Bulgarian Chemical Communications, Volume 47, Number 4 (pp. 1084 – 1088) 2015

Physical model and industrial test of small inclusions removal by bubble adhesion

C. Yang[1*], F. Tang[2], M. Shen[1], H. Yu[1]

[1]*University of Science and Technology Liaoning, Anshan City 114053, Liaoning, China*
[2]*Anshan Iron and Steel Group Company, Anshan City 114014, Liaoning, China*

Received April 5, 2015

A variety of methods have been used to reduce the content of inclusions in metals. As one of the important refining equipments between steelmaking and continuous casting, RH vacuum refining plays an important role in removing inclusions from the molten steel. In this paper, a physical model is established at a geometric similarity ratio of 1:4, to simulate a real 180-t RH vacuum refining device. Inclusions removal from molten steel by bubble adhesion in an RH degasser is analyzed using the physical model. The effects of variables such as bubble size, treatment time, lift-gas flow rate, amount of added $NaHCO_3$, are investigated. The results of the 180-t RH industrial test reveal that bubbles of carbon dioxide are formed by the decarburization reaction of calcium hydrogencarbonate, which effectively removed inclusions from the molten steel.

Key words: Bubble adhesion, inclusion removal, physical model, industrial test.

INTRODUCTION

It is generally known that nonmetallic inclusions in molten steel can lead to serious defects in the final product. In order to satisfy the requirements for the degree of cleanliness of steel, controlling the amount, size distribution and shape of inclusions is of great importance in the steelmaking process. Inclusions in steel greatly affect its physical and chemical properties, such as fatigue life, machinability and corrosion resistance [2]. Big size inclusions are primarily removed by Stokes floating. However, inclusions less than 50 µm in diameter cannot rise rapidly and tend to remain in the steel [3-5]. During steel secondary refining aided by surface tension forces from non-wetting contact, some solid inclusions, such as alumina and silica tend to collect on surfaces such as bubbles [6,7] and therefore can adhere to the bubbles and be transported to the surface of molten steel [9].

Technologies for clean steelmaking are being continuously developed to fulfil the ever increasing demands on material properties [10]. The composition, quantity and size distribution of non-metallic inclusions are important in influencing the physical properties of steel. RH refining process to a significant degree has become the main refining operation for removing inclusions from liquid steel in order to minimize the inclusions that could potentially form defects in the finished product or adversely affect the product properties [10, 11].

Therefore, special methods have been developed to remove non-metallic inclusions from molten steel [12,13]. Furthermore, Miki [7] and Thomas in [5, 6, 23] developed a mathematical model to predict the removal of alumina inclusions from molten steel in a continuous casting tundish. Although several papers have been written on inclusion removal by gas bubbles flotation in water modeling [14-17] there are few papers systematically studying the fundamentals of inclusion removal by bubble attachment in liquid steel in an RH vacuum degasser and the effects of bubble size, treatment time, lift-gas flow rate, etc.

This paper presents fundamental models to quantify the removal of inclusions by bubbles in molten steel. A water model is used to study the influences on fine inclusions removal in a 180-t RH vacuum refiner. The industrial test proved that the inclusions in molten steel can be removed effectively by the addition of calcium carbonate.

EXPERIMENTAL PRINCIPLE AND METHOD

To make the prototype and the model identical in both geometry and dynamics, a physical model of a 180-t RH vacuum degasser was established with a geometric similarity ratio of 1:4. Table 1 shows the operational and geometrical parameters of the prototype and the physical model.

A diagram of the experimental apparatus is shown in Fig.1. Liquid steel was simulated by 400 L of acidified water, and fine inclusions - by 20 g of high-density polypropylene beads; compressed air was used as the lift gas. The inclusions are put into 500 ml water in a beaker and stirred using an ultrasonic stirrer to make sure the inclusions were fully wetted. The water with inclusions is then

* To whom all correspondence should be sent:
E-mail: chunjieyang_utsl@126.com

transferred into the experimental vessel. The snorkels are dipped into the liquid in the ladle to a depth of 100 mm.

The relevant parameters of the media (namely, the densities ρ of the liquid and the inclusions) for the model and prototype are shown in Table 2.

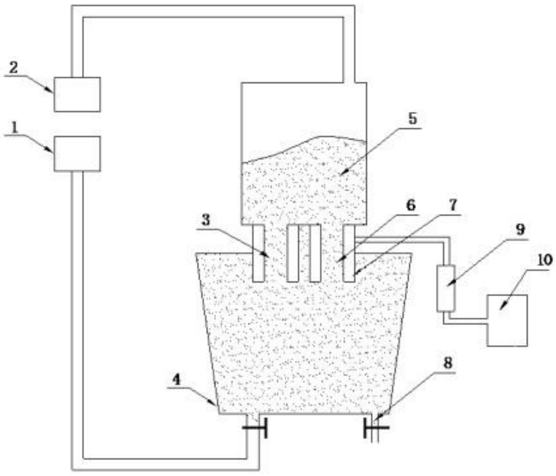

Fig. 1. Schematic drawing of the experimental apparatus – 1 water tank; 2 vacuum pump; 3 downleg snorkel; 4 ladle; 5 vacuum chamber; 6 upleg snorkel; 7 distribution chamber for lift-gas; 8 valve; 9 velocity-meter; 10 air cylinder.

Table 1. Main parameters of the prototype and the physical model (in mm).

Equipment	Dimensions	Prototype	Model
Ladle	Height	4450	1112
	Upper internal diameter	3130	782
	Lower internal diameter	2800	700
Vacuum vessel	Internal diameter	1786	446
Snorkel	Length	900	225
	Internal diameter	560	140

Table 2. Relevant parameters of the media for the model and prototype

Density	Prototype	Model
ρ_{liquid}/kg m^{-3}	7.0×10^3 (steel)	1.0×10^3
ρ_{inc}/ kg m^{-3}	3.9×10^3 (Al_2O_3) or 2.7×10^3 (SiO_2)	0.91×10^3 (polypropylene)

The contact angle of the inclusions with water is 118°, particle size (μm) distribution curves are shown in Fig.2.

The morphology of the inclusions in the water model is shown in Fig.3.

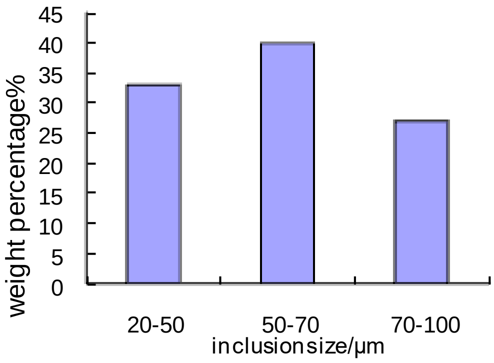

Fig. 2. Inclusions particle size distribution.

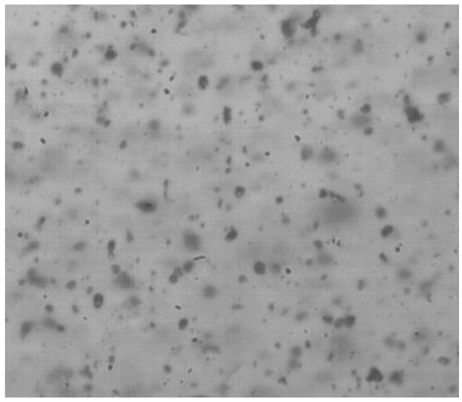

Fig. 3. Morphology of the polypropylene beads in the water model.

The inclusion removal rate after the first j time intervals is calculated from the formula

$$\eta_j = \frac{\sum_{i=1}^{j} m_{ti}}{m_0}$$

Where m_{ti} is the removed amount of inclusions in the ith time interval, and m_0 is the total amount of inclusions.

Acidified $NaHCO_3$ was used to produce fine bubbles of CO_2 according to the reaction:

$$HCl(aq) + NaHCO_3(aq) = NaCl(aq) + H_2O(l) + CO_2(g)$$

or:

$$HCO_3^-(aq) + H^+(aq) = CO_2(g) + H_2O(l)$$

The fine bubbles of CO_2 were distributed evenly over the water, thus increasing mechanical collisions between bubbles and inclusions.

Hydrolysis equilibrium exists and the ionization equilibrium reaction is as follows:

$$HCO_3^- = H^+ + CO_3^{2-}$$

$$HCO_3^- + H_2O = H_2CO_3 + OH^-$$

$$H_2CO_3 = H_2O + CO_2$$

$$H^+ + OH^- = H_2O$$

Overall reaction:

$$2HCO_3^-(aq) = CO_3^{2-}(aq) + CO_2(g) + H_2O(l)$$

Bubble shape changes with size [18]; bubbles smaller than 3 mm are spherical, bubbles 3 to 10 mm are spheroidal, and bubbles larger than 10 mm are spherical-cap shaped [19-21]. Almost all of the bubbles produced by adding $NaHCO_3$ to acidified water are spherical due to their size of 0.5~1.5 mm.

The influence of treatment time, flow rate and method of addition of lift-gas, and amount and time of $NaHCO_3$ addition on the inclusion removal rate was examined.

RESULTS AND DISCUSSION

The process of inclusions adhesion to bubble

The process of inclusions adhesion to bubble is shown in Fig.4. Finer bubbles provide a larger gas/liquid interfacial area and higher attachment probability of inclusions to bubbles [22]. Inclusions tend to pass the midpoint of the bubble and first touch the bubble surface toward the bottom side. If the normal distance from the inclusion center to the surface of the bubble quickly becomes less than the inclusion radius, then collision attachment takes place [23]. Bubbles capturing inclusions move within the molten steel, and remove some of them to the top [24, 25].

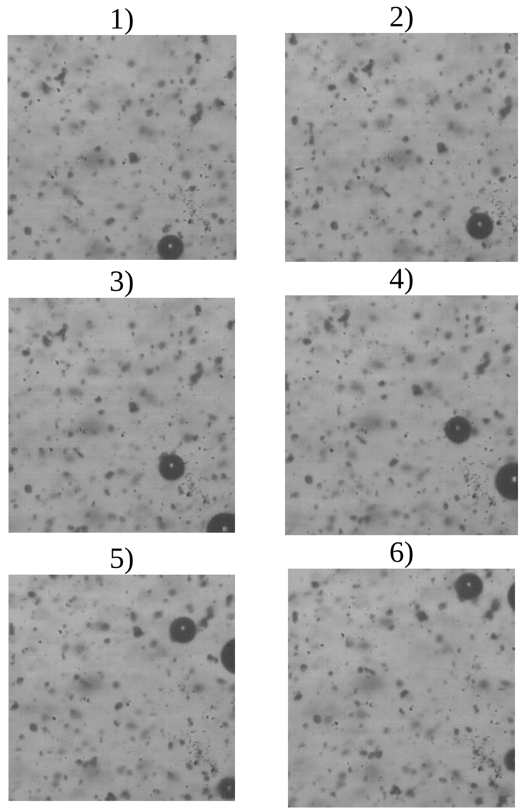

Fig.4. The process of inclusions adhesion to bubble.

It can be concluded that the smaller bubbles have a greater rate of inclusions removal. This conclusion is in agreement with Zhang's fundamental analysis [22]. The average equivalent size of bubbles is estimated to be 0.5~1.5 mm in diameter in the mold investigated in this work.

Effect of treatment time on inclusion removal rate

The relationship between inclusion removal rate and treatment time is show in Fig.5. The inclusion removal rate increased gradually with increasing treatment time, and most inclusions were removed between 0 and 15 min.

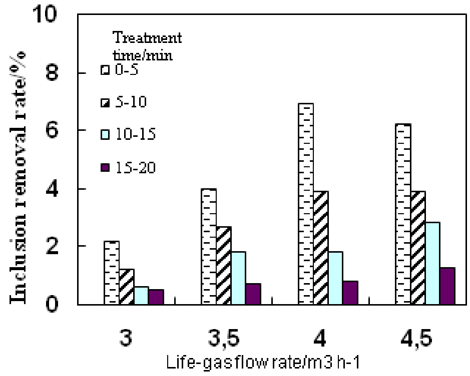

Fig. 5. Relationship between inclusion removal rate and treatment time

Effect of lift-gas flow rate on inclusion removal rate

As can be seen from Fig.6, for a treatment time of 20 min, the inclusion removal rate increased rapidly as the lift-gas flow rate was raised from 3.0 $m^3\ h^{-1}$ to 5.0 $m^3\ h^{-1}$, after which it tended to stabilize.

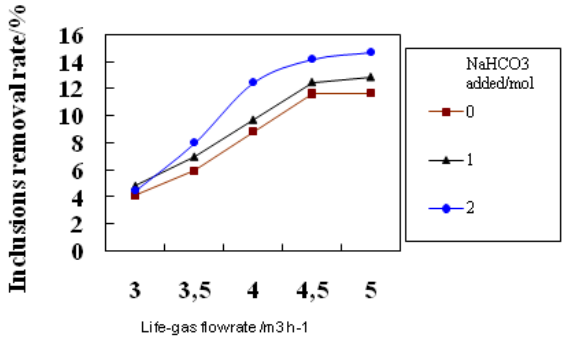

Fig. 6. Relationship between inclusion removal rate and lift-gas flow rate

With increasing lift-gas flow rate, the circulation rate initially increases, and consequently so does the inclusion removal rate. However, if the lift-gas flow rate becomes too high, the flow pattern of the liquid steel alters. Over-rapid flow of liquid steel inhibits the flotation and removal of inclusions. There is, therefore, an optimum value of the lift-gas flow rate: in this experiment, the highest inclusion removal rate was registered when the lift-gas flow rate was about 4.5 $m^3 h^{-1}$.

Effect of amount and time of $NaHCO_3$ addition on inclusion removal rate

Figure 7 shows the relationship between inclusion removal rate and the amount and time of $NaHCO_3$ addition for a treatment time of 20 min at the optimum value of the lift-gas flow rate of 4.5 $m^3 h^{-1}$. It can be seen that the inclusion removal rate increases gradually with the addition of greater amounts of $NaHCO_3$, although, under conditions of industrial production, to avoid the introduction of excessive amounts of impurities, various factors need to be considered. The effect is greatest at the beginning of $NaHCO_3$ addition.

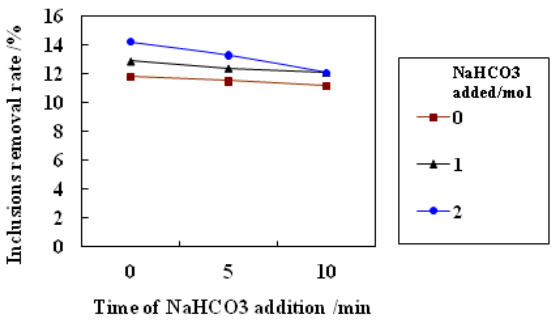

Fig. 7. Relationship between inclusion removal rate and amount and time of $NaHCO_3$ addition.

CONCLUSIONS

The influence of treatment time, lift-gas flow rate and amount and time of $NaHCO_3$ addition on the inclusion removal rate was investigated using a water model of 1:4 linear scale for a 180-t RH-TB degasser. The following conclusions can be drawn from the results:

1. The average equivalent size of bubbles is estimated to be 0.5~1.5 mm in diameter in the mold investigated in this work.

2. The inclusion removal rate increases gradually with increasing treatment time, with most inclusions being removed between 5 and 18 min. In this water model experiment, the treatment time was chosen as 20 min to obtain the best effect.

3. The inclusion removal rate increases with increasing lift-gas flow rate until an optimum value is reached, which in this experiment was 4.5 $m^3 h^{-1}$.

4. The inclusion removal rate increases gradually with the addition of $NaHCO_3$, and the effect is greatest at the beginning of $NaHCO_3$ addition.

5. Industrial test results indicate that bubbles of carbon dioxide are formed by the decarburization reaction of calcium hydrogencarbonate, thus inclusions can be effectively removed from molten steel.

REFERENCES

1. M.Y. Zhu, Z.Q. Xiao, Simulation on the secondary refining process, Beijing, Metallurgy Industry Press., 1998, p.320
2. J. Cheng, R. Eriksson, P. Jonsson, *Ironmaking and Steelmaking*, **30**, 66 (2003).
3. R. Dekkers, PhD thesis, Katholieke Universiteit Leuven, 2002; http://members.home.nl/rob.dekkers/pdf-files/contents.pdf
4. A. W. Cramb: 1998, http://neon.mems.cmu.edu/afs/afs2/form.html.
5. L. F. Zhang, B. G. Thomas, Proc. 7th European Electric Steelmaking Conf., Venice, Italy, May 2002, AIM, p. 277.
6. L. Zhang, B. Rietow, K. Eakin, and B.G. Thomas: *ISIJ Inter.*, **46**, 2006, , in press.
7. Y. Miki, S. Takeuchi, *ISIJ Int.*, **43**, 1548 (2003).
8. F. Tang, Z. Li, X. Wang, B. Chen and P. Fei, *Int. J. Miner. Metall. Mater.*, **18**, 144 (2011).
9. M. Söder, Licentiate Thesis, Royal Institute of Technology, Stockholm, Sweden, 2000.
10. P. Kaushik, M. Lowry, H. Yin, H.Pielet, *Ironmaking and Steelmaking*, **39**, 284 (2012).
11. J. H. Wei, H. T. Hu, *Ironmaking and Steelmaking*, **32**, 427 (2005).
12. T. Lee, H. J. Kim, B. Y. Kang, S. K. H-Wang, *ISIJ Int.*, **40**, 1260 (2000).
13. H. Yin, H. Shibata, T. Emi, M. Suzuki, *ISIJ Int.*, **37**, 946 (1997).
14. H. J. Schulze, *Developments in Mineral Processing*, **4**, 65 (1984).
15. L. Wang, H.-G. Lee, P. Hayes, *ISIJ Int.*, **36**, 7 (1996).
16. X. Zheng, P. Hayes, H.-G. Lee, *ISIJ Int.*, **37**, 1091 (1997).
17. N. Ahmed, G.J. Jamson, *Metall. Rev.*, **5**, 77 (1989).
18. R.M. Wellek, A.K. Agrawal, A.H.P. Skelland, *AIChE J.*, **12**, 854 (1966).
19. Y. Sahai, R.I.L. Guthrie, *Metallurgical Transactions B*, **13**, 193 (1982).
20. H. Tokunaga, M. Iguchi, H. Tatemichi, *Metallurgical and Materials Transactions B*, **30**, 61 (1999).
21. M. Iguchi, H. Tokunaga, and H. Tatemichi: *Metallurgical Transactions* B., 1997, 28, 1053-1061.
22. L. F. Zhang, S.Taniguchi, K.Matsumoto, *Ironmaking and Steelmaking*, **29**, 326 (2002).
23. L. F. Zhang, J.A. Brian, G. Thomas, *Metallurgical and Materials Transaction B*, **37B,** 361 (2006).
24. L. Zhang, S. Taniguchi, *International Materials Reviews*, **45**, 59 (2000).
25. G. Abbel, W. Damen, G. de Dendt, W. Tiekink: *ISIJ International*, **36**, 219 (1996).

ФИЗИЧЕН МОДЕЛ И ПРОМИШЛЕН ТЕСТ ЗА ОТСТРАНЯВАНЕ НА ГАЗОВИ ВКЛЮЧВАНИЯ ЧРЕЗ АДХЕЗИЯ НА МЕХУРИ

Ч. Янг[1*], Ф. Танг[2], М. Яен[1], Х. Ю[1]

[1]*Научно-технологичен университет Ляолинг, Аншан сити, Ляолинг, Китай*
[2]*Аншанска компания за желязо и стомана, Аншан сити, Ляолинг, Китай*

Постъпила на 5 април, 2015 г.

(Резюме)

Използвани са различниметоди за намаляване съдържанието на включвания в металите. RH-вакуумното рафиниране, приложено между добиването на стоманата и непрекъснатото й изливане, има важна роля за отстраняването на включванията в разтопената стомана. В настоящата работа е създаден физичен модел при геометрично отношение на подобие 1:4 за симулирането на реален180-t RH-уред за вакуумно рафиниране. Анализирано е отстраняването на включвания от разтопена стомана чрез адхезия на мехури. Изследван е ефекта на различни параметри вRH-дегазера (размер на мехура, време за третиране, дебит на газа, колиество добавен $NaHCO_3$).При промишления 180-t RH-тест се оказва, че се образуват мехури от въглероден диоксид при разлагането на калциев карбонат, при което става ефективно отстраняване на включванията.