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Analysis and industrial application of the soft reduction model in continuous bloom casting of C92D2 steel

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Soft reduction is a key method to reduce or eliminate the internal quality defects of high carbon steel in blooming castings. In the present work, the total reduction amount and the distribution of the reduction amount at various casting speeds were calculated using the obtained model of the soft reduction amount. Industry experiments were carried out on soft reduction in continuous casting to improve the internal quality of C92D2 high carbon steel blooms by means of the model. The results show a remarkable improvement of the internal quality of C92D2 high carbon steel blooms by applying a suitable reduction mode during continuous casting.

Keywords: soft reduction, C92D2 high carbon steel, continuous casting bloom, internal quality.

Аналіз та промислове застосування моделі м'якого обтискання при безперервному литті блюму зі сталі C92D2. *Yujun Li, Yihong Xu*

М'яке обтиснення є ключовим методом зменшення або усунення внутрішніх дефектів високовуглецевої сталі у виливках з блюмінгу. У цій роботі, використовуючи модель м'якого обтискання, розраховані загальна величина обтиснення та розподіл величини обтиснення при різних швидкостях лиття. Проведено промислові експерименти з м'якого обтискання в безперервному литті з метою покращення внутрішньої якості блюмів із високовуглецевої сталі C92D2. Результати показують помітне покращення внутрішньої якості блюму з високовуглецевої сталі C92D2 за рахунок застосування відповідного обтиснення під час безперервного розливання.

1. Introduction

In order to reduce or eliminate internal quality defects, like macrosegregation, porosity and shrinkage cavities, of high carbon steel in bloom castings, the casters should be well equipped with auxiliary devices such as EMS and/or mechanical soft reduction [1]. The method of soft reduction operation has been proved to be one of the most effective ways to reduce the internal quality defects mentioned above [2]. When using soft reduction technology, the correct value of reduction can not only compensate for the central shrinkage in the crater mushy zone, but also suppress residual melt flow caused by negative pressure. Thus, an improved strand density can also be obtained.

It is necessary to conduct a large number of industry experiments and laboratory studies to determine the favorable parameters for soft reduction [3]. However, most of the results obtained are only suitable for specific steel grades and/or casting formats, so they cannot be used as general criteria, except as a guide.

There are also some mechanism modeling methods along with numerical simulation or mathematical derivation for soft reduction amount or reduction gradient [4–10], in which the soft reduction amount model proposed by the author of this paper achieved good metallurgical results after application [1].

The present work is mainly focused on the optimization of the soft reduction parameters to improve the internal bloom quality of the C92D2 high carbon steel by using the soft reduction model derived by the author in another paper [2]. The appropriate reduction parameters, including the total reduction amount and the reduction amount distribution under the reduction roll, were determined according to the process parameters of the casting machine. Extensive plant trials were carried out based on the selected reduction amount parameters. The effects of soft reduction on internal quality defects in the strand, as well as element homogeneity were evaluated.

2. Soft reduction model

On the basis of overall mass balance in the casting direction, the soft reduction amount model could be expressed as follows [2]:

$$R_i = \frac{2}{37} \frac{\int_0^W \int_0^{Th} (f_{s,i} - f_{i,i-1}) dxdy}{W\eta_i}, \quad (1)$$

where R_i is the soft reduction amount of the i^{th} strand point, m; W and Th are the width and thickness of the bloom strand, respectively, m; f is the temperature dependent solid fraction; x and y are the coordinate axes along the width and thickness directions of the strand, respectively, m; η is the reduction efficiency.

The solid fraction f can be described by:

$$f_s = \begin{cases} 0, T \geq T_l \\ \dfrac{T_l - T}{T_l - T_s}, T_s < T < T_l, \\ 1, T \leq T_s \end{cases} \quad (2)$$

where T_l and T_s are the liquidus and solidus temperature, respectively, K.

The reduction efficiency η can be expressed as follows [11]:

$$\eta = \exp(2.36\lambda + 3.73) \cdot \left(\frac{r}{420}\right)^{0.587}, \quad (3)$$

where r indicates the diameter of reduction roll, mm; λ is the shape index described as:

$$\lambda = V_r \cdot F_r \cdot S_r, \quad (4)$$

Table 1. Distance from each soft reduction stand to mold meniscus

Soft reduction stand	Distance to mold meniscus, m
No.1	9.5
No.2	10.5
No.3	11.5
No.4	12.5
No.5	13.5
No.6	14.5
No.7	15.5
No.8	16.5
No.9	17.5

in which, V_r is the ratio of the unhardened volume to the whole volume; F_r is the flatness ratio, namely, the bloom width to thickness ratio; and S_r is the ratio of the length of the unhardened section to the length of the contact. It can be seen from Eqs. (1)–(4) that the reasonable reduction amount under the i^{th} reduction roll can be obtained only by determining the temperature field of the bloom solidification process.

In order to calculate the temperature field, and thus obtain the value of the center solid fraction, the reduction efficiency and the reduction amount from Equations (1)–(3), a two dimensional transient heat transfer and solidification model was built to predict the temperature field of entire strand under steady casting conditions. The main model assumptions, governing equation, boundary and initial conditions, and material properties can be found in [12].

3. Experimental

On the basis of the soft reduction amount model mentioned above, the verification trial for high-carbon steel C92D2 during casting was conducted in Qingdao Special Steel, in which a curved three-strand bloom caster with soft reduction was employed. The bloom caster has nine soft reduction stands per strand, and the distance from each stand to the mold meniscus is shown in Table 1. The main process parameters of the industry experiment are given in Table 2. The chemical composition of C92D2 high carbon steel is listed in Table 3.

As shown in Table 1, the caster soft reduction can be realized in a total length range of 8 m. By using a suitable soft reduction zone calculated by the transfer and solidification model under the various con-

Table 2. Main process parameters of the bloom caster

Parameters	Values	Units
Sectional dimension	180×240	mm^2
Casting Speed	0.8–1.5	m/min
Caster radius	10	m
Mold length	850	mm
Pouring mode	Submerged	
Soft reduction roll diameter	400	mm

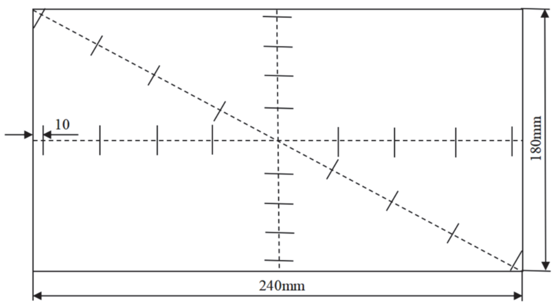

Fig. 1. Sampling schematic for wet chemical analysis in bloom cross sections.

ditions such as steel grade, casting speed, superheat temperature and cooling intensity, and so on, the bloom caster can more flexible adjust the hydraulic pressure in a larger range.

The soft reduction should act on the region, where the molten steel could not flow freely. Based on the previous research, [2] the soft reduction zone was chosen from the center solid fraction f_{sc} = 0.3 to 0.8 to effectively compensate for localized shrinkage during final solidification.

4. Results and discussion

Using the center solid fraction difference and the soft reduction efficiency, under identical superheat degree of 30 K, a specific water flow rate of 0.41 L/kg, the reduction amount for C92D2 high carbon steel per each reduction roll in the reduction zone were calculated form Eq. (1), and the results are shown in Table 4. From the table, the soft reduction amount per each reduction roll increases in the casting direction since the solid fraction change increases and the reduction efficiency decreases in the casting direction (see Eq. (1)). It is shown that the total soft reduction amounts for a section of 180×240 mm bloom from C92D2 high carbon steel are between 2.13 and 5.68 mm at given casting speeds. It can be also seen that the reduction amount increases with the casting speed.

To further verify the soft reduction calculation model, the soft reduction amounts for C92D2 high carbon steel given in Table 4 were applied to the above blooming casting machine. Taking into account that a larger reduction amount may increase casting resistance and, thereby, result in motor torque jumping, the casting speed was set to 1.30 m/min.

To investigate the effect of soft reduction on the carbon segregation, the samples 5 mm long and 5.5 mm in diameter were obtained by drilling through the cross section of the bloom as shown in Fig. 1.

Table 3. Chemical composition of C92D2 steel, wt%

C	Si	Mn	P	S	Al	Cr	Sn	As	N
0.92	0.23	0.35	0.015	0.008	≤0.005	0.22	≤0.007		

Table 4. Calculation results of soft reduction amount for C92D2 steel with different casting speeds

Casting speed, m/min	Soft reduction amount withdrawal units, mm									
	1	2	3	4	5	6	7	8	9	Total
1.00	2.13									2.13
1.10	0.90	1.96								2.86
1.20		0.85	1.20	1.56						3.60
1.30			0.71	1.11	2.48					4.30
1.40				0.50	1.09	1.20	2.22			5.01
1.50					0.31	1.00	1.13	1.25	1.99	5.68

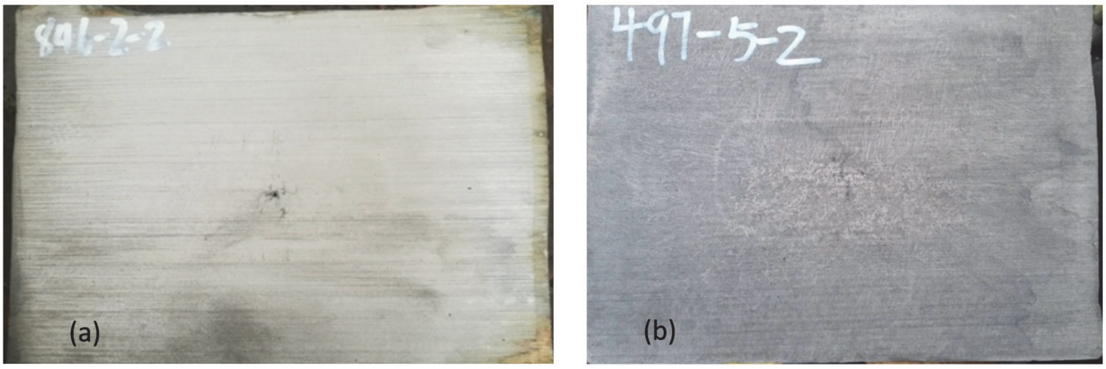

Fig. 2. Hot etched bloom cross section for C92D2 steel: a) without soft reduction; b) with soft reduction.

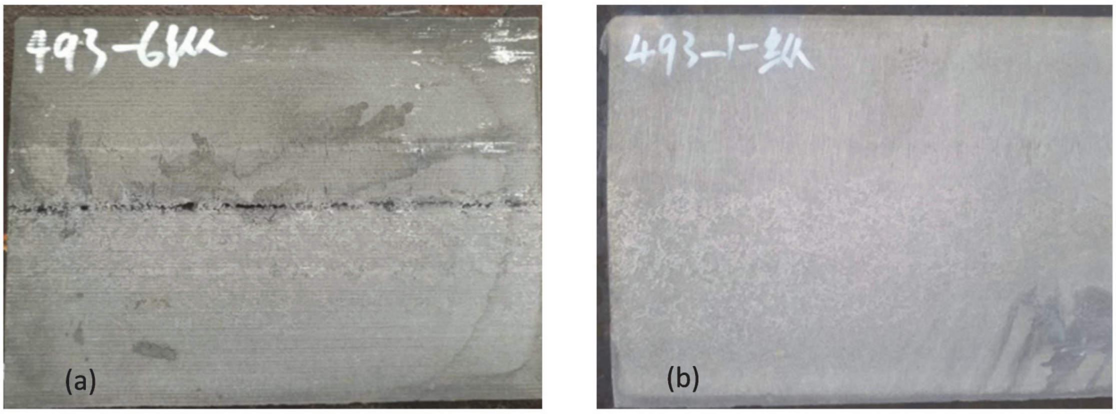

Fig. 3. Hot etched bloom longitudinal sections for C92D2 steel: a) without ssoft reduction; b)with soft reduction.

The carbon segregation index K is obtained based on the carbon analysis of a sample as follows:

$$K = \frac{nC_i}{\sum_{i=1}^{n} C_i}, \quad (5)$$

Here C_i and n denote the local carbon content and sampling number, respectively, as shown in Fig. 1.

Figs. 2–3 show a typical hot etched bloom cross section and a longitudinal section, respectively, for C92D2 steel without and with soft reduction. It is clear that after soft reduction, the center porosity and center shrinkage cavities of the bloom are significantly healed, and the macrostructure of the bloom becomes more homogeneous. Figs. 4–6 show the carbon segregation index along the bloom thickness, width, and diagonal, respectively, with and without soft reduction. The results show that after the soft reduction, the maximal carbon segregation index decreased from 1.35 to 1.08 and the uneven distribution of carbon has been significantly reduced. Accordingly, the internal quality defects of the bloom including shrinkage cavity, porosity, and segregation were significantly eliminated, and the chemical composition of the bloom was more homogeneous by using the soft reduction model.

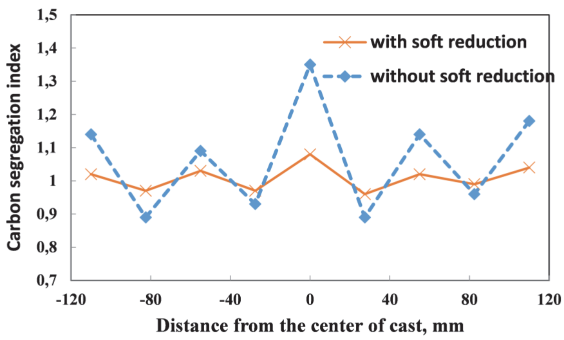

Fig. 4. Effect of soft reduction on the carbon segregation index along the bloom width.

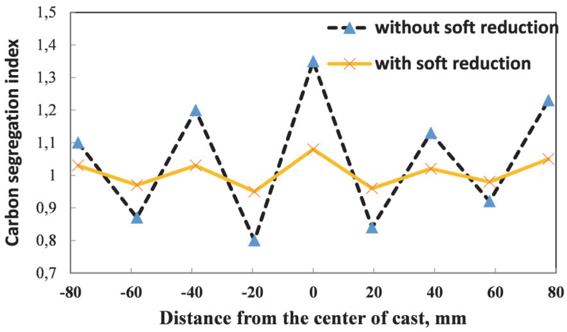

Fig. 5. Effect of soft reduction on the carbon segregation index along the bloom thickness.

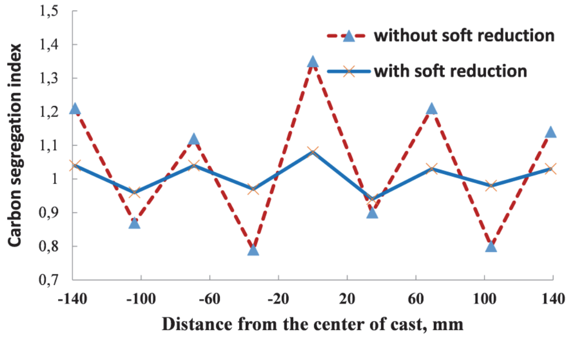

Fig. 6. Effect of soft reduction on the carbon segregation index along the bloom diagonal.

5. Conclusion

The soft reduction amount for C92D2 high carbon steel under reduction roll in the soft reduction zone increases in the casting direction, the total soft reduction amount also increases with casting speed according to the soft reduction model calculation. Industrial results show that the internal quality of the C92D2 high carbon steel bloom was improved remarkably after applying soft reduction in accordance with the present soft reduction strategy, and the maximum carbon segregation index decreased from 1.35 to 1.08 along with a more homogeneous overall chemical distribution.

References

1. K.Liu, Q.Sun, J.Zhang, C.Wang, *Metallurgical Research Technology*, **113**, 504 (2016).
2. Y.Li, L.Li, J.Zhang, *Steel Research International*, **12**, 88 (2017).
3. C.Ji, S.Luo, M. Zhu, *ISIJ International*, **3**, 54 (2014).
4. S.Sugimaru, J.Nakashima, K.Miyazawa, S.Ogibayashi, *Materials Science and Engineering A*, **8**, 173(1993).
5. C.Cheng, J.Shuai, L.Yu, W.Wan, Z.Liu, *Journal of Wuhan University of Science and Technology*, **2**, 34 (2011).
6. Q.Lin, M.Zhu, *Acta Metallurgica Sininca*, **12**, 43 (2007).
7. Q. Lin, M.Zhu, *Acta Metallurgica Sininca*, **2**, 45 (2009).
8. R.Chu, Z.Li, J.Liu, *Journal of Iron and Steel Research*, **3**, 28 (2021).
9. N.Ali, L.Zhang, H.Zhou, *Materials Today Communications*, **3**, 26 (2021).
10. Y.Li, L.Li, P.Lan, *Continuous Casting*, **4**, 43 (2018).
11. Y.Ito, A.Yamanaka, T.Watanabe, *La Revue Metallurgie-CIT*, **10**, 16 (2000).
12. Y.Li, Y.Xu, *Functional Materials*, **29**, 429 (2022).