Effect of a Novel Hot-core Heavy Reduction Rolling Process after Complete Solidification on Deformation and Microstructure of Casting Steel

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Hot-core Heavy Reduction Rolling (HHR^2) is a novel technology designed for eliminating center defects of casting steel by using the large temperature gradient, which performed heavy reduction to bloom or slab with rolling mill after the position of solidification end of the strand. This works mainly focus on the effect of HHR^2 process on the shrinkage elimination and microstructure evolution. Firstly, bonding plate rolling experiment were carried out, which proved HHR^2 process with large temperature gradient in thickness direction could improve the internal deformation of workpiece. Meanwhile, the deformation permeability was beneficial to the microstructure refinement of center layer. Secondly, the HHR^2 process was studied by analysis of the results of FEM to explore the influence of some process parameters on shrinkage closure. In this study, the G_m index and volumetric residual percentage V/V_0 were used as evaluation index in mechanical analyses and quantitative comparison, the results reflected the void tend to closing with the reduction ratio and roll diameter increasing, as well as with the reduction position moving towards the solidification end after complete solidification. Finally, the pilot plant trail of HHR^2 was carried out before industrial application, and the results reflects the HHR^2 process can eliminate the large central shrinkage cavity and refine the center microstructure.

KEY WORDS: Hot-core Heavy Reduction Rolling; bonding plate rolling experiment; shrinkage closure; microstructure refinement.

1. Introduction

Industrial fields such as transportation, petrochemical engineering, heavy machinery manufacturing, shipbuilding and bridge construction request excellent steel raw materials without defects. To satisfy these needs, the internal crack, surface crack, center segregation and porosity of casting slabs and blooms should be eliminated. A representative technology for decreasing defects such as center segregation and porosity is soft reduction (SR) process.1–3) Soft reduction is usually applied to mushy zone, where center segregation is formed by solute-enriched residual molten steel collected in and around a shrinkage cavity, which is formed during continuous casting process. The soft reduction region is usually determined in terms of the solid fraction of the strand core (the solid fraction f_{s, start} at the start position and the solid fraction f_{s, end} at the end position). The reduction intensity of soft reduction is usually defined by reduction ratio, which is the reduction amount divided by the length of reduction segment.2) Depending on the casting format and steel grade, the suggested reduction region may be different (e.g. the solid fraction form 0.2 to 0.9 for higher carbon steel,4,5) from 0.2 to 0.7 for low carbon steel6,7) from 0.37 to 0.51 for a medium carbon steel8). According to Thome and Karste,9) the optimum reduction intensity of mechanical soft reduction should be determined to compensate shrinkage during solidification without creating internal cracks. Therefore, the soft reduction technique usually allows a small reduction amount (a total reduction amount: 4–7 mm) in order to avoid the formation of internal cracks.10) In this case, the reduction force at surface region is not easy transmitted to the thickness center region of the casting blooms or slabs, so that the porosity is not fully compressed. Especially for blooms or slabs with larger section sizes, the reduction amount of the regular soft reduction technique is not enough to conquer the dissipation of the reduction energy caused by the thicker shell deformation, and the center quality could not be efficiently improved. Furthermore, the porosity which is formed after the soft reduction zone (with a solid fraction above f_{s, end}) cannot be decreased by soft reduction technique.

According to the above-mentioned reasons, some heavy reduction (HR) technologies have been proposed to heal the solidification shrinkage cavity and improve the center density, which impose a larger reduction percentage amount at the end location of solidification stage corresponding to the solid fraction of 0.8–1.0. In the early 1990s, Kawasaki Steel
Corp. proposed and applied a technology called “Forging” in the bloom continuous casting process to control the center density, segregation, solidification shrinkage cavity. In the process, a pair of flat anvils was installed at the final stage of solidification to perform reduction. Sumitomo Metal Industries also developed a new technology called Porosity Control of Casting Slab (PCCS) to reduce the center porosity of the slab with thickness up to 300 mm in Kashima Works. In PCCS technology, center porosity can be decreased by the roll reduction on the slab just before complete solidification. Using this method, it is possible to manufacture sound heavy plates with thickness up to 150 mm through caster rolling line. POSCO had also developed a technology called the PosHARP to prevent and minimize internal defects of slab. Compared with soft reduction, the macrostructure of thick slabs was improved better with PosHARP. However, internal cracks are found to occur in the solid fraction 0.8–0.99. Kobayashi indicated that solid fractions of 0.8 and 0.99 corresponded to the zero strength temperature (ZST) and the zero ductility temperature (ZDT), respectively. Won et al. considered that the formation of cracks was closely related to the strength and ductility of steels in the mushy zone between ZST and ZDT. In this zone, the second dendrite arms link each other and have no ductility. When this brittle zone is slightly deformed perpendicular to the solid front, the linked arms will be ruptured. Then if the solute enriched molten metal cannot be sucked into the rupture, the internal cracks will occur. Yamanaka, et al. concluded that internal cracks occur providing the strain (not the total strain) applied between ZST and ZDT exceeds the critical strain, and the critical strain is constant.

Whether soft reduction or heavy reduction technology, deformation is performed to casting steel with a liquid core, and the reduction amount of those technologies will be limited by internal cracking. In current paper, a novel technology called Hot-core Heavy Reduction Rolling (HHR) has been proposed to improve the internal qualities of casting steel with a large section. In HHR process, a two-high rolling mill is installed after the solidification end of the strand. The schematic view of reduction region for SR, HR and HHR is shown in Fig. 1. As plastic elongation of the steel rises after solidification brittle zone (Brittle temperature range), the increase of strain will not affect internal cracking. Compared with heavy reduction, more large reduction amount can be used at the region that the solidification is completely finished for HHR process. In this work, laboratory rolling experiments of bonding plate with temperature gradient are designed firstly to verify the deformation penetration to the center. Then the effects of reduction location, reduction amount and roll diameter of HHR on the penetration of deformation to the center are investigated with FEM simulation method. Finally, the pilot plant experiment has been carried out before industrial application and the results with and without HHR are compared.

2. Laboratory Rolling Experimental Procedure and FEM Simulations

2.1. Bonding Plate Rolling Experiment

Ten experimental blocks with 20 mm thickness, 120 mm width, and 300 mm length are selected from the same hot rolled plate with chemical composition of 0.17%C, 1.45%Mn, 0.145%Si, 0.037%Al, 0.019%Cr, 0.015%S, 0.02%P. After surface grinding and roughening treatment, those plates were divided into two groups, and each group plates were welded together. It is shown in Fig. 2(a), the blocks are coded by a, b, c, d, and e before welding. As shown in Fig. 2(b), two workpieces with 100 mm thickness, 120 mm width, and 300 mm length denoted by A and B were prepared for rolling experiment after welding. The workpiece A was reheated to 1350°C (due to the limit of reheating furnace, more higher temperature cannot be obtained) and held on 2 hours in high-temperature box resistance furnace. After discharging from furnace, the workpiece A...
surface was cooled from 1350°C to 950±10°C by water cooling and followed by rolling. A large temperature gradient in thickness of workpiece A was obtained to simulate the casting steel after solidification. The workpiece B was reheated to 1200°C and held on 2 hours. After discharging from furnace, the workpiece B was cooled from 1200°C to 1150±10°C by air cooling and followed by rolling. The workpiece B was used to simulate the traditional rolling process compared with HHR². The surface temperature was measured with a hand-held infrared thermometer. Both A and B were rolled from 100 mm to 75.00 mm thick about with single pass. The roll diameter is 450 mm, and roll face width is 450 mm. The rolling speed was 0.25 m/s. After rolling, air cooling and cold sawing, deformation of each layer was measured with micrometer. Metallography specimens were taken from the surface, quarter thickness and center layer of workpiece A and B. Then they were ground, and polished following at conventional metallographic technique in which 4% Nital etchant was used to reveal the microstructures of ferrite and pearlite. The microstructures were observed by optical microscopy.

2.2. Thermal-mechanical FEM Model of HHR²

In current work, a 3-strand bloom continuous caster of Chinese HBIS Group SHISTEEL Company was chosen as the specific research objective as shown in Fig. 3. The hot-core heavy reduction was carried out in a boom with 300 mm × 360 mm section. A typical bearing steel GCr15 was used in this research, and the main composition is listed in Table 1. The simulation process was divided into two stages: continuous casting and HHR². The temperature field of bloom was calculated in continuous casting stage, and then the temperature field was used as initial temperature distribution of HHR². During continuous casting stage, a 3-D thermal model was developed using the commercial software ABAQUS. Tetrahedral finite elements were used to mesh the computation domain. According to the real production condition, the superheat in tundish and casting speed were kept at 36.5°C, and 0.55 m/min, respectively. The thermal parameters, including the thermal conductivity, specific heat, density, etc., were calculated by the phase fraction, which have been described in detail by Li and Thomas.¹⁸ The solid fraction and phase transformation were gotten according to the Thermocalc software. In the secondary cooling zone, the spray water density and thermal radiation were considered in calculating the equivalent con-

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Fig. 2. Assembly drawing of the experimental plate (a) The schematic of experimental plate size and code before welding, (b) The photos of two steel plates after welding. (Online version in color.)

Fig. 3. The schematic of the bloom continuous caster. (Online version in color.)

Table 1. Chemical composition of the steel grade (GCr15), wt%.

| C    | Si  | Mn  | P    | S    | Cr   | Mo  | Ti  | Ni  | Cu  | Al  | Als |
|------|-----|-----|------|------|------|-----|-----|-----|-----|-----|-----|
| 0.98 | 0.23| 0.31| 0.012| 0.005| 1.45 | 0.002| 0.005| 0.021| 0.063| 0.012| 0.011|
vection coefficients of each of the cooling zones.

The HHR\textsuperscript{2} stage was based on the temperature field of continuous casting, so the secondary cooling and heat radiation process was fully considered in calculating of the temperature evolution. And this evolution of key positions of bloom is shown in Fig. 4. Meanwhile, the thermal imager FLIR SC620 was used for measuring the surface temperature of bloom to verify the simulated results. The Fig. 5 are the infrared images collected from the on-line production, which were located at the strand position of 19.50 m and 24.80 m distance from meniscus, respectively. Obviously, the predicted and measured results are consistent at the corresponding positions, and the absolute value of the relative error less than 20°C, which was mainly caused by the water vapor and oxide scale.

During HHR\textsuperscript{2} stage, the 3-D thermal-mechanical coupled FE model was established using the commercial software DEFORM-3D. The quarter model of HHR\textsuperscript{2} was shown in Fig. 6. An elliptical void was placed in the center of bloom that the length of axes were 3 mm, 3 mm and 6 mm, respectively. In the FE model of HHR\textsuperscript{2}, the roller was defined as a rigid body and the bloom was considered as viscoplastic material. Tetrahedral mesh were used, and it performed local mesh refinement to the elliptical void. The number of elements is 18356.

Based on the results of continuous casting, the initial temperature field was written in the file by defining the node data. The heat conduction, thermal radiation of bloom and the heat transfer between the roll and bloom were considered in the deformation process. The temperature dependent Poisson’s ratio was calculated by using the Thermocalc software. The Young modulus and Yield stress of GCr15 steel had been obtained by Gleeble-3800, and the
temperature range and strain rate range of hot compression test were 800–1 250°C and 0.01–1 s⁻¹ respectively. The Hansel-Spittel model was chosen for describe the relationship between strain and stress, and the material coefficients were identified through non-linear regression, shown as Eq. (1). The contrast between experimental curves and the model data were presented in Fig. 7, and the correlation coefficients R of the model was 0.990. The friction between the work roller and the workpiece adopted the shear friction model, and friction coefficient decreased with the temperature increased in the hot rolling, which was expressed as Eq. (2).

\[
\sigma = 6.97 \times 10^6 e^{-0.000037T} e^{0.59 \varepsilon -0.22} e^{(1+\varepsilon)^{0.0027T}} \quad \ldots (1)
\]

where \(\sigma\) is flow stress, MPa; \(\varepsilon\) is strain; \(\dot{\varepsilon}\) is strain rate, s⁻¹ and \(T\) is temperature, °C.

\[
\begin{align*}
\tau_f &= mk \\
m &= 1.06 - 0.0006T \\
\end{align*}
\]

(2)

Where \(\tau_f\) is the friction stress, MPa; \(m\) is the friction factor; \(k\) is the shear yield stress, MPa and \(T\) is temperature, °C.

3. Results and Discussions

3.1. Bonding Plate Rolling Experiment Results Analysis

The each layer thickness and reduction ratio of workpiece A and B after rolling is presented in Table 2. The thickness of layer a and e were averaged and used to calculated surface layer strain. The thickness of layer b and d were averaged and used to calculated quarter thickness layer strain. The strain distributions for workpiece A and B are shown in Fig. 8. Compared with workpiece B, the surface layer strain of workpiece A decreased about 17.4%, and the quarter thickness and center layer strain increased about 16.3% and 18.3% respectively. Therefore, more deformation of HHR² process can penetrate to the center than traditional rolling.

Microstructures of surface, quarter thickness, and center layer of workpiece A and B are shown in Fig. 9. The microstructure of workpiece A and B consisted of polygonal ferrite and pearlite. The grain size of polygonal ferrite in workpiece B increases from 11 μm in surface layer to 20 μm in center layer, while for workpiece A, the polygonal ferrite grain size of workpiece A is about 17 μm along thickness.

| Plates code | a | b | c | d | e |
|-------------|---|---|---|---|---|
| Workpiece A | Thickness after rolling/mm | 14.46 | 14.85 | 15.63 | 15.24 | 14.85 |
| | Reduction ratio/% | 27.7 | 25.8 | 21.9 | 23.8 | 25.8 |
| Workpiece B | Thickness after rolling/mm | 13.92 | 15.85 | 16.24 | 15.46 | 13.53 |
| | Reduction ratio/% | 30.4 | 20.7 | 18.8 | 22.7 | 32.3 |

Fig. 8. Strain distributions for workpiece A and B.

Fig. 9. The different layers microstructure of workpiece A (a–c) and workpiece B (d–f). (a), (d) surface layer; (b), (e) quarter thickness layer; (c), (f) center layer.
The temperature distribution along thickness of workpieces were calculated with finite-difference temperature model. The surface measured temperature was used to verify the model’s feasibility. The temperature distribution along thickness of workpiece A and B are presented in Fig. 10. The temperature difference between center and surface of workpiece A is about 360°C before rolling, while that of workpiece B is only about 50°C. The temperature difference between center and surface of workpiece A is obviously large than that of workpiece B. As a result, the center layer of the workpiece A has more lower deformation resistance compared to the surface, the plastic deformation is more easily penetrated into the center, leading to dynamic recrystallization will more easily occurred at center layer, corresponding to the center layer austenite grains are significantly refined. Furthermore, according to the classical transformation theories for steels, fine austenite grains would like to lead to fine grain size and better toughness after deformation, so the microstructures of workpiece A is more uniform than workpiece B at room temperature. The results above indicate that HHR process contributes to deformation penetrating to center layer and improving microstructure uniformity cross thickness.

3.2. Effect of Reduction Ratio on the Deformation

Reduction ratio is one of the critical factors in controlling the quality and deformation of production during hot rolling process. In order to study the influence of this parameter, it was assumed that the heavy reduction rolling mill was installed at the position of the last tension leveler stretcher. The reduction percentage were set as 10%, 15% and 20%, based on the same temperature field of blooms.

The effective strain distribution along thickness direction from upper surface to core of bloom are shown in Fig. 11. In general, the value of effective strain are small at the surface and core position of blooms, but it obtain the maximum values at the position that are 28.3 mm, 33.4 mm and 37.8 mm distance from the surface of blooms corresponding to the reduction ratio of 10%, 15% and 20%. This means the permeability of deformation increases with the increasing of reduction rate. In addition, when the reduction rate increase, the level of strain arise integrally, which is helpful in promoting void closure. The value of effective strain at the core position of blooms are 0.128, 0.195 and 0.267 with the reduction ratio of 10%, 15% and 20%, respectively.

After HHR process, the residual volume of void decrease from 21.76 mm³ to 10.24 mm³ with the increasing of reduction percentage from 10% to 20%. The shape of void tend to fusiform from roundness presented in the cross section of blooms. The Fig. 12 reflects that the distribution of strain at the local position of voids is inconsistent after deformation, strain concentration performs at the tip of fusiform length axis, but the value of effective strain is small at the short axis of fusiform. The ratio of lengths of short axis and long axis are 0.71, 0.58 and 0.41 respectively, when the corresponding reduction ratio are 10%, 15% and 20%. It means the void profile in cross-section from round turns to fusiform, and finally closing at the short axis direction, if the compressive deformation is only performed at the thickness direction.

3.3. Effect of Reduction Location on the Deformation

During HHR process, the heavy reduction mill will be set on the continuous casting production line, so the temperature fields are the essential differences among the distinct reduction locations. In this paper, three typical positions are selected for installing heavy reduction hot rolling mills. They are the positions of last tension leveler stretcher, between the last tension leveler stretcher and flame cutting and of the exit of flame cutting machine, which were labelled as A, B and C respectively.

The Figs. 13(a)–13(c) shows the distribution of temperature before HHR process corresponding to the positions of A, B and C, and Figs. 13(d)–13(f) reflect the distribution of effective strain at this three positions after rolling. They reveals the difference intuitively, when the reduction location is near the final solidification position the bloom has higher temperature level and greater temperature difference between the core and surface. After HHR process, the greatest permeability of deformation are obtained with instilling the mill at position A. In addition, the maximum value of effective strain distribute at the positions of one sixth of thickness near the surface in the cross section of
At position A, it has a smaller difference of effective strain in bloom, which may be good for obtaining the uniform microstructure.

The initial temperature distribution of HHR\textsuperscript{2} in thickness and width directions can be reflected quantitatively in Figs. 14(a) and 14(b) respectively. From position A to C, the temperature difference between the core and surface of bloom in thickness directions decrease from 336.2°C to 167.6°C, and it fall from 369.4°C to 187.5°C in width direction. In addition, when the position is near the solidification end point, higher level of temperature gradient can be obtained in both directions of thickness and width.

During HHR\textsuperscript{2} process, the evolution of effective strains at the core of bloom are shown in Fig. 15. The value of effective strains are 0.278, 0.264 and 0.252 respectively at A, B and C positions. Obviously, it can accumulate greater effective strain at the core of blooms when the hot rolling position is closer to the end of solidification. This phenomenon can be explained that when a remarkable temperature gradient is obtained in thickness direction of position A, it also performs a gradient of deformation resistance along this direction. During the hot rolling process, the distribution of gradient of deformation resistance makes the interior deformation is much easier preformed relative to that of surface parts.

The behavior of void closure can be analyzed by void closure evaluation index $G_m$, which is the integral of the stress triaxiality ratio over the effective strain, proposed by Tanaka et al.\textsuperscript{21} According to the results, voids tend to closing with the value of $G_m$ increasing. As shown in Fig. 16,
the value of $G_m$ at positions of A, B and C are 0.15, 0.12 and 0.11 respectively, which means a better effect on void closure can be achieved with the hot rolling deformation preformed near the solidification end.

$$G_m = \int_0^\infty \eta \sigma_{eq} = \sum \left( -\sigma_m / \sigma_{eq} \right) \Delta \sigma_{eq} \quad ....... (2)$$

Where $\eta$ is stress triaxiality ratio ($\eta=\sigma_{eq}/\sigma_{eq}$), $\sigma_m$ is mean stress, MPa, $\sigma_{eq}$ is effective stress, MPa, $\sigma_{eq}$ is effective strain, $\varepsilon_f$ is Critical effective strain, $t$ is the number of analysis step.

Based on the expression of $G_m$, void closure is related with the strain state and stress triaxiality simultaneously at the core of blooms. During HHR$^2$ process, the stress triaxiality is negative, and the evolution of opposite of stress triaxiality at the core position of blooms are also revealed in Fig. 15. A higher level of opposite of stress triaxiality is obtained at position A, for influence of the greater lateral temperature difference. The greater gradient of deformation resistance along lateral direction can limit the deformation of lateral spread and provide a greater hydrostatic stress to the core metal. So, when heavy reduction hot rolling is performed near the solidification end, advantageous strain state and stress state are obtained simultaneously.

The volumetric residual percentage $\frac{V}{V_0}$ are also used, where $V$ is the residual volume after rolling and $V_0$ is the initial void volume, which reflects the change of void volume quantitatively during HHR$^2$ process. The Fig. 16 reveals the evolution of voids, and the value of $\frac{V}{V_0}$ at A, B and C are 0.37, 0.42 and 0.48 after HHR$^2$ process, which proved the conclusion above.

3.4. Effect of Roll Diameter on the Deformation

In order to explore the influence of roll diameter, the thermo-mechanical rolling model with different roll diameters ranged from 600 mm to 1 000 mm were established. The two-high hot rolling mill was installed replacing the position of last tension leveler stretcher, and the reduction percentage was 20% to the blooms. The two-high hot rolling mill was installed replacing the position of last tension leveler stretcher, and the reduction percentage was 20% to the blooms. The Fig. 17 shows that the void tend to closure with increasing of the diameter of roll, which the value of $\frac{V}{V_0}$ are 0.43, 0.37 and 0.32 respectively corresponding to the effect of rolls whose diameters are 600 mm, 800 mm and 1 000 mm. By calculation, the evolution of effective strain and opposite of stress triaxiality are reflected in Fig. 18. Different from the effect of reduction location, although the value of effective strains are so close that the difference are in parts per thousand, but the difference of stress triaxialities are significantly for different roll diameter. The level of opposite of stress triaxiality is higher for the roll with larger diameter.

Stress triaxiality is a common mechanical parameter defined as the rate of mean stress and effective stress. The
similar effective stress can be gotten for the core position of blooms, for which have the same strain state and temperature level. The Fig. 19 shows the comparison results of mean stress in the deformation zone. It can be seen that a higher absolute value of mean stress is obtained by using the roll with larger diameter. In another words, the level of hydrostatic stress is the most significant factor in affecting to void closure, when roll diameter changes.

4. Pilot Plant Trial of HHR$^2$

The pilot plant trial of HHR$^2$ was carried out in a vertical-type billet continuous caster with 135×135 mm cross section before industrial application. The chemical composition of billet was 0.35% C, 0.55% Mn, 0.028% Si, 0.019% Al, 0.83% Cr, 0.015% S and 0.02% P. The pilot plant trail procedure was presented in Fig. 20. After casting, a work piece with 1000 mm length was cut immediately by a gas caster from the hot billet, then the work piece was transported to the rolling mill with forklift. Hot-core heavy reduction rolling consisted of one pass with a reduction ratio of 22.2%, surface temperature of 950°C and rolling speed of 0.5 m/s. The work piece was air cooled to room temperature after rolling. For comparison purposes, the normal hot rolling experiment is also carried out to verify the effect of HHR$^2$ process. The billet was also used as workpiece, after the soaking pit process at 1200°C and descaling, the workpiece was rolled immediately with same reduction ratio and rolling speed. In order to illustrate the results of different procedure, hydrochloric acid solution was used for Macrostructure corrosion procedure, and Nitric alcohol on 4% concentration was used for Microstructure corrosion respectively.

The macrostructure were investigated and compared among the billet without HHR$^2$ process, the workpieces with HHR$^2$ process and with normal rolling process. As shown in Fig. 21, the continuous casting billet (without HHR$^2$ process) and the workpiece after normal hot rolling has obviously central shrinkage cavities. At the core of continuous casting billet, the maximum diameter of the center shrinkage cavities are around 4 mm, and a lot of small center porosities are around cavities, the region of shrinkage cavity in center of the billet is larger than 11.5 mm. While, the maximum diameter of shrinkage cavities are 1.8 mm at the core of normal hot rolled workpiece, and the region of remaining

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**Fig. 17.** Geometric outline of void in cross section after HHR$^2$ process performing with work roll of different diameters.

**Fig. 18.** Effective strain and stress triaxiality evolution at the core of bloom during HHR$^2$ process performing with work roll of different diameters.

**Fig. 19.** Mean stress distribution at deformation zone of HHR$^2$ process with work roll of different diameters. (a) roll diameter = 600 mm, (b) roll diameter = 1000 mm.
shrinkage cavities is about 5.5 mm. Compared with continuous casting billet and the normal hot rolled workpiece, the workpiece with HHR\textsuperscript{2} process can obtained the best effect on closing of shrinkage cavities, and all the large central shrinkage cavities has disappeared.

The Fig. 22 showed microstructure of different positions of continuous casting billet (without HHR\textsuperscript{2}) and hot-core heavy reduction rolled billet (with HHR\textsuperscript{2}) respectively. The microstructure of both continuous casting billet and HHR\textsuperscript{2} billet consisted of ferrite net and pearlite. However, the size of ferrite net in continuous casting billet and HHR\textsuperscript{2} billet are different. In continuous casting billet, the size of ferrite net increased slightly from surface to center position, which is calculated to be 642 μm, 778 μm and 800 μm, respectively. In HHR\textsuperscript{2} billet, the size of ferrite nets was calculated to be 296 μm, 203 μm and 201 μm from surface to center,
which was significantly decreased and more homogeneous compared that of continuous casting billet. During HHR$^2$ process, the HHR$^2$ billet has large temperature gradient in thickness direction, resulted in deformation easily penetrated to the center position. Dynamic recrystallization occurs and center microstructure can be sufficiently refined. As a result, large central shrinkage cavity can also be eliminated and the homogeneous microstructure can be achieved along the thickness of HHR$^2$ billet.

5. Conclusions

(1) Two groups of bonding plate rolling experiment were carry out to simulate the hot-core heavy reduction rolling process and the traditional hot rolling process. The stacked experimental plates were welded for the workpieces, and the results of reduction ratio of each plate revealed the HHR$^2$ process with greater temperature gradient in thickness direction could improve the internal deformation of bloom. In addition, the deformation permeability was beneficial to the microstructure refinement obviously.

(2) According to the continuous casting temperature evolution of bloom, the HHR$^2$ process was studied using FEM, which reflected the shrinkage tend to close with the reduction percentage and diameter of roll increasing, as well as with the reduction position moving towards the solidification end. The behavior of shrinkage closure is related to the effective strain and level of stress traxiality. Remarkably, a high level of hydrostatic stress can promote void closure, which is the main reason analyzing the effect of diameter of roll.

(3) Based on the HHR$^2$ experiment on industrial application, longitudinal corrosion photographs and microstructures of the blooms with conventional production and that after HHR$^2$ process were contrasted. The results reflects the HHR$^2$ process can eliminate the large central shrinkage cavity and refine the microstructure of internal bloom.

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