A study on quantitative evaluation of soft reduction amount for CC bloom by thermo-mechanical FEM model

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Abstract – Soft reduction has been proved to be the most promising way to minimize center segregation together with the strand center porosity elimination. The negative pressure driven residual melt flow could be balanced by a reasonable reduction amount to compensate the volume shrinkage in the crater mushy zone. The optimum soft reduction amount to bloom casting for given heavy railway steel has been studied in the paper from the point of view of the volume shrinkage compensation. A solidification analysis model was developed to determine the reduction amount based on the local shrinkage in the final solidification stage. The volume shrinkage in the center inter-dendritic region has been quantitatively calculated through the evaluation to the changing melt density. Another thermo-mechanical coupled FEM model was developed to investigate the bloom deformation behavior upon soft reduction operation. The squeezing effect of the soft reduction on the center mushy zone at various solid fractions was revealed quantitatively as well. The results shown that the theoretical soft reduction amount should decrease from 12.2 mm to 4.0 mm corresponding to the solid fraction from 0.3 to 0.9. A new definition for the calculation of the internal soft reduction efficiency was proposed and compared with the conventional one. The nomogram for the determination of optimum soft reduction has been presented for the bloom casting at various center solid fraction. Accordingly, an optimized soft reduction practice was determined for quality high speed railway steel production with clearly improved strand soundness.

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The centerline segregation and shrinkage porosity in bloom castings are proved to be very detrimental to the following hot rolling production and the final railway product service properties. For the high carbon heavy railway steels, like U71Mn or U75V, the bloom casters should be well equipped with auxiliary devices such as M-EMS and/or dynamic soft reduction for the internal quality control. The method of soft reduction operation has been proved to be the most promising way to minimize center segregation and to eliminate the strand center porosity [1,2]. Upon the implementation of soft reduction, the negative pressure driven residual melt flow could be balanced by a reasonable reduction amount to compensate the center solidification shrinkage

in the crater mushy zone. In addition, it has been proved that any possible reduction induced internal cracks or shell bulging can be avoided together with improved strand soundness under the soft reduction operation with reasonable process parameters.

For the determination of optimum soft reduction parameters, lots of industry experiments and laboratory research have been carried out for given steel grades and casting formats. For example, the center solid fraction region of 0.2–0.9 [3] for high carbon steel grades, 0.4–0.8 [3] for spring steel grade, 0.3–0.78 [4], 0.6–0.85 [5], 0.4–0.9 [6] for heavy rail steel, have been concluded by industry experiments for the location of strand reduction operation. And the soft reduction amount of 7–10 mm [3], 5 mm [7],

2–7.5 mm [6] have also been reported for different steel grades under regular bloom casting processes. However, quantitative evaluation to the optimum soft reduction implementation still remains to be a challenge for the maximum improvement to the strand internal soundness.

The local interdendritic condensed liquid steel flow induced by the volume shrinkage in the crater mushy zone of strands has been considered as the main contribution to the formation of the final centerline macrosegregation. Otherwise, the center porosity defect will be produced if there is a limited melt flow to feed the shrinkage. On the other side, if the compensation could be rightly supplied by the reduction operation to the crater end, there will be no shrinkage induced melt flow except the unavoidable double diffusion convection. Accordingly, both the porosity and centerline segregation can be alleviated to minimizing level. For this reason, the quantitative analysis to the optimum soft reduction amount and its internal reduction efficiency is vital to address the internal quality issue especially for the high carbon grade of railway steel. As an important parameter to reflect the extent of reduction amount reaching the solidifying core of the casting strands, the so called internal reduction efficiency is defined as the ratio between the local thickness changing of mushy zone and overall strand as given in Equation (1):

$$\eta = \frac{\Delta i}{\Delta s} \quad (1)$$

Where, Δs is the thickness reduction amount of total strand and Δi is the counterpart produced in the internal mushy zone. Due to the non-uniform temperature distribution in the bloom castings cross-section, roughly 500–600 °C difference between the shell and the pasty zone, the soft reduction induced deformation at the bloom section will also be inhomogeneous as a result of the much different thermal deformation resistance. Because of the inhomogeneous deformation behavior existing in bloom cross-section, only a discounted thickness reduction could be transferred to the center region. Ito et al. [8] have given a regression equation from a geometrical point of view to evaluate the effects of the cast shape and liquid core thickness on

internal reduction efficiency η_{REG} , as shown in Equation (2):

$$\eta_{REG} = \exp(2.36\lambda + 3.73) \times \left(\frac{R}{420}\right)^{0.587} \quad (2)$$

In which, λ is the shape index and R is the diameter of rolls, and η_{REG} is the internal reduction efficiency. Additionally, the calculation was based on the measurement to a cast strand block under given liquid core with thickness of 2–63 mm. Therefore, the Ito's reduction efficiency is not identical to the physical process and solidification status of the continuous casting situation. As we mentioned above, the center solid fraction commonly should range from 0.3 to 0.8 for the adoption of soft reduction, which means the center part of the casting strand is in a mushy state closely dependent on the steel chemical. Therefore, the internal reduction efficiency should be re-defined for the situation of continuous casting with the consideration of various casting format and chemistry related solidification situation. Together with the consideration of the precise calculation to the optimum soft reduction amount, a rate related constitutive relation has been adopted for the combined analysis to the solidification and the thermo-mechanical deformation in the paper. A 2D coupled FEM model has been established to determine optimum soft reduction parameters through the temperature dependent steel thermal physical properties, especially for the changing density upon solidification. The reduction efficiency for continuously casting blooms is given at the same time, which is beneficial to the final determination of soft reduction operation to the railway steel bloom castings.

1 Computation method description

1.1 Computation procedures for optimum soft reduction amount

The implementation of the numerical method for determining the optimum soft reduction has been carried out based on the flowchart as shown in Figure 1, and its detailed procedure is as follows:

- Step1: Developing a solidification analysis model to reveal thermal history

Fig. 1. Flow chart of the numerical method for optimum soft reduction amount determination.

together with the volume shrinkage in interdendritic crater end region during the strand solidification process. In the solidification analysis model, the casting format and temperature dependent steel thermal physical properties for the given steel grade are included. Through the solidification analysis model, 2D temperature field in the bloom cross-section at any focused position in the bloom caster could be exported by a developed subroutine.

- Step2: Developing a thermo-mechanical coupled FEM model to study the effect of soft reduction operation on the local compensation of volume shrinkage in the center mushy zone, in which the predetermined soft reduction amount ranges from 0 mm to 12 mm. The temperature distribution at the cross-section with its center solid fraction of 0.3, 0.41, 0.50, 0.61, 0.71, 0.80, 0.90, respectively were saved

from the thermal analysis model as the initial temperature condition.

- Step3: Comparing the volume shrinkage in the inter-dendritic areas for specific initial temperature condition and area reduction amount of the center mushy zone induced by the soft reduction operation, the reasonable total soft reduction amount for the given soft reduction applying position could be revealed.

1.2 Internal reduction efficiency

The deformation behavior of bloom casting under the operation of MSR (mechanical soft reduction, which is virtually applied through the roll gap reduction of the local pinch rollers), is illustrated in Figure 2. The narrow side shell will bulge outward with the decrease of the overall bloom thickness.

As shown in Figure 2, the upper and lower parts of solidification front are under

Fig. 2. Typical deformation behavior of bloom casting under mechanical soft reduction.

compression status due to the load application from MSR, and the right and left parts of solidification front are moving toward outside as well along with the bulging side shell. It should be emphasized that the different deformation trends around the solidification front upon MSR will not only induce the presence of its complicated stress/strain status but also influence the compensation to the volume change in core area due to solidification. For the sufficient compensation to the volume shrinkage in center mushy zone through the operation of MSR, the discounted soft core reduction will be calculated by the aid of a developed subroutine

Obviously, the expression contributed by Y. Ito through the calculation of thickness reduction ratio can not reflect the extent of compensation by the operation of soft reduction to the volume shrinkage in the bloom center mushy zone. A new definition for the calculation of the internal soft reduction efficiency has been proposed here based on the forced area reduction ratio as given by Equation (3):

$$\eta_{REG} = \frac{A'_m}{A_m} = \frac{\sum_{j=1}^n \Delta A_j}{A_m}. \quad (3)$$

In which, ΔA_j denotes the area variation of element j in the mushy zone, η denotes the number of element in mushy zone, A_m denotes the total area of the mushy zone before the operation of soft reduction, A'_m denotes

the total area of mushy zone after the operation of soft reduction.

2 Solidification analysis

2.1 Model description

In the thermal analysis, only the surface cooling and heat transfer are included in the 2D model to determine the local temperature distribution and shell thickness of the casting bloom at soft reduction region. The temperature field calculated is saved for the following thermo-mechanically coupled FEM analysis at the location or time step while the bloom section with different solid fraction at the mushy zone center. The heat transfer equation for the strand from mold meniscus to the following secondary cooling and air cooling zones is described by:

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + \rho L \frac{\partial f_s}{\partial t} \quad (4)$$

where, f_s denotes the temperature dependent solid fraction of steel. ρ , C , λ , L denote the density, the specific heat, the conductivity, the solidification latent of given steel grade, respectively. The parameters of casting condition and steel grade included in the solidification analysis model are given in Table 1.

The boundary conditions in the mold, the following secondary cooling and air cooling zones were adopted as heat flux boundary condition, heat film boundary condition and radiation boundary condition, respectively. For the given steel grade, the thermal physical properties change with temperatures. The initial casting temperature was preset to 1490 °C with superheat around 25 °C. The temperature histories of several typical nodes from surface to the center in bloom cross-section are revealed as shown in Figure 3.

2.2 Volume shrinkage upon solidification

The center volume shrinkage is calculated based on the melt density change upon solidification in the mushy zone. With different

Table 1. Parameters in the solidification analysis model.

Parameters of the steel grade		Parameters of the bloom caster	
Carbon content, %	0.71	Cross-section size, m ²	0.28 × 0.38
Solidus temperature, °C	1320	Basic radius, m	12
Liquidus temperature, °C	1465	Casting speed, m/s	0.01217

starting points of the soft reduction operation, the amount of the volume shrinkage in the following mushy zone is different accordingly which should be compensated. If a right exact reduction amount is given, the operation can be expected to compensate the volume shrinkage during the final stage of solidification, which will make the possible shrinkage porosity and melt flow induced centerline segregation to minimum.

According to the reports from previous researchers, the maximum solid fraction for the mass feeding (solid moving together with liquid) in the mushy zone is roughly to be 0.29–0.35 [9] for high carbon steel and stainless steel. Accordingly, we can assume that the volume shrinkage in the interdendritic areas could be compensated by the liquid steel from the upper stream with solid fraction smaller than around 0.3. The upper stream volume shrinkage does not need to be additionally compensated by any squeezing action through soft reduction.

The volume shrinkage in the following pasty zone can be determined by the density change of given steel grade in high temperatures around solidification. The relationship of the densities for different phases to their temperature is determined as follows [10], as given in Figure 4:

$$\begin{aligned}\rho_{\gamma-\text{Fe}(T, \%C)} &= (8099.79 - 0.506T) \\ &\quad \times (1 - k_{\gamma} \times \%C) \\ \rho_{\text{liquid}-\text{Fe}(T, \%C)} &= (8319.49 - 0.835T) \\ &\quad \times (1 - k_{\text{liquid}} \times \%C) \quad (5)\end{aligned}$$

where, $\rho_{\gamma-\text{Fe}}$ (kg/m³) and $\rho_{\text{liquid}-\text{Fe}}$ (kg/m³) are the densities of austenite phase and liquid steel, respectively; %C is carbon content; T is temperature, °C.

The method to calculate the volume shrinkage in the center mushy zone is given in Equation (6), which has been included in

Fig. 3. Temperature histories of several typical positions in the bloom cross-section. **Fig. 4. Density of the given steel grade as a function of temperature.**

the solidification analysis FEM model.

$$\begin{aligned}V_s &= \sum_{i=1}^n \left(A_i \frac{\Delta \rho_i \times L}{\rho_i \times L} \cdot (f_{si}) \right) \\ &= A_i \cdot \sum_{i=1}^n \left(\frac{\Delta \rho_i}{\rho_i} \cdot (f_{si}) \right) \quad (6)\end{aligned}$$

In which, V_s is the volume shrinkage in the interdendritic areas in the center mushy zone. A_i is the local area of element i in the

Fig. 5. Center solid fraction as a function of temperature.

mushy zone, which is constant in the solidification analysis model using uniform mesh size. A_m is the total area of mushy zone before the operation of soft reduction. $\Delta\rho_i$ is the melt density changing of steel in element i during the solidification process as given in Figure 4. ρ_i is the local density of steel in element i after solidification. f_{si} is the local solid fraction in element i .

2.3 Solid fraction

As the local center solid fraction f_s is of great importance to influence the internal soundness improvement effectiveness by the operation of soft reduction, it is necessary to predict the local center solid fraction under the given temperature field accurately. If the effect of the solidification micro-segregation is considered, the local liquidus and solidus temperatures could be determined more accurately than that given by conventional empirical equation as a function of steel initial composition [11]. For this consideration, the following cosine equation [12] has been introduced into the FEM model to calculate solid fractions for easier implementation into FEM code without losing accuracy.

$$f_s = \frac{T_L - T + \frac{2}{\pi}(T_S - T_L) \left\{ 1 - \cos \left[\frac{\pi}{2} \times \frac{T - T_S}{T_S - T_L} \right] \right\}}{(T_L - T_S) \left[1 - \frac{2}{\pi} \right]} \quad (7)$$

in which, T_L indicates the liquidus temperature, T_S indicates the solidus temperature.

The compared results of solid fraction as a function of temperature obtained from both the cosine equation and the micro-segregation model were given in Figure 5.

3 Thermo-mechanical coupled model

3.1 Initial condition and boundaries conditions

As the critical criterion of the optimum soft reduction amount is that the area reduction amount induced by soft reduction operation only compensate the volume shrinkage in the final solidification stage but not to force interdendritic residual melt flow to upstream or downstream. Thus, 2D model is reasonable enough to determine the volume shrinkage and soft reduction induced area reduction in mushy zone. Taking half of the bloom cross-section as computational domain, a fixed displacement boundary condition along x direction is applied in the symmetry line of the bloom because of geometry and deformation symmetrical characteristic. Considering the line contact between bloom and local pinch rollers, the loose side roller and the fixed side roller was simplified as two rigid lines in the 2-D

coupled FEM model. A fixed displacement boundary condition along y direction is applied to the fixed side roller. The implementation of soft reduction is considered as a displacement boundary condition applied on the loose side roller as the same situation of soft reduction operation pattern. The details of the thermal boundary conditions and mechanical boundary conditions are given in Figure 6. The typical initial temperature condition at the location of soft reduction is illustrated in the right side of Figure 6.

3.2 Materials properties

An important step for the accurate mathematical analysis of the mechanical phenomenon during casting process is to find and evaluate materials constitutive equations. The proper constitutive equations should reasonably describe the complex relationship between stress, strain, and time at elevated temperatures. These equations should be able to characterize mechanical behavior of the strand under the condition encountered during the soft reduction operation process. Choices in previous works include time-independent elasto-plastic relationships, elasto-plastic models with creep, unified models with evolving internal state variables, and elasto-viscoplastic models. Each of these models has both merits and problems in accuracy and numerical stability.

It has been demonstrated that the steel shows an obvious visco-plastic behavior at an elevated temperature including both strain-rate independent plasticity and time dependant creep. A creep law is applied in our work for the casting material. The creep equation for the thermo-mechanical analysis is adopted as follows [13]:

$$\dot{\varepsilon} = C \exp\left(-\frac{Q}{T}\right) \sigma^n t^m \quad (8)$$

$$C = 0.3091 + 0.2090 (\%C) + 0.1773 (\%C)^2 \quad (9)$$

$$Q = 17160 \quad (10)$$

$$n = 6.365 - 4.521 \times 10^{-3}T + 1.439 \times 10^{-6}T^2 \quad (11)$$

$$m = -1.362 + 5.761 \times 10^{-4}T + 1.982 \times 10^{-8}T^2 \quad (12)$$

Fig. 6. Mesh details, boundaries conditions and the initial condition in the coupled FEM model.

where, σ (MPa) and ε (s^{-1}) denote the equivalent stress and the creep strain rate, respectively. C , n , m denote the carbon content-dependent function, temperature-dependent time exponent, temperature-dependent net stress exponent, respectively. $\%C$ and T denote the carbon content and temperature, respectively. Q denotes the activation energy constant (Kelvin).

As shown in Figure 7, the accuracy of the constitutive equation applied here can be validated by the predicted relationship between strain and stress under different temperatures and constant strain rates compared with that measured by Wray. In another aspect, the accuracy of the constitutive equation under constant load can also be validated by the predicted relationship between strain and time as compared with the measured data contributed by Suzuki [14], given in Figure 8.

For the high carbon railway steel grade, the relationship between strain and stress under the typical strain rates were predicted using the creep constitutive equation as shown in Figures 9 and 10.

The Poisson's ratio and Young's modulus vary with temperature for the thermo-mechanical analysis, as shown in Figure 11.

4 Results and discussions

To determine the optimum soft reduction amount and internal reduction efficiency under the operation of soft reduction, seven typical calculation cases are established with different initial temperature conditions through the developed coupled FEM model, in which the center solid fraction

Fig. 7. Calculated tensile test curve vs. temperature at constant strain rate compared with Wray data [4].

Fig. 8. Calculated creep curve vs. time under constant load compared with Suzuki data [15].

Fig. 9. Stress vs. strain at various temperatures and constant strain rate of $6.0 \times 10^{-4} \text{ s}^{-1}$ for the steel.

Fig. 10. Stress vs. strain at various temperatures and constant strain rate of $2.4 \times 10^{-3} \text{ s}^{-1}$ for the steel.

Fig. 11. Young's modulus and Poisson's ratio as a function of temperature.

are 0.31, 0.41, 0.50, 0.61, 0.71, 0.80 and 0.90, respectively.

4.1 Volume shrinkage in the mushy zone

As shown in Figure 12, the center solid fraction (f_s) is given as a function of temperature in the cross-section center, represented by the blue dot line. The relationship between the volume shrinkage in the center mushy zone and the local temperature is also given in the Figure 12. In this figure, the black solid line indicates the volume shrinkage while the center solid fraction is larger than 0.3

and the red dash line indicates the case when the solid fraction is smaller than 0.3. Clearly, the volume shrinkage that should be compensated increases with the decreasing center solid fraction, which means larger soft reduction amount should be applied with higher temperature in the mushy zone if the local volume shrinkage could not compensated by upstream melt steel.

4.2 Internal reduction efficiency

The relationship between internal reduction efficiency produced by Ito' expression and soft reduction amount is calculated as shown

Fig. 12. Volume shrinkage amount and solid fraction in the mushy zone as a function of temperature.

Fig. 13. Internal reduction efficiency defined by Ito vs. the soft reduction amount at different center solid fraction.

in Figure 13. For a given local center solid fraction, the internal thickness reduction efficiency drops with the increasing soft reduction amount at the very beginning, to around 2 mm in total. Over the range from 2.0 mm to 12 mm of the increased soft reduction amount, the internal reduction efficiency basically keeps to be a constant at the given center solid fraction. From the results given above, we know that the internal reduction efficiency decreases from around 60% to 22.5% while the center solid fraction increases from 0.3 to 0.9, which corresponds to the increased thickness and deformation resistance of the shell.

Figure 14 shows the variation trend of internal reduction efficiency given through the authors' formula against the soft reduction amount. It can be seen that the new defined internal reduction efficiencies, or forced mushy zone area reduction ratio, at different center solid fraction are proportional to the soft reduction amount applied to the bloom surface. Obviously, the mushy zone area keeps to contract along with the increasing soft reduction amount. Under the same soft reduction amount, the internal reduction efficiency is inversely proportional to the center solid fraction. As the center solid fraction increases from 0.3 to 0.9, the

Fig. 14. New defined internal reduction efficiency vs. soft reduction amount at different center solid fraction.

Fig. 15. Nomogram for the determination of optimum soft reduction amount at various center solid fraction.

maximum internal reduction efficiency of the forced mushy zone area reduction ratio drops from 5.5 to 3.5×10^{-3} at the given top reduction amount.

As shown in Figures 13 and 14, the variation trends of internal soft reduction efficiency given by Ito' formula and that by the authors are different due to the different definition expression. Though both the efficiencies show identical increase inversely with the center solid fraction, only the authors' new defined formula can reflect the persistent squeezing effect of the solidified

shell on the mushy zone upon the increasing soft reduction amount. Factually, from Equation (3), we know that the internal soft reduction efficiency is directly related to the mushy zone area reduction.

4.3 Optimum soft reduction amount

Figure 15 shows the area reduction amount of the center mushy zone as a function of center solid fraction caused by the operation of soft reduction. For a given initial center solid

Table 2. Concluded optimum soft reduction amount from the nomogram.

Solid fraction	Optimum soft reduction amount ($\times 10^{-3}$, m)
0.30	12.2
0.41	10.8
0.50	9.9
0.61	8.8
0.71	7.6
0.80	6.6
0.90	4.0

Table 3. Parameters for bloom casting and soft reduction operation.

Item	Value
Casting speed, m/s	0.01133
Super heat, °C	20
Local soft reduction position from meniscus, m	17.837, 19.536
Solid fractions at the local operation stand	0.6, 0.85

fraction, the volume shrinkage in the interdendritic areas can be determined by the red solid line given in the nomogram. The values of the center solid fraction and volume shrinkage in the mushy zone could be read from the top abscissa and right ordinate.

As shown in the same figure, the area reduction amount of the center mushy zone is proportional to the soft reduction amount dependent to the center solid fraction. The values of soft reduction amount and area reduction amount could be read from the bottom abscissa and left ordinate, respectively.

To compensate the volume shrinkage caused by solidification, the proper soft reduction amount is easily to determine by comparing the volume shrinkage and the area reduction amount. For example, the volume shrinkage amount in the mushy zone while center solid fraction is 0.7 could be got from the red solid line, indicated as grey square point "A". To balance the volume shrinkage and prevent residual melt flow, the optimum area reduction amount in mushy zone could be obtained from the yellow shot dash line for the center solid fraction of 0.7, indicated as grey square point "B". The corresponding optimum total soft reduction amount, roughly 7.6 mm, could be easily read from the grey square point "C" at the bottom abscissa.

Identically, the required soft reduction amount for the railway steel bloom casting should be 4.0 mm, 6.6 mm, 7.6 mm, 8.8 mm, 9.9 mm, 10.8 mm and 12.2 mm while the

local solid fraction in the center is 0.9, 0.8, 0.71, 0.61, 0.50, 0.41 and 0.30, respectively, as given in Table 2.

4.4 Application

A domestic designed six-strand bloom continuous caster was successfully commissioned equipped with the devices for the operation of dynamic soft reduction, of which the second level control system was designed by ourselves [6]. The hydraulically adjustable soft reduction units of the bloom caster were designed into the five pulling and unbending machine stands per strand, which allows the soft reduction operation upon the final solidification stage dynamically. The relevant production parameters are given in Table 3.

The acid etched bloom of its longitudinal section under two different soft reduction amounts are given in Figure 16, in which the internal quality of strand under the operation of soft reduction with the soft reduction amount of 4.5 mm and 7.0 mm was improved to different extent.

To evaluate the center segregation at the vicinity of bloom center quantitatively, chemical analysis method was applied for the bloom produced under different soft reduction pattern. The equally spaced drilling metal samples were taken from the bloom longitudinal section at the casing direction, as illustrated in Figure 17.

Fig. 16. Acid etched blooms of their longitudinal sections.

Fig. 17. Illustration of the taken position of drilling metal samples in the longitudinal section.

The formula to calculate the segregation index is given in Equation (9).

$$CSI = C_i / C_{tundish} \quad (13)$$

where, C_i denotes the carbon content of the drilling metal sample and $C_{tundish}$ denotes the average carbon content in the tundish.

Figure 18 shows the variations of segregation index of carbon along casting direction at the vicinity of bloom longitudinal section applying "NO SR" pattern and "SR4.5 mm" pattern. The "NO SR" pattern was such that the bloom was produced without the operation of soft reduction technology and the "SR4.5 mm" pattern was such that the bloom was casted applying soft

reduction technology with a total soft reduction of 4.5 mm.

As shown in Figure 18, both the center segregation indexes produced under the "NO SR" pattern and "SR4.5 mm" pattern varied along casting direction. But, the amplitude of variations in center segregation in the casting direction is decreased from 0.41 to 0.22 apply the soft reduction pattern "SR4.5 mm", compared to "NO SR" pattern.

Figure 19 shows the variations of segregation index of carbon along casting direction at the vicinity of bloom longitudinal section applying "NO SR" pattern and "SR7.0 mm" pattern. As shown in Figure 19, the amplitude of variations in center segregation in the casting direction is decreased from 0.35 to 0.13 apply the soft reduction pattern "SR7.0 mm", compared to "NO SR" pattern.

It could be concluded, from the chemical analysis and acid etched result, that the operation of soft reduction amount with 4.5 mm is not sufficient enough to compensate the volume shrinkage in the interdendritic areas, and the heavy railway bloom can be produced under the soft reduction amount of 7.0 mm for clearly improved internal

Fig. 18. Variations of segregation index of carbon along casting direction at the vicinity of bloom longitudinal section applying “NO SR” pattern and “SR 4.5 mm” pattern.

Fig. 19. Variations of segregation index of C at the bloom center in longitudinal direction applying “NO SR” pattern and “SR7.0 mm” pattern.

soundness. On the other side, we know that the solid fraction under soft reduction region ranges from 0.6 to 0.85 from the solidification analysis. And the optimum soft reduction amount should range from 6.6 to 8.8 mm from the nomogram given above, which show satisfactory agreement to the production operation. At the same time, the popular centerline segregation has been effectively controlled under the acceptable level to meet the requirements for the following hot-working and final railway service prop-

erties, which can be referred to as the contribution of the optimum soft reduction as well due to the balanced negative pressure driven residual melt flow in the crater mushy zone.

5 Conclusions

For the clarification to optimum soft reduction amount and internal reduction efficiency for continuous casting, a solidification analysis model and a

thermo-mechanical coupled FEM model were developed in the paper. The analysis of the solidification and deformation behavior for the given bloom format of high carbon railway steel has been carried out. The following conclusions can be drawn out.

The solidification volume shrinkage in the mushy zone is determined under various solid fraction in the center of the bloom casting. For the control of the centerline soundness and/or macro-segregation, the volume reduction of the mushy zone by operation of soft reduction should increase inversely with the local center solid fraction through the compensation to the following exact volume shrinkage.

Soft reduction efficiency increase inversely with the center solid fraction. The persistent squeezing effect of the solidified shell on the mushy zone upon the increasing soft reduction amount can be revealed by the new defined efficiency expression, which shows that the internal soft reduction efficiency is directly related to the mushy zone area reduction.

The nomogram for the determination of optimum soft reduction has been presented for the bloom casting at various center solid fraction upon the implementation of soft reduction. And the clearly improved internal soundness for high carbon railway steel has been expected in production under the soft reduction operation in agreement with the nomogram.

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