast γ structure.^{8,11–13)} It was reported that the simultaneous addition of Al and P, both of which are known as ferrite-stabilizing elements, is effective in refining the CCG structure in 0.2 mass% carbon steel.¹³⁾ This refinement originates from the pinning effect of δ -ferrite or liquid phases stabilized at lower temperatures due to the segregation of these elements. In this study, we focus on the addition of Cr which is also known as one of the ferrite-stabilizing elements. Cr is practically utilized as an alloying element which improves corrosion and wear resistances of steel. However, the effects of Cr addition on the as-cast γ structure have not been clarified in detail. Therefore, in this study, we investigate the effects of Cr addition on the as-cast γ structure in 0.2 mass% carbon steel.

2. Experimental Procedures

A 0.2 mass% carbon steel rod with a diameter of 26 mm was used as a raw material. A piece of steel bar was placed in a MgO crucible with an inner diameter of 28 mm and a depth of 70 mm. Granular Cr (99.7 mass%) was placed in the MgO crucible together with the steel bar. The total weight of the sample was about 180 g. The composition of the samples used in this study is shown in **Table 1**. The samples without Cr addition and with 3 mass% Cr addition are called 0.2C and 0.2C+3Cr samples, respectively, in this paper. Each sample was melted at 1570°C in a SiC furnace filled with a five-nine pure Ar gas and held at the temperature for 1 h, followed by casting the melt into the rapid cooling unidirectional solidification equipment shown in **Fig. 1**. This equipment consists of a MgO pipe and a water cooled copper mold. The MgO pipe was preheated to 1570°C and was placed on the water cooled copper mold just before casting in order to realize upward unidirectional solidification. Especially, this equipment enables detailed investigation of the formation process of the microstructures during and after solidification by dropping the sample together with the MgO pipe very quickly into an iced water bath at predetermined timings after casting. In our preliminary experiment, the cooling rate just after solidification in the present sample was measured to be about 10°C/s at a point in the sample 10 mm away from the copper mold. This is quite comparable to that in the practical C.C. slab with the similar composition. The as-cast sample has a columnar shape with a height of 40 mm and a diameter of 28 mm. The ingot was sectioned vertically through the center axis of the columnar sample and the cross section was

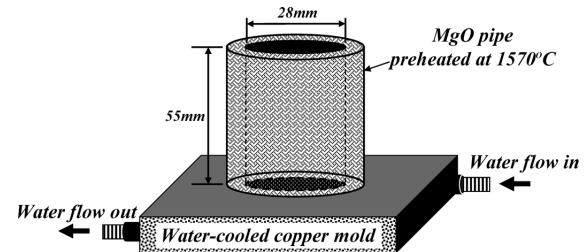


Fig. 1. Schematic illustration of rapid unidirectional solidification equipment used in this study.

polished. The as-cast γ structure and the dendrite structure were observed after the etching with 3%-nital and Oberhofer's solutions, respectively.

In addition to the samples cooled to Room Temperature (RT), the observations were carried out for the samples quenched when predetermined periods (10–100 s) past after casting in order to clarify the formation process of the γ structure during casting. An Electron Probe Micro Analyzer (EPMA) was employed to analyze the concentration distribution of elements in the quenched sample.

3. Results and Discussion

3.1. Microstructures of the As-cast Samples

Figures 2(a) and **2(b)** show the as-cast γ structure and the dendrite structure in the 0.2C sample cooled to RT, respectively. The bottom side of these figures corresponds to the mold side of the ingot. The bright lines in **Fig. 2(a)** represent the as-cast γ grain boundaries which are visible because of primary ferrite phase precipitating on the former γ grain boundary. It is seen that the CCG with a minor axis diameter of a few mm develops from the mold side toward the upper side of the cast sample. The aspect ratio of the CCGs in this sample was measured to be 4.6 on average. In **Fig. 2(b)**, the columnar dendrites develop from the mold side toward the upper side of the sample. From the microstructural observations, unidirectional growth of the dendrite was confirmed over the whole observation area.

Figures 3(a) and **3(b)** show the as-cast γ structure and the dendrite structure in the 0.2C+3Cr sample cooled to RT, respectively. The γ grain structure is not observed very clearly in the figure in this case because the addition of Cr suppressed the formation of the primary ferrite phase on the former γ grain boundary. For the visual aid, accordingly, the as-cast γ grain boundaries were traced based on the direct microscopic observation of the sample and drawn in **Fig. 3(c)**. The dendrite structure in the 0.2C+3Cr sample is quite similar to that in the 0.2C sample. However, the addition of Cr leads to the change in the as-cast γ structure. A lot of equi-axed grains are seen together with the CCGs. The CCGs in this sample have much shorter major axis diameter than the sample shown in **Fig. 2(a)**. The average aspect ratio of CCGs in the 0.2C+3Cr sample was measured

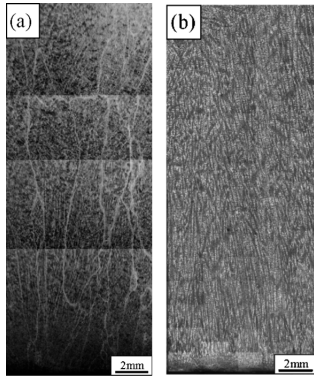


Fig. 2. Micrographs of the 0.2C sample cooled to RT. (a) As-cast γ structure, (b) Dendrite structure. The bottom side corresponds to the mold side of the ingot.

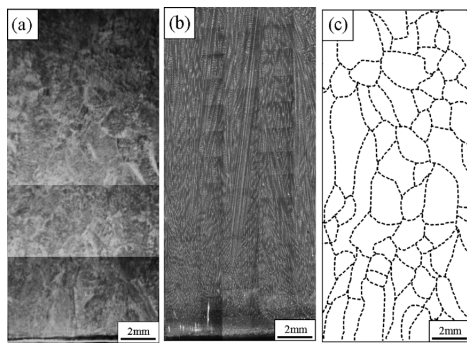


Fig. 3. Micrographs of the 0.2C+3Cr sample cooled to RT. (a) As-cast γ structure, (b) Dendrite structure, (c) Trace of γ grain boundaries. The bottom side corresponds to the mold side of the ingot.

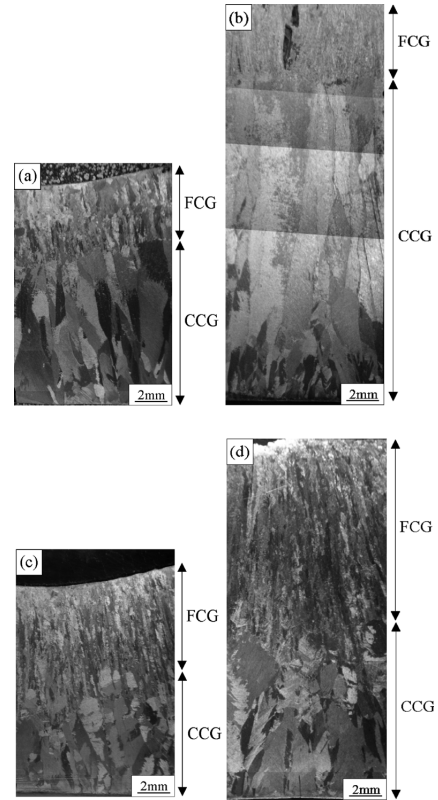


Fig. 4. Micrographs of the γ structures in (a) 0.2C sample quenched at 20 s, (b) 0.2C sample quenched at 40 s, (c) 0.2C+3Cr sample quenched at 20 s and (d) 0.2C+3Cr sample quenched at 40 s after casting. The bottom side corresponds to the mold side of the ingot.

to be 2.0, which is much smaller than 4.6 in the 0.2C sample.

3.2. Development of CCG Structure During Solidification

In our recent report,¹⁰⁾ it was found that the FCG structure exists at the front of CCG region during solidification in metal mold casting. The temperature at the FCG/CCG boundary corresponds to T_γ . **Figure 4** shows the microstructures in the 0.2C and 0.2C+3Cr samples quenched at 20 s and 40 s after casting operation. The FCG structures are observed at the front of the CCG region in all the micrographs. It should be noted that the length of the FCG region is long in the 0.2C+3Cr sample compared with that in the 0.2C sample. Also, the length of the CCG region measured from the mold side, L_{CCG} , is reduced by the Cr addition. **Figure 5** shows the time dependence of L_{CCG} in 0.2C and 0.2C+3Cr samples. In both samples, L_{CCG} gradually increases with the increase in time. It is obviously shown that L_{CCG} in the 0.2C+3Cr sample is always shorter than that in the 0.2C sample. In other words, the migration velocity of the FCG/CCG boundary is reduced by the Cr addition.

As mentioned above, the temperature at the FCG/CCG boundary corresponds to T_γ in the 0.2C samples.¹⁰⁾ **Figure 6** shows the phase diagram of Fe-0.2C-0.8Mn-0.2Si-0.02P-xCr (mass%) steel calculated by the CALPHAD method.¹⁴⁾ One can see that the addition of 3 mass% Cr does not change T_γ substantially. However, it is considered that T_γ is

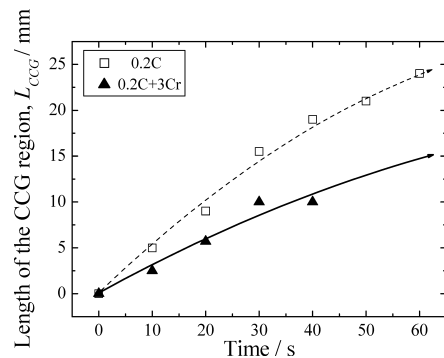


Fig. 5. Temporal change of L_{CCG} during solidification.

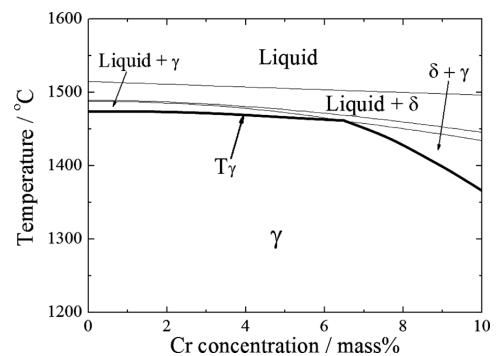


Fig. 6. Phase diagram of Fe-0.2C-0.8Mn-0.2Si-0.02P-xCr (mass%) steel calculated by CALPHAD method.

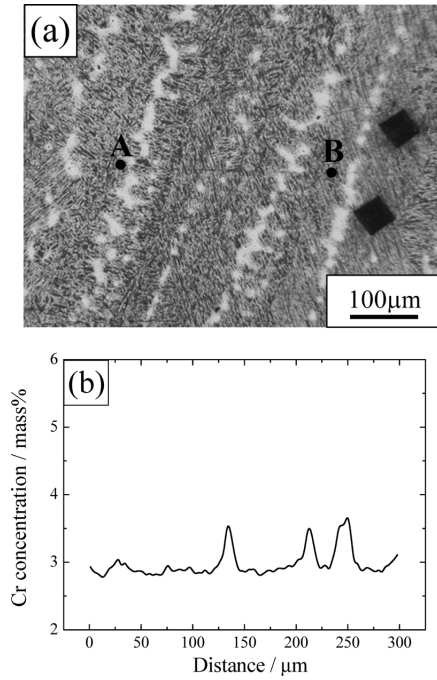


Fig. 7. (a) Dendrite structure in the CCG region in 0.2C+3Cr sample quenched at 20 s. (b) Distribution of Cr concentration obtained by EPMA analysis between points A and B in Fig. 7(a).

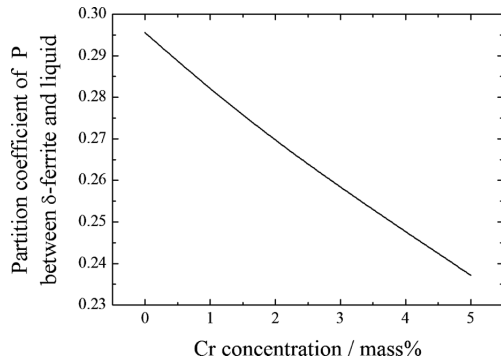


Fig. 8. Effect of Cr addition on the partition coefficient of P between δ and liquid phases at 1500°C, calculated by CALPHAD method. The composition is Fe-0.2C-0.8Mn-0.2Si-0.02P-xCr (mass%).

appreciably reduced at local regions of the structure, if the microsegregation of Cr occurs during the solidification process. Hence, we investigated Cr concentration profile across the dendrites. **Figure 7(a)** shows the dendrite structure in the CCG region and **Fig. 7(b)** shows the result of the EPMA analysis for Cr concentration. The bright parts in **Fig. 7(a)** correspond to the interdendritic regions. The line analysis for Cr concentration was performed between the points A and B in **Fig. 7(a)**. It can be seen in **Fig. 7(b)** that the segregation of Cr occurs at the interdendritic regions. However, the degree of segregation is quite small. Therefore, the decrease in T_γ should not substantially occur only by the Cr segregation.

It was reported that Al addition to 0.2 mass% carbon steel enhances the P segregation at the interdendritic region during the solidification, and as-cast γ structure was refined by the decrease in T_γ due to the P segregation.¹³⁾ **Figure 8** shows the dependence of the partition coefficient of P

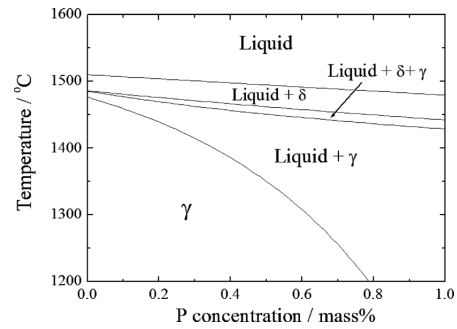


Fig. 9. Phase diagram of Fe-0.2C-0.8Mn-0.2Si-xP (mass%) steel calculated by CALPHAD method.

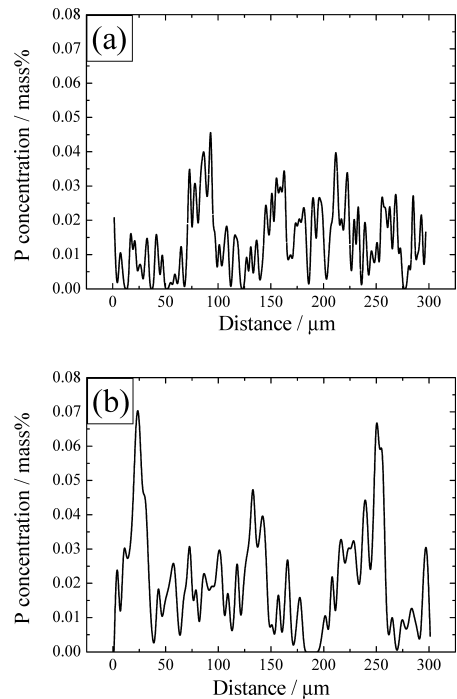


Fig. 10. Distribution of P concentration in the CCG region of (a) 0.2C and (b) 0.2C+3Cr samples quenched at 20 s, obtained by EPMA analysis along the lines between points A and B in **Fig. 11** and **Fig. 7(a)**, respectively.

between δ -ferrite and liquid phases on Cr concentration. The partition coefficient was calculated for Fe-0.2C-0.8Mn-0.2Si-0.02P-xCr (mass%) steel at 1500°C. The Cr addition lowers the partition coefficient of P significantly. Therefore, it is expected that the Cr addition enhances the P segregation. In **Fig. 9**, the phase diagram of Fe-0.2C-0.8Mn-0.2Si-xP (mass%) steel is presented. T_γ substantially decrease with the increase in the P segregation. **Figure 10** shows the results of EPMA analysis for P concentration in the CCG region of the 0.2C (**Fig. 10(a)**) and 0.2C+3Cr (**Fig. 10(b)**) samples quenched at 20 s. The EPMA analysis on the 0.2C and 0.2C+3Cr samples was performed between the points A and B in **Fig. 11** and **Fig. 7(a)**, respectively. In both the samples, the P segregates at the interdendritic regions and, importantly, the P segregation is enhanced by the Cr addition. From these results, the addition of Cr lowers T_γ because of the enhancement of P segregation at the interdendritic regions.

As mentioned above, the Cr addition lowers T_γ at the interdendritic region. Therefore, in the 0.2C+3Cr samples,

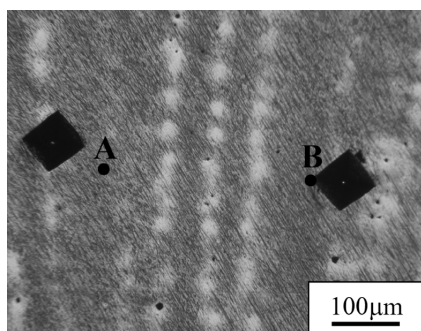


Fig. 11. The dendrite structure in 0.2C sample quenched at 20 s.

the liquid phase exists at lower temperatures, providing the pinning effect on the migration of the FCG/CCG boundary. This should be the reason for the reduction of the migration velocity of FCG/CCG boundary by the Cr addition observed in Fig. 5.

3.3. Formation Mechanism of Relatively Equi-axed CCG Structure

In our recent report,¹⁰⁾ it was found that the CCG region develops by consuming the FCG region. Figures 12(a)–12(c) show the schematic illustrations of this process. The bottom of the each illustration corresponds to the mold side of the sample. At temperatures above T_γ , the γ grains cannot grow due to the remaining liquid phase at the interdendritic regions, while the grains can grow at temperatures below T_γ . The large difference in grain size between FCGs and CCGs provides the large driving force for the development of CCG toward FCG region. Hence, the CCGs rapidly develop toward the FCG region immediately after the liquid phase disappears in the FCG region.

The mobility of the boundary between the FCG and CCG regions is an important parameter controlling the development of the CCG region. It is well known that the grain boundary mobility largely depends on temperature. The migration velocity of the FCG/CCG boundary, *viz.*, the velocity of the development of CCG region should decrease with the decrease in the growth temperature. Therefore, if T_γ is lowered, the temperature at the FCG/CCG boundary decreases and, accordingly, the migration velocity of the CCG region decreases. As mentioned above, T_γ in 0.2C+3Cr sample was lowered locally at interdendritic regions by P segregation. Therefore in the 0.2C+3Cr sample, it is considered that due to the lowering of T_γ , the CCG region does not extend toward the FCG region immediately after the liquid disappears. Hence, the FCGs remain even at temperatures below T_γ and the liquid phase disappears in the FCG region. Then, the grain growth is allowed to take place in the FCG region. As a result, the size of some grains in the FCG region becomes comparable to the size of CCG. When the coarse grains exit in the FCG region, the development of the CCG region is retarded because the driving force originating from the difference in the short axis diameter between the CCG and FCG vanishes. This process results in the formation of the CCGs having small aspect ratio in the sample cooled to RT. The detail of this process is schematically illustrated in Figs. 13(a)–13(c). In the 0.2C+3Cr sample, the temperature for

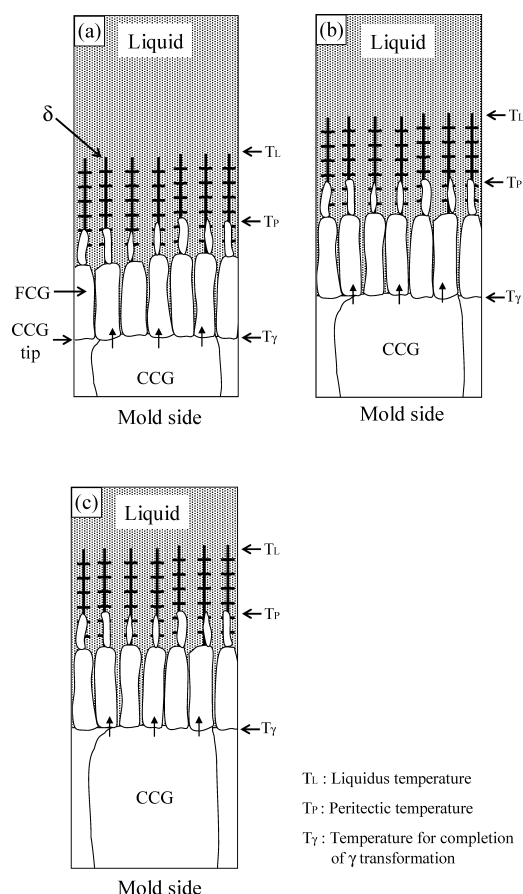


Fig. 12. Schematic illustrations for the formation process of the CCG structure in the 0.2C sample. The solidification proceeds from (a) to (c).

the FCG region is lower than T_γ and the liquid phase does not exist in the FCG region. As shown in Fig. 13, a relatively large grain “A” grows in the FCG region, and it becomes the coarse grain. The driving force for the development of CCG toward FCG region significantly diminishes in the vicinity of the coarse grain “A” in FCG region. Then, the CCG does not grow along the long axis direction and, instead, the grain “A” becomes the coarse columnar shape and it finally grows into the CCG. Ahead of this CCG, the coarsening of a relatively large grain “A” will occur in the FCG region as shown in Fig. 13(c). This sequential formation of large grains in FCG region leads to the formation of CCGs having short major axis diameter in the 0.2C+3Cr sample. In fact, as shown in Fig. 14, it was observed that the relatively large grain exists in FCG region of the 0.2C+3Cr sample quenched at 20 s.

From the previous studies,^{8,11–13)} it has been known that the addition of some alloying elements such as P and Al leads to the decrease of T_γ and the refinement of CCG structure. In this study on the Cr addition, it was demonstrated that the decrease of T_γ leads to the reduction of the migration velocity of the FCG/CCG boundary, and it results in the decrease in the major axis diameter of the CCGs. Therefore, it is considered that the lowering of T_γ is effective not only in the refinement of CCG structure but also in the prevention of development of CCG structure at the surface of C.C. slab.

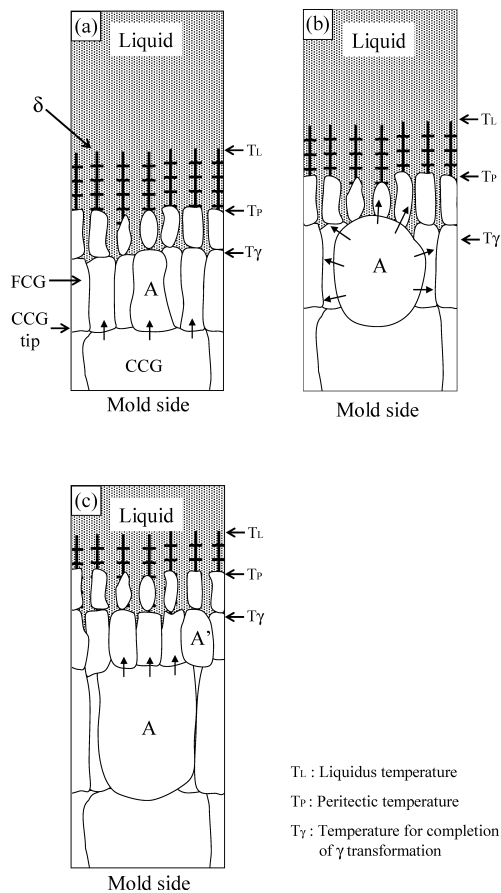


Fig. 13. Schematic illustrations for the formation process of the CCG structure in the 0.2C+3Cr sample. The solidification proceeds from (a) to (c).

4. Conclusions

The early studies demonstrated that the addition of the ferrite stabilizing element such as P and Al refines the as-cast γ structure in peritectic carbon steels because of the pinning effect of δ -phase.^{8,11-13} In this study, we investigated the effect of Cr, which is one the ferrite stabilizing elements, on the as-cast γ structure in the 0.2 mass% C steel by using a rapid unidirectional solidification method. It was found that the addition of Cr yields the as-cast γ grain structure consisting of relatively equiaxed coarse grains. In contrast to our expectation, this effect of Cr addition is ascribable not to the pinning effect of δ phase due to Cr segregation but to the pinning effect of liquid phase due to the P segregation enhanced by the Cr addition. The important findings are summarized as follows.

(1) In the samples with and without Cr addition cooled to room temperature, the as-cast γ structure consists of Coarse Columnar γ Grains (CCGs). The addition of 3 mass% Cr reduces the major axis diameter of the CCGs, resulting in the decrease in aspect ratio from 4.6 to 2.0.

(2) During solidification process, the Fine Columnar γ

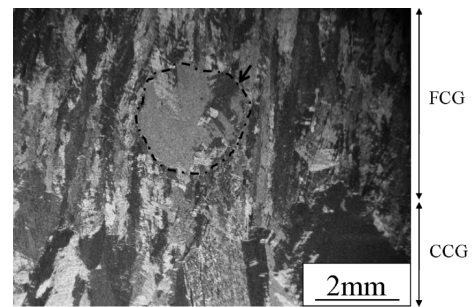


Fig. 14. A relatively large equi-axed grain observed in the FCG region in the 0.2C+3Cr sample. A dashed-dotted line indicates the γ grain boundary of the relatively large equi-axed grain.

Grains (FCGs) forms at the front of the CCG region in the samples with and without Cr addition. The migration velocity of the FCG/CCG boundary was reduced, by the Cr addition.

(3) The Cr addition lowers the temperature for completion of γ transformation, T_γ , by enhancing high P segregation. Then, the lowering of T_γ reduces the migration velocity of the FCG/CCG boundary and relatively large grains grow into coarse grains in the FCG region in the sample with 3 mass% Cr, which results in the formation of the CCGs having shorter major axis diameters.

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