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Improvement of Inner Quality of Continuous Cast Round Billets by FCR Technology at Wakayama Works[*1]

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Abstract

Seamless pipes for energy-related line pipes and Oil Country Tubular Goods (OCTG), used in a harsh environment, are manufactured at Wakayama Works. These products are manufactured using round CC cast billets. At the casting process, the occurrence of internal defects at the billet center (center cavity) causes defects in the pipe forming process and quality problems. As countermeasures to such problems, the optimum conditions for the final solidification cooling technology (Final Compressive cooling for Round billets: FCR) were clarified here. First, the casting speed was adjusted to match the final solidification position with the FCR zone. Furthermore, when applying FCR to larger diameter billets with a diameter of 310 mm or more, the internal quality deteriorates due to the generation of tensile stress at the center due to the γ → α expansion transformation accompanied by the decrease in surface temperature. Therefore, further optimization of cooling conditions was performed. As a result, we achieved a significant reduction in the incidence of cracks in the pipe making process.

1. Introduction

In the line pipes manufactured from round continuous cast (hereinafter referred to as CC) billets, the occurrence of internal defects during pipe rolling due to internal defects at the billet center (center cavity) is a problem. Therefore, technology for improving the internal quality of line pipes was developed and an outstanding improvement effect was confirmed.

2. Background

2.1 Seamless pipe manufacturing process from as cast round CC billets

Figure 1 shows the outline of the seamless pipe manufacturing process at Wakayama Works of Nippon Steel Corporation using as cast round CC cast billets. At Wakayama Works, pipes are manufactured in the pipe mill directly connected to the steelmaking process of the Kanbara reactor (KR) – Dephosphorization furnace – Decarburization furnace – Vacuum degassing (RH) – Continuous Casting (CC).

2.2 Product configuration of seamless pipes manufactured at Wakayama Works

Figure 2 shows the product configuration of seamless pipes manufactured at Wakayama Works. The energy-related pipes (line pipe, corrosion-resistant OCTG) occupy about 80% of the entire configuration. Line pipes in the configuration are used for the transportation of oil and natural gas. In **Fig. 3**, features of line pipes are shown. To comply with any installation surroundings, line pipes of various sizes are required. Furthermore, high toughness is required since line pipes are installed in deep sea areas or in cold regions, and to cope with the deterioration of the toughness of welds at pipe connection, steel materials with low carbon content ([C]=0.05–0.07 mass%) are used.

3. Problem of Line Pipe Quality and Countermeasures

Figure 4 shows the features of the internal defect of as cast billets for line pipes. The internal defect takes the form of cracks developed in the radial direction at the center of a billet (center cavity).

[*1] Reproduced from the Iron and Steel Institute of Japan 156th Steelmaking Subcommittee presentation paper

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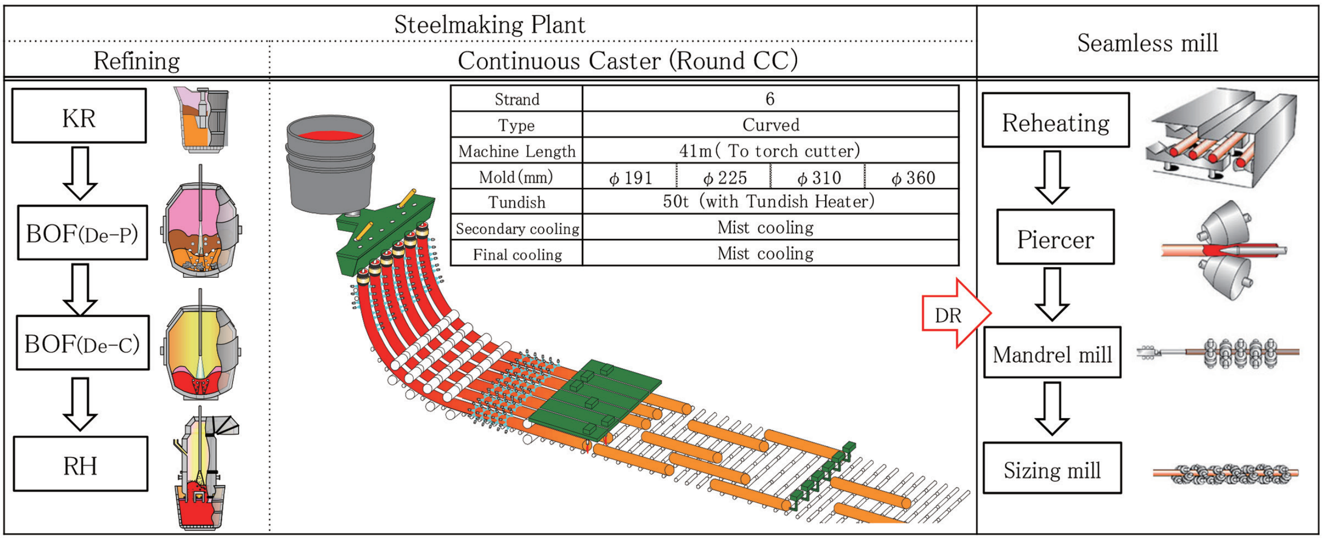


Fig. 1 Seamless pipe manufacturing process in Wakayama Works (medium size seamless pipe from as cast billet)

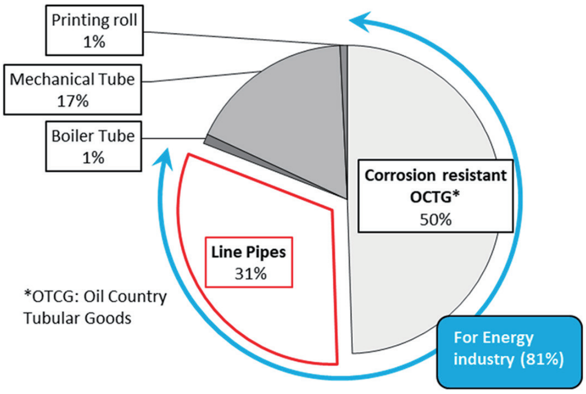


Fig. 2 Product configuration of seamless pipe at Wakayama Works

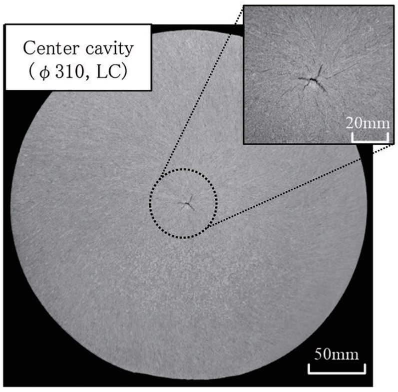


Fig. 4 Feature of internal defect of billet (center cavity, low carbon steel)

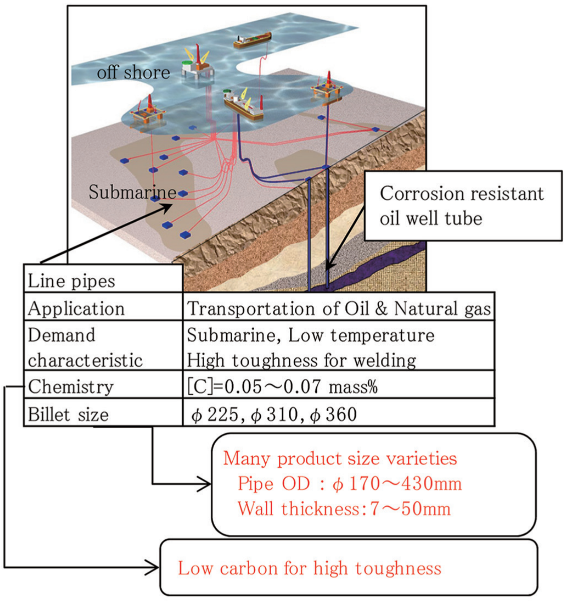


Fig. 3 End use of seamless pipe

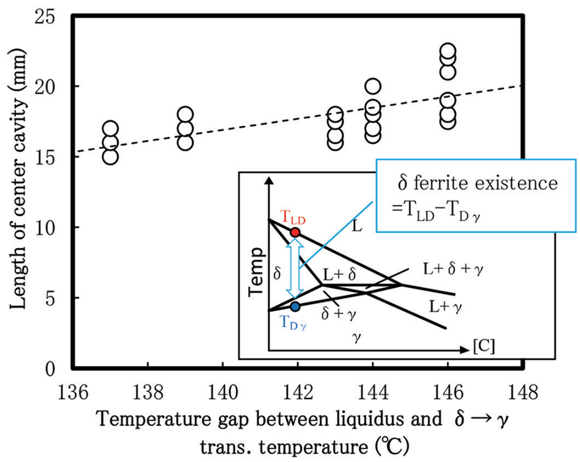


Fig. 5 Relation between temperature range of δ ferrite existence temperature and center cavity length[1, 2]

In **Fig. 5**, the relationship between the range of δ ferrite existence temperature[1)] and the center cavity length is shown. The center cavity propagates along the brittle ferrite phase layer. Therefore, the center cavity becomes larger in the low carbon steel where the δ ferrite existence temperature range is large.

Figure 6 shows the constraint on rolling of as cast round CC billets and the mechanism of center cavity occurrence. In round CC, the section figure (roundness) needs to be strictly controlled to avoid problems in pipe rolling. Therefore, mechanical reduction with rolls is difficult. Tensile stress is generated at the center due to the solidification contraction of the liquid that remains at the final solidification position. As a result, the center cavity is generated along the brittle ferrite phase layer.

4. Clarification of Fundamental Characteristics of Final Solidification Cooling Technology through Experimental Casting

4.1 Outline of Final Solidification Cooling Technology

As an internal quality improvement technology that does not exert adverse influence on a section figure, attention was focused on Final Compressive cooling for Round Billets (FCR)[2–4] shown in **Fig. 7**. FCR applies rapid cooling to the billet surface at the final solidification position. By the rapid cooling, thermal contraction is generated in the subsurface zone and compressive stress is generated at the center, and the center cavity is suppressed thereby. Moreover, since mechanical reduction is not applied, there is no adverse influence on the section figure.

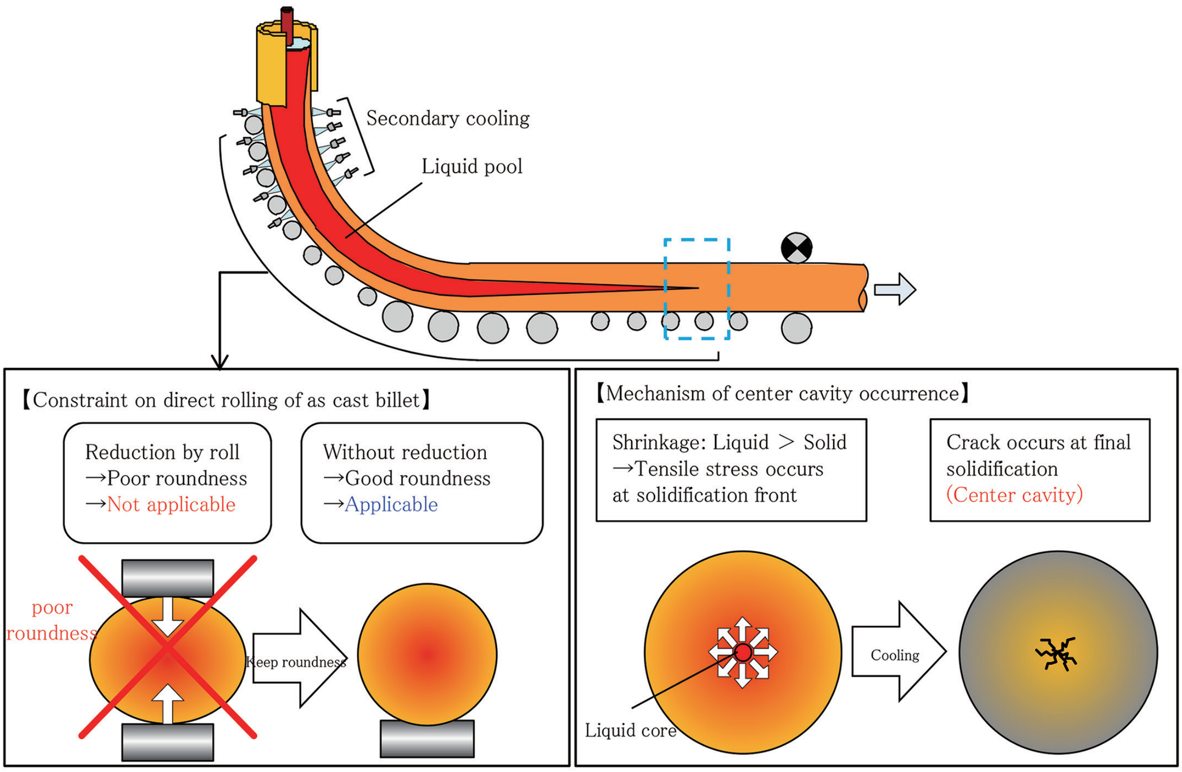


Fig. 6 Constraint on direct rolling of as cast billet and mechanism of center cavity occurrence

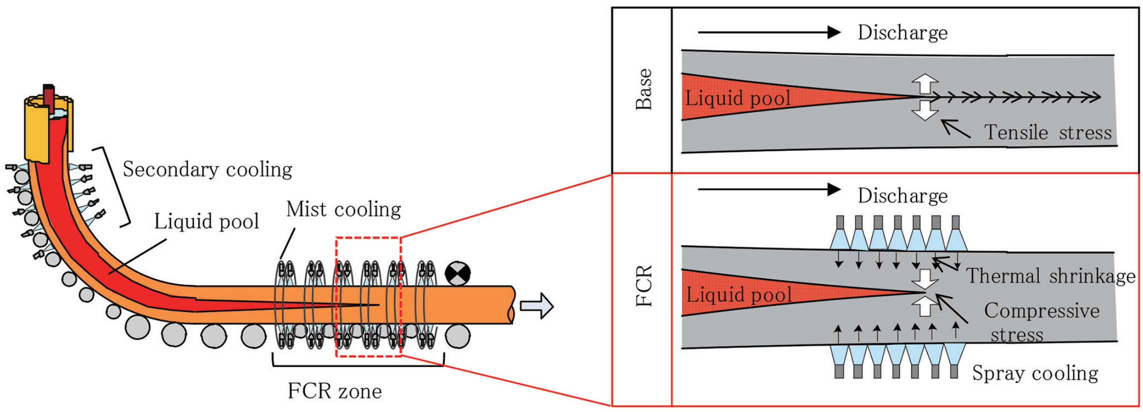


Fig. 7 Schematic drawing of FCR

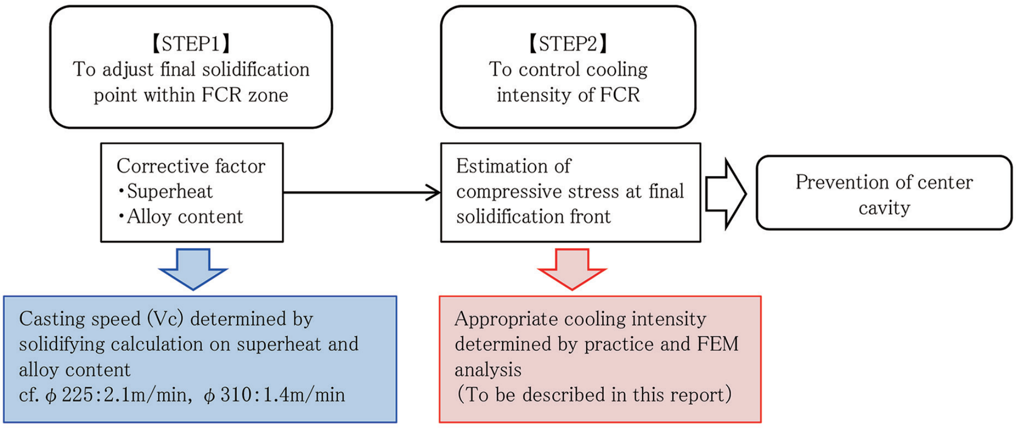


Fig. 8 Procedure to determine appropriate FCR condition

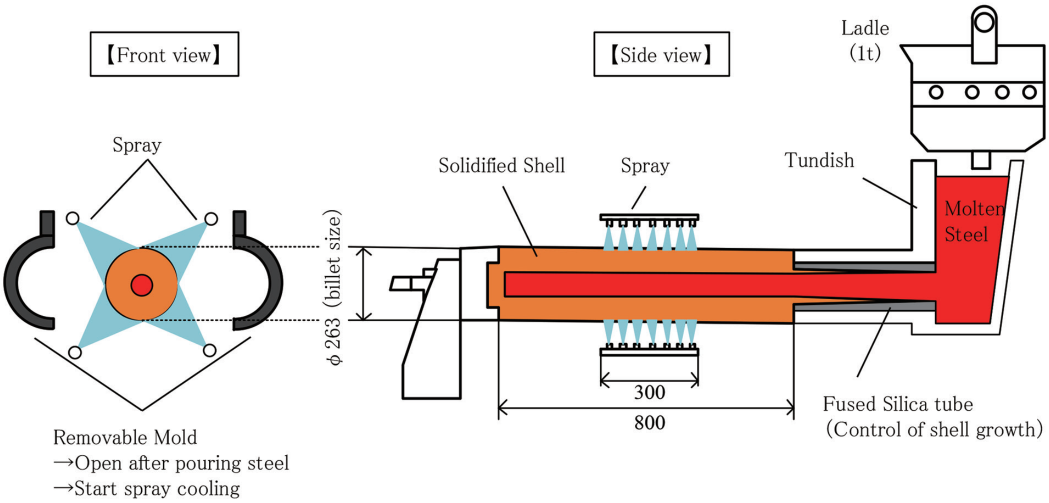


Fig. 9 Schematic drawing of pilot caster

4.2 Procedure to determine appropriate FCR condition

Figure 8 shows the procedure to determine the appropriate FCR condition. In FCR technology, rapid cooling needs to be applied to the surface at the final solidification position where the center cavity occurs and the final solidification position needs to be fitted to the FCR zone. Then, by prior solidification calculation, the pattern of optimum casting velocity (Vc) with respect to molten steel super heat (ΔT) and alloy contents was prepared. Then, compressive stress needs to be generated at the center by an appropriate FCR cooling in the FCR zone. Appropriate values of the FCR water flow rate were already determined by the laboratory experimental casting, the content of which is explained hereunder.

4.3 Determination of optimum water flow rate by FCR experiment

4.3.1 Experimental casting condition

Table 1 shows the experimental casting condition and the schematic diagram of the pilot caster used for the experimental casting is shown in **Fig. 9**. The experimental casting was conducted by the pilot caster having a removable type mold, and the internal quality improving effect at each water flow rate level was evaluated. The optimum FCR water flow rate was determined by means of FEM analysis based on the result of the experimental casting.

Table 1 Experimental casting condition

Size	φ263 mm
CC	Pilot caster
Procedure	① Molten steel pouring into mold through tundish
	② 4 min later after pouring, mold gap open by 5 mm
	③ Another 7 min later, mold open
	④ Spray cooling start

4.3.2 Result of experimental casting

Figure 10 shows the relationship between the water flow rate and the length of the center cavity. The cavity improvement effect of FCR is confirmed. However, it is also confirmed that the effect deteriorates when the FCR water flow rate becomes excessive, and that an optimum point exists in the FCR water flow rate.

4.3.3 Derivation of optimum water flow rate based on FEM analysis incorporating the result of experimental casting

Figure 11 shows the FEM analysis model. A part of a section was used for the model wherein the heat transfer coefficient determined based on the experimental casting result was used. In **Fig. 12**, the calculated radial stress with respect to the quantity ratio of cool-

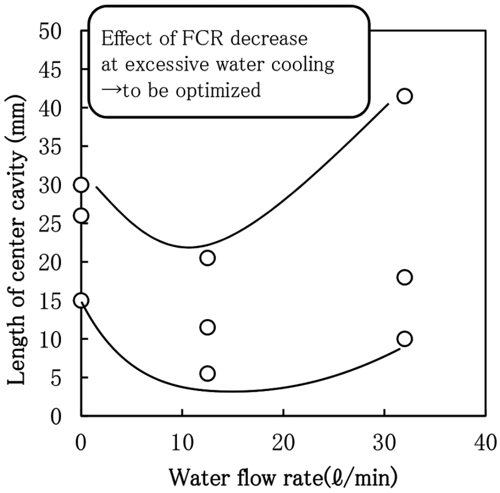


Fig. 10 Influence of water flow ratio on center cavity

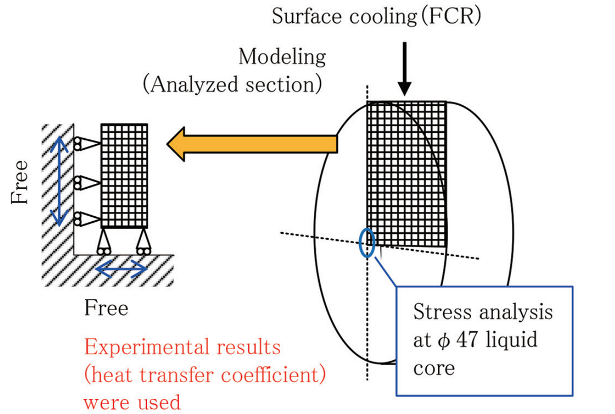


Fig. 11 Analysis of thermal elastic-plastic stress and strain during cooling of cylindrical ingot by FEM

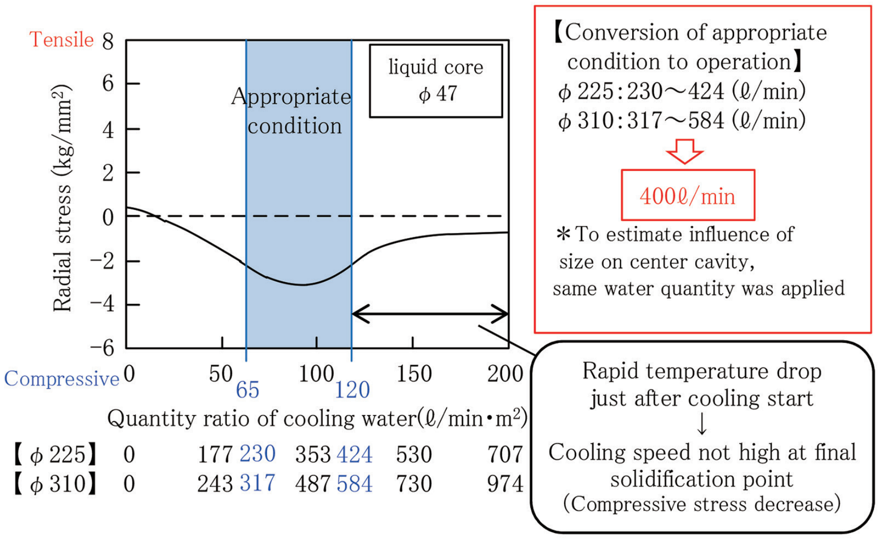


Fig. 12 Influence of cooling intensity on calculated radial stress

ing water is shown. Similarly to the result of the experimental casting, an optimum point that maximizes compression stress is confirmed. In addition, when the water flow rate is excessive, the surface is rapid-cooled directly after the start of cooling, and the surface temperature drops. As a result, the cooling rate at the final solidification position is decreased and the compressive stress is reduced. Based on this, for the on-line round CC machine experiment, the FCR water flow rate was set at 400 ℓ/min that is effective for either 225 mm diameter billets or 310 mm diameter billets, and evaluation of the effect including the influence of the size difference was conducted.

5. On-line Experiment of Final Compressive Cooling for Round Billets (FCR)

5.1 On-line experiment condition

Table 2 shows the on-line experiment condition. The on-line experiment was conducted for the billets 225 mm in diameter and 310 mm in diameter wherein the need for improving line pipe internal quality is high. The steel material was of low carbon content for line pipe use and the FCR water flow rate was set at 400 ℓ/min based on the results of the laboratory experimental casting and FEM analysis.

5.2 Result of on-line FCR experiment

Figure 13 shows the result of the on-line FCR experiment. In the 225 mm diameter billets, the center cavity was improved by FCR as revealed from the result of the experimental casting. However, in the 310 mm diameter billets, a defect running through a billet at its center occurred by the application of FCR, and the deterioration of the inner quality as compared with that of without FCR was confirmed. Then, factors pertaining to the deterioration of the internal quality in 310 mm diameter billets were investigated and the FCR condition was reviewed.

5.3 Investigation of quality deterioration of 310 mm diameter billets due to application of FCR and study on countermeasures

5.3.1 Study on billet-size-wise FCR mechanism

In **Fig. 14**, the internal state of the respective billets is arranged with regards to the influence of the thermal contraction and expansion when FCR is applied. Steel contracts when cooled. However, in

Table 2 Actual casting condition with FCR

Item	Condition		Remark
Steel grade	Low carbon steel (line pipe, X65)		[C]=0.05–0.07 mass%
Billet size	φ225 mm	φ310 mm	–
FCR	400 ℓ/min		Conversion of appropriate condition to operation from experimental results

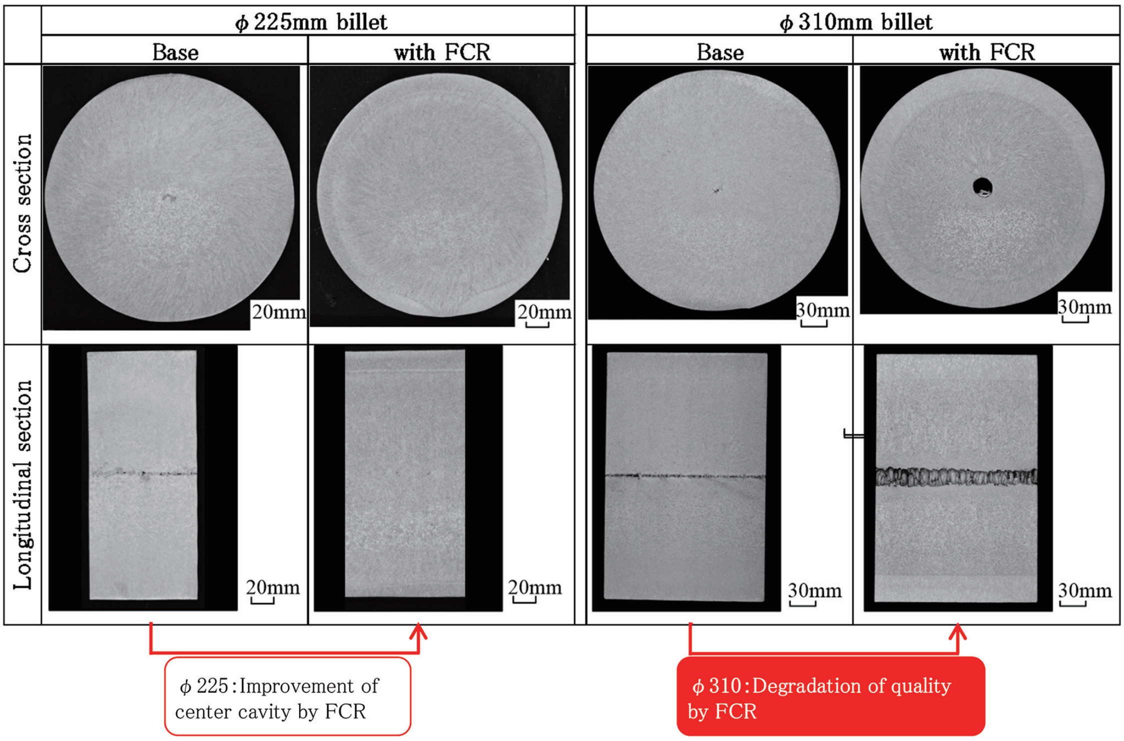


Fig. 13 Result of center cavity with/without FCR

the vicinity of 860°C, expansion transformation occurs due to the phase transformation from the γ phase (fcc) to α phase (bcc). In the case of the 225 mm diameter billets, from the result of solidification calculation, the expansion transformation region was confirmed not to exist in the FCR temperature range from the entry side to the final solidification position. Accordingly, at the billet center, compressive stress always acts in the FCR zone from its entry to the final solidification position.

On the other hand, in the case of the 310 mm diameter billets, since the final solidification position has to be adjusted to be in the FCR zone, Vc is decreased and temperature becomes lower than that of the 225 mm diameter billets. Therefore, at the entry to FCR, temperature drops and the billet temperature enters the expansion transformation temperature region before reaching the final solidification position. As a result, as the expansion transformation occurs in the subsurface zone, excessive tensile stress is considered to occur at the center. From this, mild FCR cooling was considered as necessary to avoid the expansion transformation before the final solidification.

5.3.2 Review of procedure to determine FCR condition

Figure 15 shows the procedure to determine the FCR condition reviewed based on the FCR mechanism of the case of the 310 mm diameter billets. In the review of the FCR application condition, it was confirmed that, pursuant to the result of the FCR on-line experiment, the review of the optimum FCR water flow rate was necessary in addition to the adjustment of the final solidification position to be in the FCR zone (determination of optimum water flow rate to avoid expansion transformation and to generate the FCR effect). Then, the procedures for determining the upper limit value of the FCR water flow rate to avoid expansion transformation, and the lower limit value of the FCR water flow rate required for generating FCR effect were reviewed.

5.3.3 Determination of FCR water flow rate to avoid expansion transformation (①FCR upper limit water flow rate)

Figure 16 shows the procedure to avoid expansion transformation by excessive cooling. Herein, the surface temperature at the final solidification position (solid phase ratio fs=1) is signified as T_F. To avoid internal quality deterioration due to FCR over cooling, T_F needs to be 860°C or above. In **Fig. 17**, the relationship between T_F acquired from solidification calculation and the FCR water flow rate is shown. In the case of the 225 mm diameter billets, T_F does not drop to below 860°C even at the facility upper capacity (600 ℓ/min). On the other hand, in the case of the 310 mm diameter billets, due to the influence of the decreased Vc (to adjust the final solidification position to be in the FCR zone.), T_F becomes lower than that of the 225 mm diameter billets. As a result, in order to maintain T_F above 860°C, the FCR water flow rate needs to be below 220 ℓ/min.

However, the result of the experimental casting shows that the minimum-required water flow rate for developing compressive stress at the center is 317 ℓ/min (Fig. 12). Therefore, according to

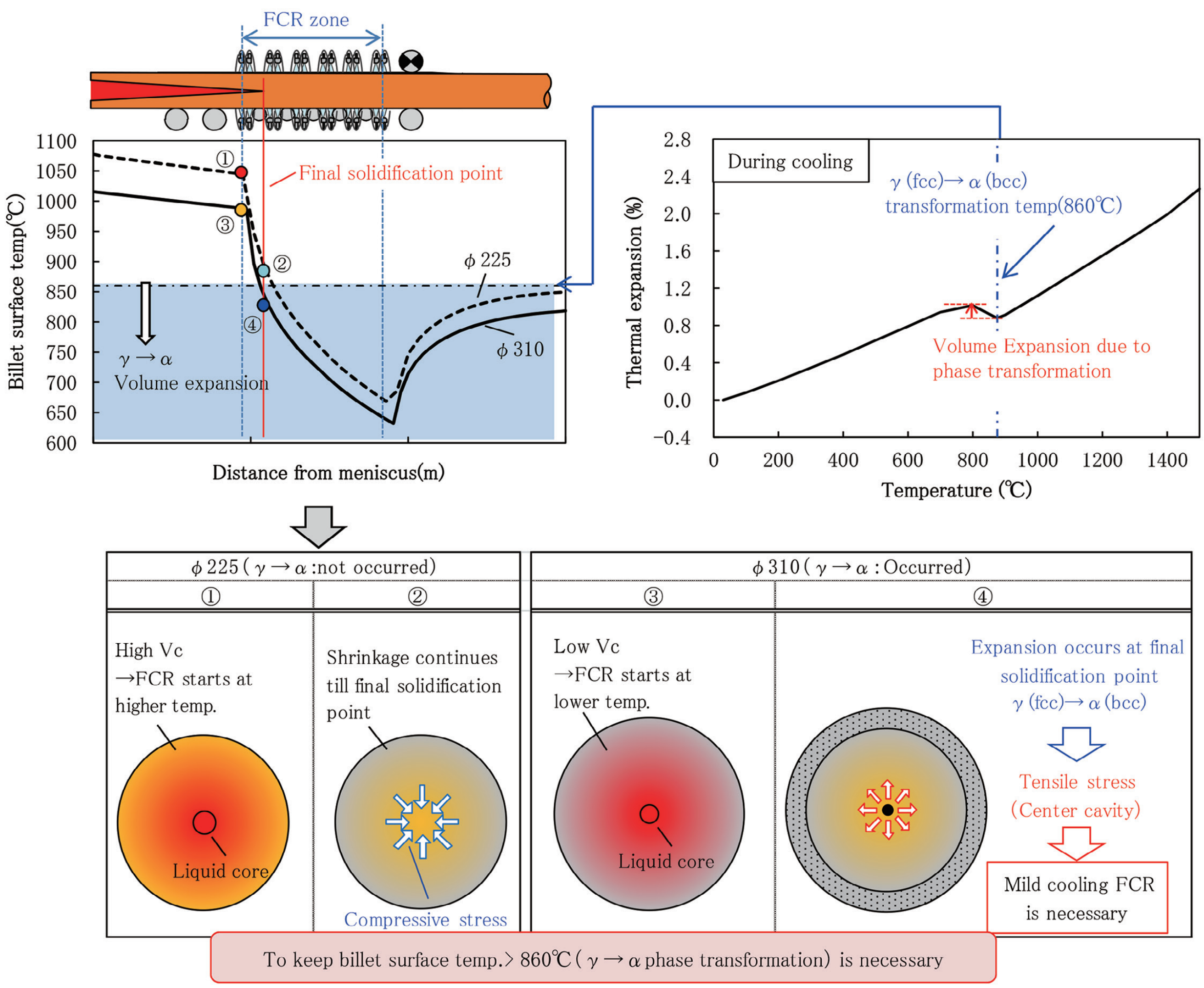


Fig. 14 Mechanism diagram of center cavity degradation on φ310 billet with FCR

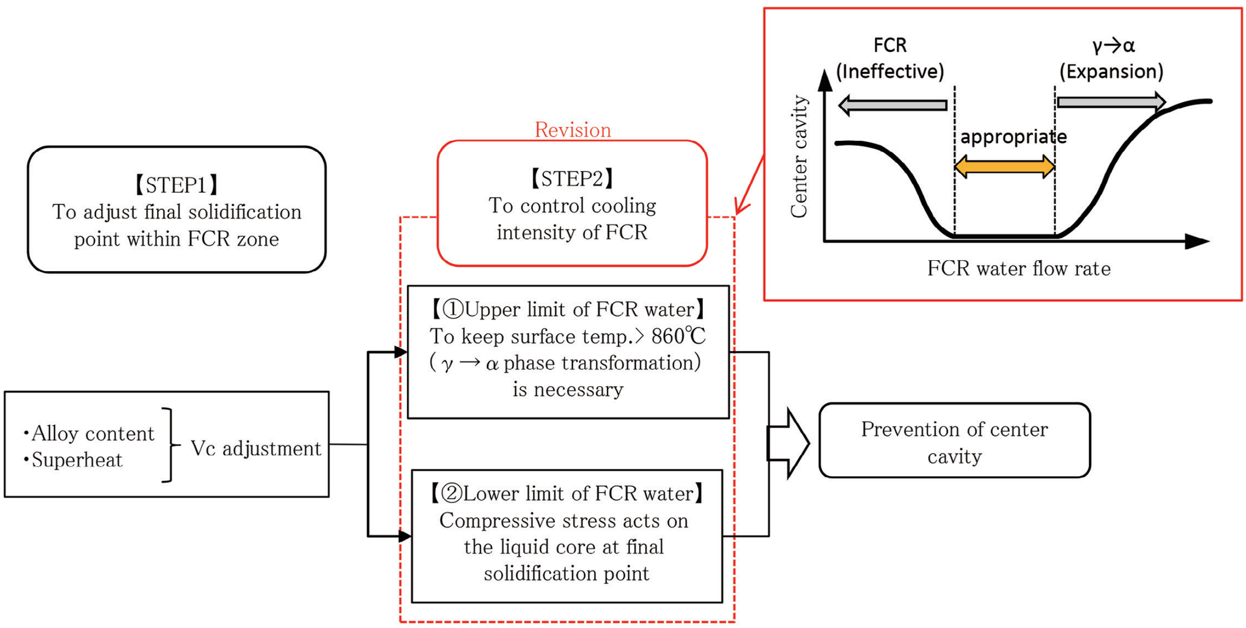


Fig. 15 Optimization of FCR condition

the previous evaluation method, the application of this value of 220 ℓ/min to 310 mm diameter billets is impossible. In the FEM analysis (a model built only on a part of a section) of the previous evaluation, the difference of the entire contraction amount on the entire billet section was not incorporated. Then, the procedure was reviewed, incorporating the difference in the amount of contraction due to the difference in the billet section area.

5.3.4 Determination of appropriate FCR water flow rate to suppress center cavity (②Determination of lower limit value of FCR water flow rate)

The water flow rate for the effective application of FCR was investigated by the model shown in **Fig. 18**. Herein, as a new evaluation index, the acting force on the liquid core considering the influence of the billet section size difference on the difference of the contraction amount was defined, and a model that derives thermal stress based on the cooling rate difference between the subsurface zone and center (the temperature of the respective positions was derived

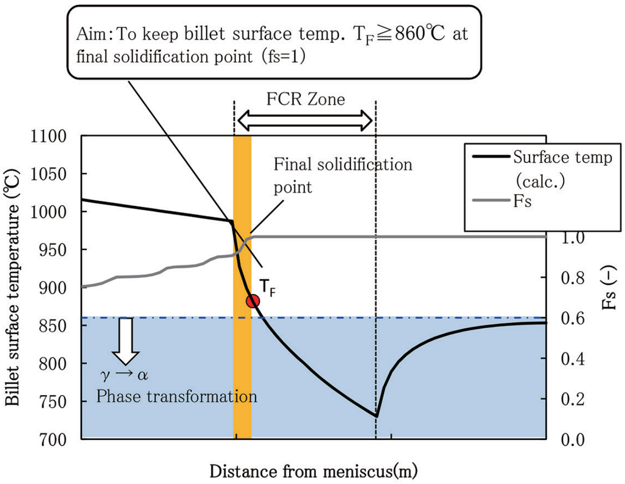


Fig. 16 Schematic view of prevention from overcooling by FCR

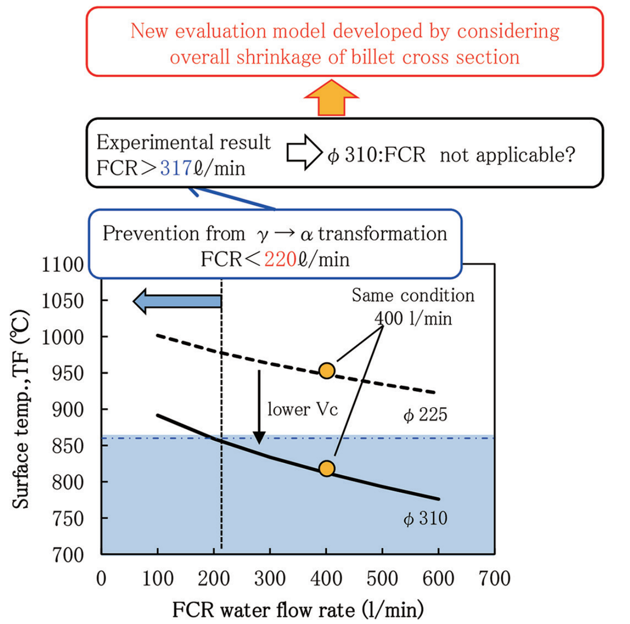


Fig. 17 Relation between FCR water and billet surface temperature at final solidification

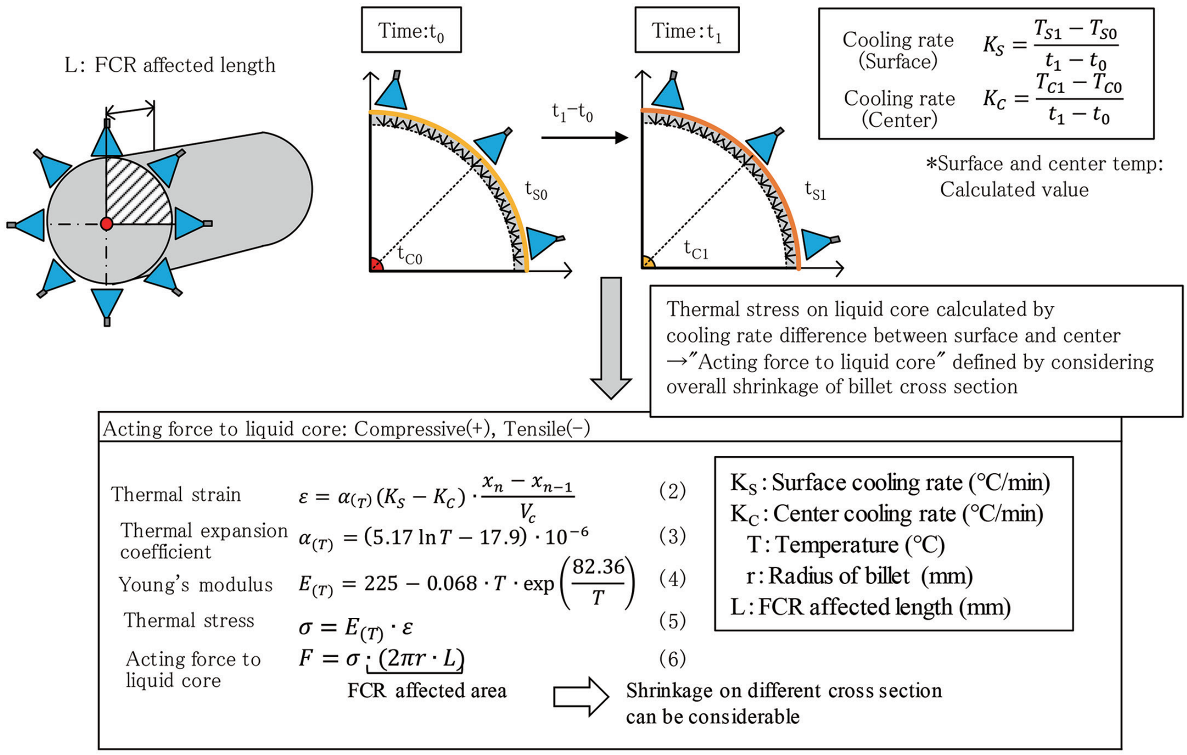


Fig. 18 New evaluation model of FCR effect

by solidification calculation). To the thermal stress, by taking into account the surface area affected by the FCR water flow rate, the contraction amount difference due to the difference in billet size was incorporated into the evaluation index.

Figure 19 shows the influence of the FCR water flow rate on the force acting on the center. As the billet diameter becomes larger, the cross section contraction amount due to FCR becomes larger than that of the smaller diameter billets, and with the same water flow rate, the force acting on the liquid core becomes larger than that of the smaller diameter billets. Accordingly, the effect of FCR can be generated with a water flow rate smaller than that of 225 mm that exhibited good results in the on-line experiment. Herein, when assuming as a standard the FCR water flow rate of 400 ℓ/min for 225 mm diameter billets wherein the center cavity improvement effect was obtained (on-line experiment), the water flow rate to obtain the equivalent force acting on the liquid core becomes 155 ℓ/min, and the application of FCR with the expansion-transformation avoiding water flow rate (under 220 ℓ/min) is possible.

5.3.5 Study on appropriate FCR condition

Figure 20 shows the result of the study on the appropriate FCR water flow rate range per each billet size. In the large diameter size billets (larger than 310 mm in diameter), the appropriate FCR water flow rate range becomes narrower as compared with that of the smaller diameter size billets (225 mm in diameter), and the application of FCR becomes harder. However, the flow rate range was reviewed and derived for an appropriate range, and it was confirmed that the newly found range is within the controllability of the present FCR facility.

5.3.6 Verification of appropriate FCR water flow rate using FEM analysis

Figure 21 shows the FEM analysis model used. In this analysis, a full 1/2 model was used to consider the influence of the billet size difference. Furthermore, by providing a vacancy of 30 mm in diameter to its center, the liquid core at the entry of FCR zone was assumed. The liquid core diameter of 30 mm was determined in the following manner. The condition of the 225 mm diameter billets under which an FCR effect was obtained was incorporated into the solidification calculation, and the liquid core diameter at the FCR zone entry obtained by the solidification calculation was assumed as the said liquid core diameter. In **Fig. 22**, the calculated change of the liquid core diameter is shown (the displacement of the plotted point in Fig. 21). As studied earlier, with the FCR water flow rate of 400 ℓ/min, growth of the liquid core diameter due to the phase transformation of γ (fcc) to α (bcc) in the subsurface zone is confirmed. On the other hand, it is confirmed that the value of 170 ℓ/min derived by restudying the FCR water flow rate prevents the growth of the diameter that occurs when FCR is not applied.

Figure 23 shows the distribution of the equivalent strain (two-dimensional strain converted to single axis strain). In the case of FCR excessive cooling (FCR=400 ℓ/min), γ to α expansion transformation occurs in the subsurface zone, and tensile strain is confirmed therein. As a result, large tensile strain occurs in the center and the deterioration phenomenon of the center cavity is reproduced. With the appropriate water flow rate of 170 ℓ/min, compressive strain occurs in the subsurface zone and compressive strain is maintained at the center likewise. From the above, as the validity of the study result was verified, the application effect of FCR on the 310 mm diameter billets was evaluated on an on-line experimental basis.

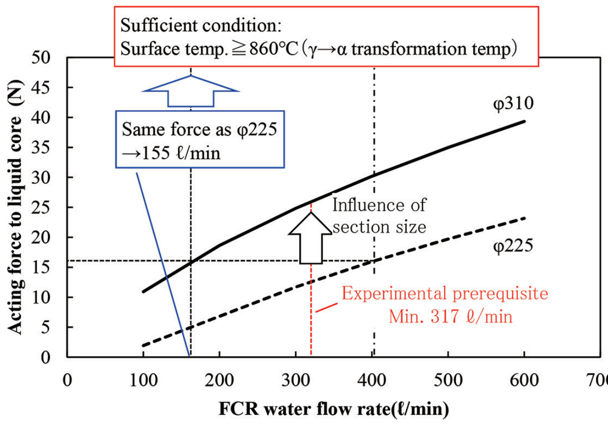


Fig. 19 Relation between FCR water flow rate and acting force to liquid core

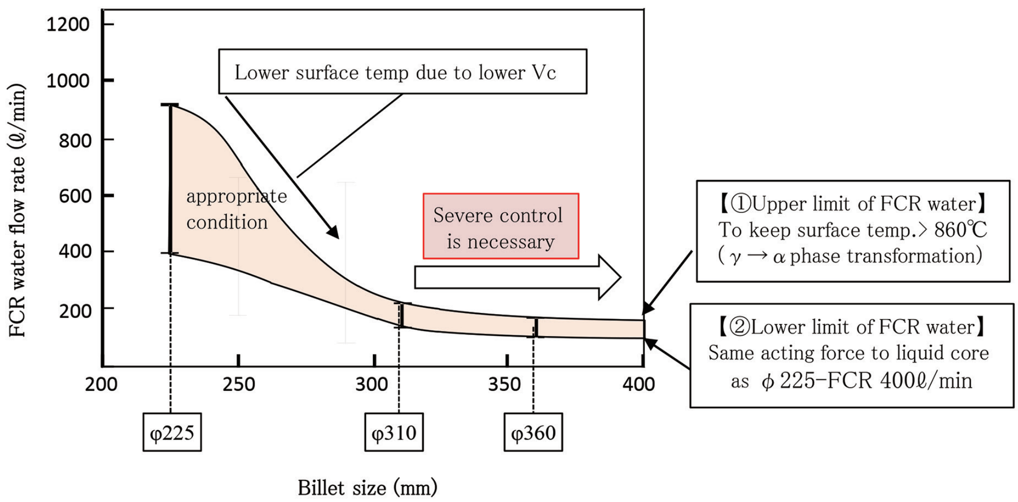


Fig. 20 Influence of section size on appropriate FCR condition

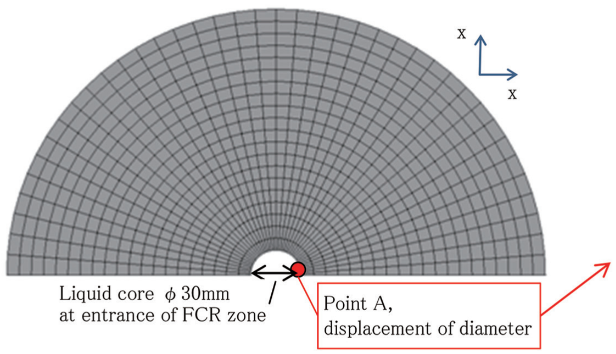


Fig. 21 FEM model

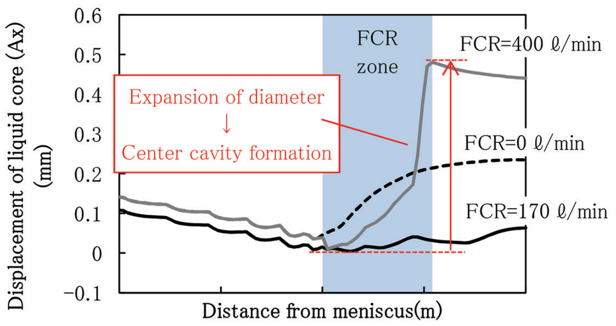


Fig. 22 Calculated displacement of liquid core during FCR

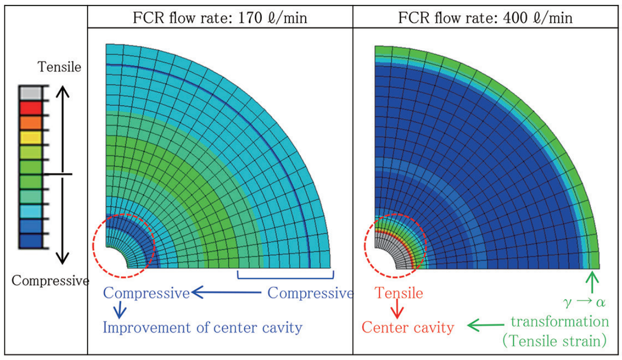


Fig. 23 Analyzed strain distribution at 2 m from the entrance of FCR zone

6. FCR Application Experiment to 310 mm Diameter Billets

6.1 FCR application experimental condition of 310 mm diameter billets

Table 3 shows the FCR application experimental condition of the 310 mm diameter billets. The subject steel grade of the experiment is a low carbon X65 of the major line pipe grades. Furthermore, in the secondary cooling, to stabilize the final solidification position, the specific water flow rate was made constant. With respect to Vc, the Vc pattern prepared by solidification calculation to adjust the final solidification position to be in the FCR zone was used. Regarding the FCR water flow rate, the experiment was conducted with two levels of water flow rate of the facility lower limit water flow rate of 170 ℓ/min and 200 ℓ/min to evaluate the influence of the change in the water flow rate, both being within the appropriate water flow rate range studied and determined earlier.

6.2 Influence of application of FCR on surface temperature

Figure 24 shows the result of the measurement of the surface temperature when FCR is applied. The surface temperature at the final solidification position could not be measured because it stayed in the FCR zone. Therefore, the temperatures calculated by solidification calculation based on the actual temperatures measured at the entry and the exit are shown. In the range where the FCR water flow rate is equal to or less than 200 ℓ/min (FCR water flow rate≤200 ℓ/min), the surface temperature above 860°C is confirmed at the final solidification position, which agrees with the result of the earlier study.

6.3 Center cavity improvement effect

Figure 25 shows the center cavity improvement effect per FCR water flow rate. In the appropriate water flow rate range determined in this study (170, 200 ℓ/min), a center cavity improvement effect is confirmed.

In **Fig. 26**, the result of the macro-segregation evaluation as per the respective water flow rate is shown. Improvement of the center cavity thanks to the application of FCR with the studied water flow rate (170, 200 ℓ/min) is confirmed on both cross and longitudinal sections. Furthermore, with the FCR water flow rate of 170 ℓ/min, a steady effect is confirmed in the casting direction, and the effectiveness of the FCR technology for the 310 mm diameter billets is confirmed. As a result, an internal quality improvement technology applicable to the diversified range of line pipes was established.

7. Internal Quality-improvement Effect Evaluated at Product Stage

Figure 27 shows the influence of the optimized FCR on the inner surface defect of pipes. The inner surface defect improvement effect with the optimized FCR for the 225 mm diameter billets and 310 mm diameter billets is confirmed. With this result, the effectiveness of the FCR technology is confirmed and the application of the technology to pipes for further sophisticated use is expected.

8. Conclusion

The final solidification cooling technology (FCR) developed and applied to round CC billets for the purpose of improving the internal quality of line pipes is summarized as below:

- In establishing the FCR condition, the following two points are important: ①adjustment of Vc to fit the final solidification po-

Table 3 Modified casting condition with FCR for φ310 billet

Item	Condition			Remark
Steel grade	Low carbon steel (line pipe, X65)			[C]=0.05–0.07 mass%
FCR		Water flow rate	Comparison	170 ℓ/min: Minimum flow rate within capability of facility
	Test ①	170 ℓ/min	0 ℓ/min	200 ℓ/min: Prevention of $\gamma \rightarrow \alpha$ transformation and estimation of influence of
	Test ②	200 ℓ/min	400 ℓ/min	flow rate

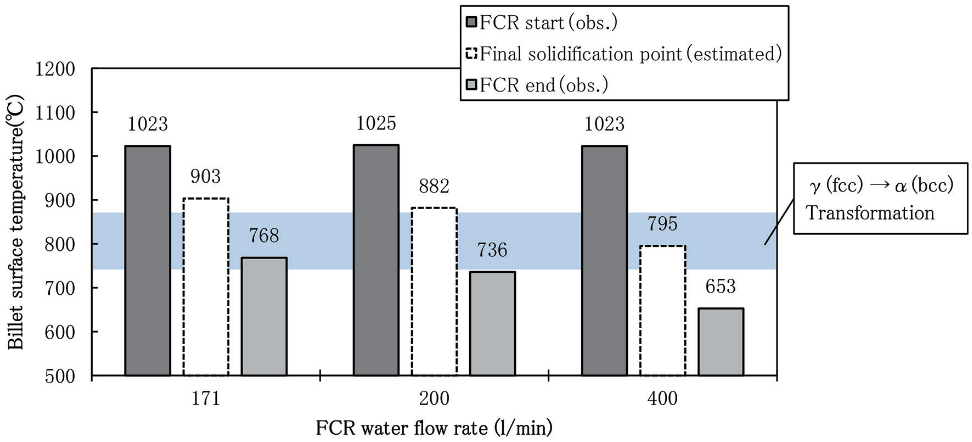


Fig. 24 Relation between FCR water and billet surface temperature

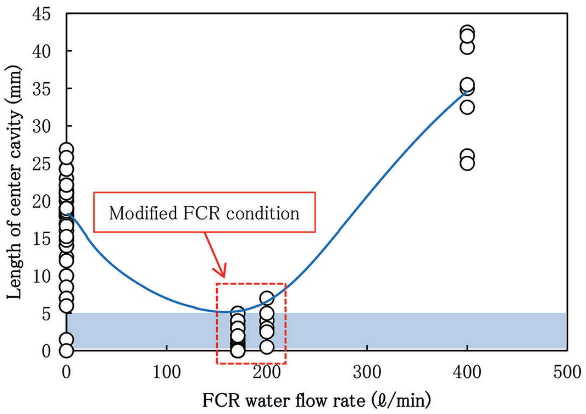


Fig. 25 Influence of water flow ratio on center cavity

sition to the FCR zone and ②setting of the optimum water flow rate to provide compressive stress at the center at the final solidification position.

- With the optimum water flow rate of 400 ℓ/min defined as an appropriate index in the earlier experimental casting, the center cavity was suppressed in the 225 mm diameter billets. However, in the 310 mm diameter billets, deterioration from the previous level was confirmed.
- In the application of FCR to large diameter billets, surface temperature drops when FCR is applied since Vc is decreased to fit the final solidification position to the FCR zone. Therefore, γ to α expansion transformation (below 860°C) occurs in the subsurface zone. As a result, tensile stress occurs at the center and internal quality is deteriorated thereby.
- In large diameter billets, to avoid expansion transformation be-

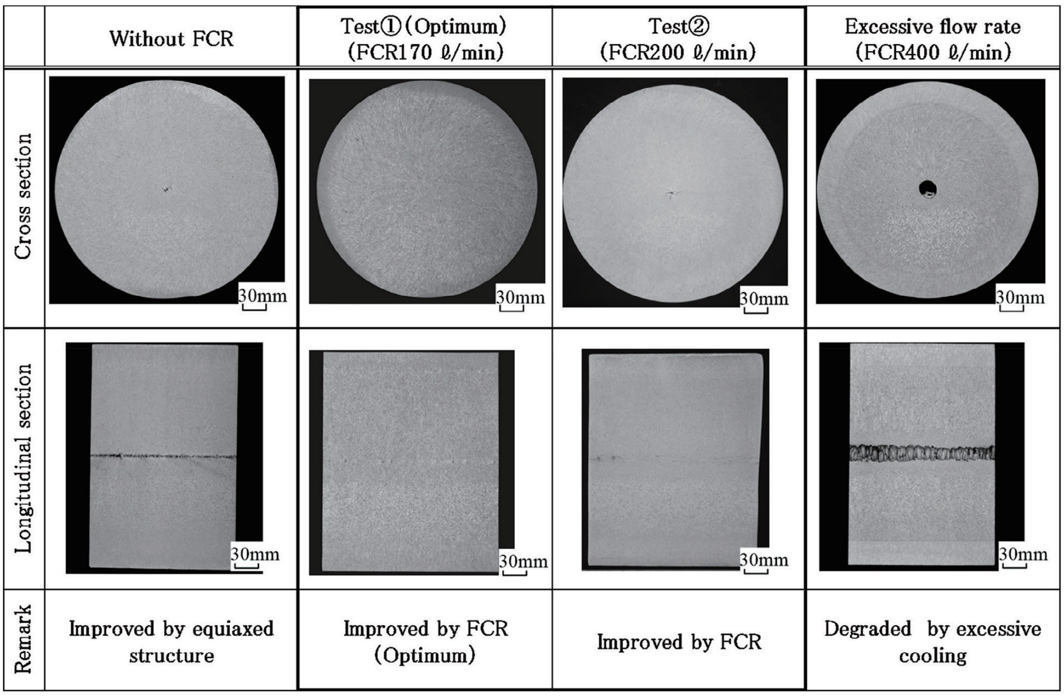
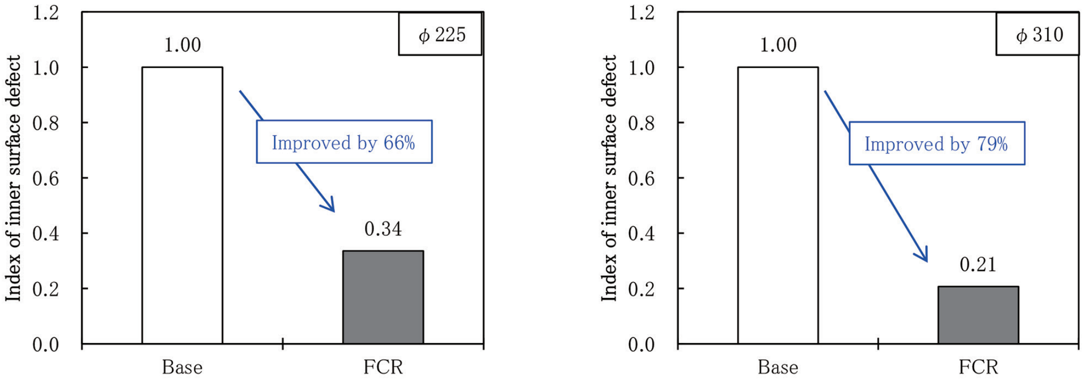


Fig. 26 Influence of FCR water flow rate on center cavity (φ 310 billet)



(a) ϕ 255 mm (b) ϕ 310 mm

Fig. 27 Influence of optimized FCR on inner surface defect of product tube

fore reaching the final solidification position, the water flow rate upper limit that is stricter than that for small size billets is applied to FCR. As a result, as the FCR-applying billet size becomes larger, the range of the optimum water flow rate becomes narrower.

- Due to the construction of the index for evaluating the FCR effect and the confirmation of the effect through the on-line experiment, application of FCR technology to large diameter billets was established.
- Due to the improvement of the center cavity of billets by FCR, the occurrence ratio of the internal defect in the pipe rolling process was significantly reduced. As a result thereof, the application of the technology to pipes for further sophisticated use has become feasible.

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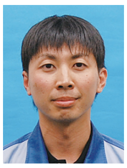
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