Effect of Size of Ferrotitanium on the Melting Behavior and the Yield in the Refining of Interstitial Free Steel by RH De-gasser

Chaojie ZHANG,1)* Yanping BAO,2) Dechi TANG,1) Chenxi JI,1) Leichuan WANG,3) Yang CUI1) and Haibo LI1)

1) Research Institute of Technology, Shougang Group Co., Ltd., Beijing, 100043 China.
2) State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing, 100083 China.
3) Shougang Jingtang United Iron and Steel Co., Ltd., Tangshan, Hebei, 063200 China.

Received on April 25, 2018; accepted on August 8, 2018; J-STAGE Advance published date: September 28, 2018

The reduction of ferroalloy consumption used in the steel making is an important approach to high-performance and low-cost steel manufacture. In this paper, the effect of size of ferrotitanium on the yield in the refining of interstitial free steel by RH de-gasser was investigated. Motion trajectory of ferrotitanium after the addition into molten steel in RH de-gasser was investigated through water model experiment. The effect of size of ferrotitanium on the melting time was investigated by numerical simulation. Combining water model experiment with numerical simulation, the loss mechanism and effect of size on the yield of ferrotitanium were discussed. It was found that the size of ferrotitanium larger than a certain value has a great opportunity of floating up to the interface of molten steel and slag in ladle and being oxidized there. Results of industrial experiment verified the mechanism. As for a 300 tons RH de-gasser, Fe-70%Ti alloy whose size was larger than 43 mm had a low yield because of oxidation by the ladle slag.

KEY WORDS: ferrotitanium; size; yield; interstitial free steel; RH de-gasser.

1. Introduction

Ferroalloys are necessary raw materials in the steel making process,1–4) which are used for deoxidation and alloying. Therefore, the cost of ferroalloys in the steel making is significant. During smelting of interstitial free (IF) steel, a certain amount of ferrotitanium is used as titanium resource. Titanium element can combine with carbon atom, which is beneficial for improving plasticity and excellent drawability of IF steel. In general, in the refining of IF steel, ferrotitanium is added into molten steel in RH de-gasser 3–5 minutes after final deoxidation. The yield of ferrotitanium decreases inevitably because of oxidation and physical loss in the addition process. In Shougang Jingtang United Iron and Steel about 0.69 kg titanium is needed per ton IF steel, which is equivalent to 1 kg Fe-70%Ti alloy. However, price of ferrotitanium is high. So, if the yield of ferrotitanium increases further, a large amount of cost could be saved.

In recent years, usage of all kinds of ferroalloys in the steel making has been receiving more and more attentions.5–11) Zhu et al.2) proposed deoxidation mechanism of Al-killed in the industrial refining based on the measured and calculated oxygen activities in Al-killed bulk steel. In order to add nitrogen into normal steel and stainless steel, Gaye et al.12) investigated nitrogen alloying of carbon or stainless steels by bottom nitrogen gas injection in converters or ladles. Ono-Nakazato et al.13) clarified the silicon deoxidation reaction in the steel including molybdenum taking the thermodynamic affinity between molybdenum and silicon into account. Besides, the yield of ferroalloy has been becoming more and more popular.14,15) Conejo et al.14) carried out a research work about optimizing aluminum consumption and assessed their efficiency under ladle furnace conditions.

The yield of ferrotitanium after the addition into molten steel in RH de-gasser is determined by many factors, such as oxygen content in molten steel after final deoxidation, oxidability of slag, physicochemical properties of ferrotitanium itself. The flow of molten steel in RH de-gasser is severe,16,17) which has a great influence on melting and motion of ferrotitanium. Both melting time and motion trajectory of ferrotitanium will affect its yield. A long melting time can cause the prolongation of vacuum treatment time of molten steel in RH de-gasser and the increase of the probability of ferrotitanium contacting with slag, which can decrease the yield of ferrotitanium. So far there have been few reports about melting and motion as well as the yield of ferrotitanium after the addition into molten steel in RH de-gasser. In this paper, methods of numerical simulation and water model experiment were combined to investigate the melting and motion of ferrotitanium after the addition into molten steel in RH de-gasser. In this paper, methods of numerical simulation and water model experiment were combined to investigate the melting and motion of ferrotitanium after the addition into molten steel in RH de-gasser. The influence of the size of ferrotitanium on the melting process was analyzed, and the motion trajectory of ferrotitanium after the addition into molten steel in RH de-gasser was discussed in detail.
Furthermore, the loss mechanism and effect of size on yield of ferrotitanium were estimated.

2. Experimental Procedure

2.1. Water Model Experiment

In order to investigate the motion behavior of ferrotitanium after the addition into molten steel in RH de-gasser, water model of RH de-gasser was established to observe the trajectory of materials with different densities after the addition into RH de-gasser.

2.1.1. Experimental Apparatus

A water model for a 300 tons RH de-gasser was designed and fabricated with plexiglass. The geometry similarity ratio is 1:6. Geometric parameters of RH de-gasser and the water model are shown in Table 1. Figure 1 shows a photograph of the water model of the RH de-gasser.

Table 1. Geometric parameters of RH de-gasser and water model.

| Parameters                      | Prototype of RH de-gasser (mm) | Water model of RH de-gasser (mm) |
|--------------------------------|--------------------------------|----------------------------------|
| Depth of ladle                 | 4 200                          | 700                              |
| Top diameter of ladle          | 3 920                          | 653.3                            |
| Bottom diameter of ladle       | 3 638                          | 606.3                            |
| Depth of molten steel          | 3 894.4                        | 973.6                            |
| Diameter of vacuum chamber     | 2 524                          | 420.7                            |
| Height of vacuum chamber       | 4 850                          | 808.3                            |
| Internal diameter of immersion | 750                            | 694.1                            |
| External diameter of immersion | 1 500                          | 250                              |
| Length of immersion            | 1 650                          | 275                              |

![Fig. 1. Water model of RH de-gasser.](image)

2.1.2. Dynamic Similarity

Reynolds number of the molten steel flow in down nozzle of RH de-gasser is $1.828\times10^5$, which is in the second self-preserving region. Namely, changing of the Reynolds number almost has no influences on properties of flow field. So, there is no need to make sure the Reynolds number in down nozzle of the water model which is the same with that of the RH de-gasser. Therefore, dynamical similarity between the RH de-gasser and the water model can be decided as Froud numbers of flow in the down nozzles.

During experiment, water was used to simulate molten steel and air was used to simulate argon. In this time, the flow type is gas/liquid two phase flow and the driving force of the flow is gravity. Therefore, a modified Froud number was used as similar principle number, as shown in Eq. (1).

$$Fr = \frac{\rho_v v^2}{g H p} = \text{const} \quad \ldots \quad (1)$$

Where $Fr$ is the modified Froud number, $\rho_v$ is gas density (kg·m$^{-3}$), $v$ is characteristic velocity (m·s$^{-1}$), $H$ is distance of RH de-gasser up-snorkel to the surface level of liquid (m), $g$ is gravitational acceleration (m·s$^{-2}$), $p$ is liquid density (kg·m$^{-3}$).

Gas flow rate $Q$ is calculated using the following equation.

$$Q = \frac{1}{4} \pi d^2 v \quad \ldots \quad (2)$$

Where $d$ is diameter of RH up-snorkel (m).

From Eqs. (1) and (2), we can obtain

$$Fr = \frac{16Q^2 \rho_v}{\pi^2 g Hd^4} = \text{const} \quad \ldots \quad (3)$$

Relationship between the gas flow rate of air in water model and argon in prototype of RH de-gasser can be described using the following equation.

$$Q_{\text{air}} = Q_{\text{Ar}} \left( \frac{\rho_{\text{air}}}{\rho_{\text{Ar}}} \right) \left( \frac{H_{\text{m}}}{H_{p}} \right) \left( \frac{d_{m}}{d_{p}} \right)^4 \quad \ldots \quad (4)$$

Where $Q_{\text{air}}$ is flow rate of air for water model (L·min$^{-1}$), $Q_{\text{Ar}}$ is flow rate of argon for prototype of RH de-gasser (L·min$^{-1}$), $\rho_{\text{air}}$ is density of argon (kg·m$^{-3}$), $\rho_{\text{air}}$ is density of air (kg·m$^{-3}$), $\rho_{\text{Ar}}$ is density of water (kg·m$^{-3}$), $\rho_{\text{Ar}}$ is density of molten steel (kg·m$^{-3}$), $H_{\text{m}}$ is distance of water model of RH de-gasser up-snorkel to level (m), $H_{p}$ is distance of prototype of RH de-gasser up-snorkel to level (m), $d_{m}$ is diameter of water model of RH de-gasser up-snorkel (m), $d_{p}$ is diameter of prototype of RH de-gasser up-snorkel (m).

In Eq. (4) the parameters $Q_{\text{air}}, Q_{\text{Ar}}, \rho_{\text{Ar}},$ and $\rho_{\text{air}}$ are all in high pressure and high temperature state, not in standard state. By transforming these parameters into the parameters under standard state, we can obtain

$$Q_{\text{air}} = Q_{\text{Ar}} \left( \frac{\rho_{\text{air}}}{\rho_{\text{Ar}}} \right) \left( \frac{\rho_{\text{Ar}}^{\text{const}}}{\rho_{\text{Ar}}} \right) \left( \frac{H_{\text{m}} + \rho_{\text{Ar}} g H_{\text{m}}}{H_{p}} \right) \left( \frac{T_{\text{m}}}{T_{\text{m}}} \right) \quad \ldots \quad (5)$$

Where $\lambda$ is geometry similarity ratio, $Q_{\text{air}}^{\text{const}}$ is flow rate of air under standard state for water model of RH de-gasser...
(NL·min⁻¹), \( Q_{\text{Ar}}^0 \) is flow rate of argon under standard state for prototype of RH de-gasser (NL·min⁻¹), \( \rho_{\text{Ar}}^0 \) is density of argon under standard state (kg·m⁻³), \( \rho_v^0 \) is density of air under standard state (kg·m⁻³), \( P_{\text{v,p}} \) is pressure in vacuum chamber of water model of RH de-gasser (Pa), \( P_{\text{v,g}} \) is pressure in vacuum chamber of prototype of RH de-gasser (Pa), \( T_p \) is temperature of blown gas and molten steel in prototype of RH de-gasser (K), \( T_m \) is temperature of blown gas and molten steel in water model of RH de-gasser (K). Table 2 shows the main parameters of prototype of RH de-gasser and water model of RH de-gasser.

In order to investigate the motion trajectories of alloy after the addition into molten steel during RH degassing process, water model simulation was conducted. Materials with different densities of 0.40, 0.76, 0.80, 0.85, 0.90, 0.95 and 1.04 g·cm⁻³ were added into water model of RH de-gasser to simulate the movement of alloys. Here, the materials were made by filling different amounts of light-weight red polyvinylchloride particles and water into transparent containers, as shown in Fig. 2. These red materials with different densities were added into water model of RH de-gasser to observe their motion trajectories. Besides, black ices with different sizes were also added into RH water model to observe the melting times and motion trajectories. The black ices were made by black ink and had the sizes of 5, 10, 15, 20, 25, 30 and 40 mm. Here the ‘size’ means equivalent spherical diameter.

![Fig. 2](image)

2.2. Industrial Scale Test in RH De-gasser

According to the investigation of melting process and motion trajectories of ferrotitanium after the addition into molten steel in RH degassing process by the water model experiment and numerical simulation mentioned below, the effect of size on the melting and motion of ferrotitanium after the addition into molten steel was investigated. Then industrial experiment was carried out to prove these mechanisms. In the industrial experiment, steel grade was interstitial free steel, and the ferrotitanium containing of 70% of Ti was used as an alloy. Ferrotitanium with the sizes of 10–50 mm and 50–65 mm were added into molten steel in RH degassing process separately. As for each range of sizes of ferrotitanium, 7 kinds of furnaces of industrial experiments were carried out respectively to compare the yields of ferrotitanium.

Before adding ferrotitanium into molten steel, the temperature of molten steel was measured with the thermocouple. The oxygen content in molten steel was measured with solid electrolyte probe. Samples of steel and ladle top-slag were taken before and 5 minutes after the addition of ferrotitanium into molten steel, respectively. The content of titanium in the steel samples were evaluated to calculate the yield of ferrotitanium. Besides, contents of titanium in slags were also evaluated to confirm the oxidation of ferrotitanium.

3. Numerical Simulation

The melting process of ferrotitanium after the addition into molten steel can be regarded as a heat transfer process between ferrotitanium and molten steel fundamentally. Therefore, the melting time of ferrotitanium with different sizes was investigated through the mathematic model of melting process of ferrotitanium in the molten steel. Assumptions were established as follows:

1) Ferrotitanium does not react with molten steel during melting.
2) Ferrotitanium is spherical and melts uniformly.

3.1. Governing Equation

Governing equation was Fourier heat transfer equation. Melting of ferrotitanium in molten steel is a three-dimensional unsteady heat transfer process. According to assumption 1), there is no heat sources in ferrotitanium. Thus, differential equation of three-dimensional unsteady heat conduction can be expressed as

\[
\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) \cdots (6)
\]

Where \( \rho \) is density (kg·m⁻³), \( c \) is specific heat (J·kg⁻¹·K⁻¹), \( k \) is thermal conductivity (W·m⁻¹·K⁻¹).

3.2. Physical Properties of Materials

Physical properties of steel and ferrotitanium were needed during the numerical simulation. Steel grade was assumed to be an interstitial free steel. Ferrotitanium was assumed to be Fe-70% Ti alloy. Thermophysical properties of steel and ferrotitanium were calculated based on their composition using ProCAST 2013.0 software. Figure 3 shows density, thermal conductivity and enthalpy of the ferrotitanium used.
After the addition of the ferrotitanium into molten steel during RH degassing process, a solid steel shell forms outside the ferrotitanium and the temperature of molten steel around the ferrotitanium changes with time. Therefore, the heat transfer coefficient between the molten steel and the ferrotitanium cannot be determined and used for numerical simulation. In consideration of this situation, the temperature distribution of molten steel in a large domain around the ferrotitanium was calculated during the numerical simulation. Flow of molten steel in RH-degasser is three-dimensional turbulent flow, which can consume a large calculation and time. Thus, the turbulent flow of molten steel was neglected and effective thermal conductivity was defined to take account of the effect of turbulent flow on thermal conductivity of molten steel more simply. In other words, the enhancement of turbulent flow of molten steel on heat transfer was converted into the effective thermal conductivity of molten steel. In this paper, the effective thermal conductivity of molten steel in RH de-gasser was obtained based on experiment and numerical simulation of melting process of ice cube in water model. Details are as follows.

Effect of turbulent flow on thermal conductivity can be defined as turbulent thermal conductivity. Effective thermal conductivity can be calculated as sum of turbulent thermal conductivity and laminar thermal conductivity, as shown in Eq. (7).

\[ k_{\text{eff}} = k_0 + k_t \]  \hspace{1cm} (7)

Where \( k_{\text{eff}} \) is effective thermal conductivity (W·m\(^{-1}\)·K\(^{-1}\)), \( k_0 \) is laminar thermal conductivity (W·m\(^{-1}\)·K\(^{-1}\)), and \( k_t \) is turbulent thermal conductivity (W·m\(^{-1}\)·K\(^{-1}\)).

Turbulent thermal conductivity is determined by turbulent viscosity and turbulent Prandtl number, as shown in Eq. (8).

\[ \text{Pr}_t = \frac{\eta_t}{\alpha} = \frac{\mu c_p}{k_t} \]  \hspace{1cm} (8)

Where \( \text{Pr}_t \) is turbulent Prandtl number, 0.7\(^{,18} \), \( \eta_t \) is turbulent kinematic viscosity (m\(^2\)·s\(^{-1}\)), \( \alpha \) is thermal diffusion coefficient (m\(^2\)·s\(^{-1}\)), \( \mu \) is turbulent viscosity (Pa·s), \( c_p \) is specific heat (J·kg\(^{-1}\)·K\(^{-1}\)).

Turbulent viscosity can be calculated with Eq. (9).

\[ \mu_t = C_p \rho \frac{K^2}{\varepsilon} \]  \hspace{1cm} (9)

Where \( C_p \) is a constant, 0.09\(^{,18} \), \( \rho \) is density (kg·m\(^{-3}\)), \( K \) is turbulent kinetic energy (m\(^2\)·s\(^{-2}\)), \( \varepsilon \) is turbulent dissipation (m\(^2\)·s\(^{-3}\)).

Turbulent thermal conductivity of molten steel in RH de-gasser can be obtained through water model simulation, numerical simulation and the geometry similarity ratio. Melting time of ice cube after the addition into water model of RH de-gasser was measured. Numerical simulation of ice cube after the addition into water model of RH de-gasser was conducted. By trial and error, when the melting time of ice calculated in the simulation was the same as that observed from water model experiment, turbulent thermal conductivity of water in water model of RH de-gasser was obtained. The value was 7.7 W·m\(^{-1}\)·K\(^{-1}\). The turbulent thermal conductivity of molten steel in RH de-gasser was estimated as follows:

Turbulent kinetic energy and turbulent dissipation have relationship with average velocity and representative length, as shown in Eq. (10).
The thermal conductivity of molten steel is 40 W·m\(^{-1}\)·K\(^{-1}\) from Eqs. (8) and (9), \(k_t\) can be expressed as

\[
k_t = \frac{P_t}{C_p \rho \frac{K_t^2}{\varepsilon}} \quad \ldots \ldots \ldots \ldots \ldots (11)
\]

Therefore, the relationship of turbulent thermal conductivity of molten steel \(k_{\text{steel}}^m\) and turbulent thermal conductivity of water \(k_w^m\) can be expressed as Eq. (12).

\[
k_{\text{steel}}^m = \frac{\left(\frac{K_{\text{steel}}^2}{\varepsilon}\right)_m}{\left(\frac{K_{\text{water}}^2}{\varepsilon}\right)_m} = \lambda \ldots \ldots \ldots \ldots \ldots (12)
\]

Where \(\lambda\) is geometry similarity ratio. The turbulent thermal conductivity of molten steel was calculated through the Eq. (13), which was 155 W·m\(^{-1}\)·K\(^{-1}\). The laminar thermal conductivity of molten steel is 40 W·m\(^{-1}\)·K\(^{-1}\). Therefore, the effective thermal conductivity of molten steel in RH de-gasser is 195 W·m\(^{-1}\)·K\(^{-1}\).

### 3.3. Geometric Model

According to assumption 1) and 2), the melting process of ferrotitanium in molten steel can be simplified as heat transfer and melting of a spherical ferrotitanium in a large spherical volume of molten steel. In consideration of the axial symmetry, one eighth was modeled. The geometries and mesh of ferrotitanium and molten steel are shown in Fig. 4. The diameter of spherical area of molten steel calculated was 300 mm. The finite element mesh of ferrotitanium and molten steel consists of 62 583 nodes and 348 387 tetrahedral elements, which were selected based on several mesh refinements.

### 3.4. Initial Conditions and Boundary Conditions

#### 3.4.1. Initial Conditions

According to statistics of industrial RH refining process data, temperatures of ferrotitanium and molten steel were set as 50 and 1 610°C, respectively.

#### 3.4.2. Boundary Conditions

Temperature of outside of the molten steel was constant, 1 610°C.

In order to investigate the melting process of ferrotitanium with different sizes after the addition into molten steel in RH de-gasser, numerical simulations of melting process of ferrotitanium with sizes of 10, 30, 50 and 80 mm were carried out, respectively.

### 4. Results and Discussions

#### 4.1. Melting Process of Ferrotitanium with Different Sizes after the Addition into Molten Steel in RH De-gasser

Since the initial temperature of ferrotitanium is much lower than that of molten steel, the temperature of molten steel around the ferrotitanium falls down rapidly. Consequently, solid steel shell forms on the surface of the ferrotitanium. It can be seen from results of numerical simulation that firstly the solid steel shell thickens gradually until it reaches a maximum thickness. Then, the solid steel shell melts little by little.

The solid steel shell may completely melt before or after the internal ferrotitanium. Therefore, the time of ferrotitanium melting into molten steel depends on not only melting time of itself but also the melting time of the solid steel shell. Figure 5 shows a schematic of melting processes of ferrotitanium with different sizes in molten steel. In Fig. 5(a), solid steel shell would form on the surface of the ferrotitanium after the addition into molten steel, then the solid steel shell would melt completely before the internal ferrotitanium. The remaining ferrotitanium would melt completely subsequently. In Fig. 5(b), solid steel shell would form on the surface of the ferrotitanium after the addition into molten steel, then the internal ferrotitanium would melt completely before the solid steel shell. The liquid ferrotitanium would melt into molten steel at the moment when the solid steel shell melted completely. Therefore, the time of ferrotitanium melts into molten steel has a strong relationship with the formation and melting of the solid steel shell.

Figure 6 shows numerical simulation results of melting times of ferrotitanium with different sizes as well as the formation and melting of the solid steel shell around the
ferrotitanium after the addition into molten steel in RH de-gasser. In Fig. 6, \( R_0 \) is initial diameter of ferrotitanium and \( R \) is residual diameter of ferrotitanium that has not melted. It was found that the maximum thickness of solid steel shell and melting times of ferrotitanium varied with the size of ferrotitanium. When the size of ferrotitanium was 10 mm, the ferrotitanium melted completely before the formation of solid steel shell. When the size of ferrotitanium was 30 mm, the steel shell melted completely in 15 s, and the ferrotitanium melted completely in 17 s, just as the sketch in Fig. 5(a). When the size of ferrotitanium was 50 mm, the steel shell melted completely in 45 s, and the ferrotitanium melted completely in 39 s, just as the sketch in Fig. 5(b). Therefore, the size of ferrotitanium had a strong effect on the melting process. It can be seen from calculation that ferrotitanium with different sizes would have different thickness of solid steel shell around them after the addition into molten steel in RH de-gasser. And the melting times of ferrotitanium with different sizes and solid steel shell could be different.

Effect of ferrotitanium size on the melting time of ferrotitanium and the solid steel shell by calculation is shown in Fig. 7. The temperature of molten steel was 1 610°C. Obviously, the melting time of ferrotitanium and the solid steel shell increased with the increase of the size of ferrotitanium. Besides, the increasing rate of melting time of solid steel shell was larger than that of ferrotitanium. When the size of ferrotitanium was 35 mm, the ferrotitanium and the solid steel shell almost melted completely simultaneously in 20 s. When the size of ferrotitanium was larger than 35 mm, the ferrotitanium melted completely ahead of the solid steel shell. When the size of ferrotitanium was smaller than 35 mm, the solid steel shell melted completely ahead of the ferrotitanium.

4.2. Motion Trajectory of Ferrotitanium after the Addition into Molten Steel in RH De-gasser

By observation of the motion trajectories of red lumps with different densities and black ice cube after the addition into water model of RH de-gasser, it was found that the motion trajectories of the materials were different from density to density.

When the density ratio of material to water was less than 0.85, the material maintained floating on the level of water above the down nozzle of water model of RH de-gasser. When the density ratio of material to water was between 0.85 and 1.0, the trajectory of material in water model of RH de-gasser was similar to that of ice cube, which could be summarized as follows:

The ice cube flew into the down nozzle of the water model of RH de-gasser and reached a certain depth in the
water model of ladle. At the same time the ice cube melted completely gradually, as shown in Fig. 8(a).

The ice cube flew into the down nozzle of the water model of RH de-gasser and reached a certain depth in the water model of ladle. Then the ice cube floated up to the surface level of water in the ladle and stayed there until it melted completely, as shown in Fig. 8(b).

The ice cube flew into the down nozzle of the water model of RH de-gasser and reached a certain depth in the water model of ladle. Then the ice cube floated up to the bottom of the down nozzle in RH and stayed there until it melted completely, as shown in Fig. 8(c).

When the density ratio of material to water was larger than 1.0, the material sank to the water model of ladle through the down nozzle in RH de-gasser, and no longer floated up.

In consideration of the randomness of the turbulence, the addition of as many as 20 tests of ice cube into the water model of RH de-gasser were conducted. Among them, 5 tests were carried out with small ice cubes and all of the trajectories looked like that in Fig. 8(a). The other 15 tests were carried out with large ice cubes. The trajectories like Fig. 8(b) were observed in 12 tests and the trajectories like Fig. 8(c) were observed in 3 tests. Figures 9 and 10 show the real photographs of melting and motion trajectories of ice cube after the addition into RH water model corresponding to Figs. 8(b) and 8(c), respectively. In this study, the trajectories shown in Fig. 8(b) were discussed further.

The density of Fe-70%Ti ferrotitanium examined with drainage method was 5317 kg·m⁻³. The density ratio of Fe-70%Ti ferrotitanium to molten steel was 0.76. In consideration of formation of solid steel shell over the ferrotitanium after the addition into molten steel, the maximum densities of ferrotitanium with the size of 30 mm and 50 mm after the addition into molten steel were calculated based on Fig. 6. Densities were 5968 kg·m⁻³ and 6319 kg·m⁻³, respectively. Density ratios of these two maximum densities of ferrotitanium with steel shell to molten steel were 0.85 and 0.90, which are close to the density ratio of ice to water. Therefore, the relationship between the motion trajectories of ferrotitanium after being added into molten steel in RH de-gasser and that of ice cube in water model can be regarded as the same. If motion trajectory of ferrotitanium is as shown in Fig. 8(b), the ferrotitanium will float up to the interface between molten steel and slag in the ladle and loss easily due to contact and reaction with the slag there.

Ice cube with large size had a long melting time after the addition into the water model of RH de-gasser. After an
ice cube was added into the water model of RH de-gasser from the charging hole, it fell down firstly through the down nozzle due to the downflow of water in the down nozzle. When the ice cube reached a certain depth, its downward velocity gradually reduced to zero. Then the remaining ice cube moved upward under the domination of buoyancy. If the ice cube is large enough, it will have time to float up to the water level. Therefore, the large size could be the main reason that the motion trajectory of ice cube in the water model of RH de-gasser was as shown in Fig. 8(b). Because ice cube with large size had a long melting time in the water model of RH de-gasser, it had enough time to float up to the water level of ladle after going down a certain depth through the down nozzle of RH de-gasser. As for the motion of ferrotitanium after addition into molten steel in RH de-gasser, it was not easy to predict the motion of ferrotitanium particle by numerical simulation precisely because the flow of molten steel in the ladle could be turbulent and complicated. However, it is possible to infer that ferrotitanium with large size has the similar motion to some degree after the addition into molten steel in RH de-gasser.

4.3. Effect of the Size on the Yield

Titanium content in steel samples that were taken during industrial experiment were analyzed. The yields of ferrotitanium with sizes of 10–50 mm and 50–65 mm is obtained as shown in Fig. 11. The average yield of ferrotitanium with the sizes of 10–50 mm was 89.0%, and the average yield of ferrotitanium with the sizes of 50–65 mm was 85.1%. The former was 4.6 percent larger than the latter. Content of TiO$_2$ in slag samples that were made during industrial experiment were detected using X-ray fluorescence analysis, and the results are shown in Table 3. It can be seen that the content of TiO$_2$ in the ladle top-slag increased after the addition of ferrotitanium with different sizes, but the increasing rates are different. The increasing rate in the case of ferrotitanium with sizes of 50–65 mm is larger than that in the case of ferrotitanium with sizes of 10–50 mm. It can be deduced that this was because the ferrotitanium with sizes of 50–65 mm had the higher probability of floating up to the interface of molten steel and slag in the ladle, and then being oxidized by the ladle top-slag. Consequently, the content of TiO$_2$ in ladle top-slag after addition of ferrotitanium with sizes of 50–65 mm were higher.

These results were similar to the results of water model experiment and numerical simulation. Namely, if size of ferrotitanium was larger than a critical size, it would be more likely to float up to the interface of molten steel and slag in the ladle before melting completely. Consequently, the ferrotitanium will be oxidized by the slag in the ladle and have a low yield. The estimation of critical size was described later.

4.4. Control of the Size of Ferrotitanium

It can be deduced from the above analysis that control of the size of ferrotitanium is the key point for improving the yield of ferrotitanium. Therefore, in order to improve the yield of ferrotitanium, the size of ferrotitanium should be no...
larger than a critical size. The critical size can be obtained through water model experiment and the similarity ratio.

During the water model experiment, the flowing trajectories and melting times of ice cubes with different sizes were measured. As for the motion trajectory of ice cube shown in Fig. 8(b), the times for ice cube to float up to the ladle water level were about 13–20 s. The times for ferrotitanium to float up to the interface of molten steel and slag in the ladle were calculated based on the similarity ratio, which were about 32–49 s. According to the numerical simulation results of melting of ferrotitanium in molten steel, the sizes range of ferrotitanium that was corresponded to the melting time of 32–49 s were 43–52 mm when temperature of molten steel was 1 610°C. Therefore, it can be deduced that for a 300 tons RH de-gasser if the size of ferrotitanium is larger than 43 mm, the ferrotitanium will have a higher probability of floating up to the interface of molten steel and slag in the ladle and then being oxidized there. Obviously, this phenomenon can decrease yield of ferrotitanium.

5. Conclusion

Motion behavior and melting process of ferrotitanium after the addition into molten steel in RH de-gasser were investigated through numerical simulation and water model experiment. Loss mechanism of ferrotitanium after the addition into molten steel during RH refining was dug out, and industrial experiment was carried out to verify the mechanism.

(1) Solid steel shell formed on the surface of ferrotitanium after the addition into molten steel, and the ferrotitanium could not be dissolved until the steel shell melted completely.

(2) The maximum thickness of solid steel shell and melting times of ferrotitanium varied with size of ferrotitanium. When the size of ferrotitanium was 30 mm, the steel shell melted completely in 15 s, and the ferrotitanium melted completely in 17 s. When the size of ferrotitanium was 50 mm, the steel shell melted completely in 45 s, and the ferrotitanium melted completely in 39 s.

(3) After the addition of ferrotitanium into molten steel in RH de-gasser, it firstly fell down a certain depth of ladle through the down nozzle of RH de-gasser. Then, ferrotitanium with large size was more likely to float up to the interface of molten steel and slag in the ladle before melting completely and be oxidized there.

(4) Ferrotitanium should not be larger than a critical size in order to ensure a high yield. As for a 300 tons RH de-gasser, if the size of Fe-70%Ti alloy was larger than 43 mm, it would have a low yield because of oxidation by the ladle slag.

REFERENCES

1) S. Lee, S. Jung, H. Lee and C. Rhee: ISIJ Int., 42 (2002), 679.
2) Z. Deng and M. Zhu: ISIJ Int., 54 (2014), 1498.
3) M. Z. Tolymbekov, A. B. Akhmetov, S. O. Baisanov, E. A. Ogurtsov and D. M. Zhiembaeva: Steel Transl., 39 (2009), 416.
4) C. J. Rick and M. Engholm: J. South. Afr. Inst. Min. Metall., 110 (2010), 759.
5) V. Vishnuh, S. Sudhakar, K. Tamilarasu, P. Prabhakaran and R. Rajasekar: Arch. Metall. Mater., 62 (2017), 1889.
6) Y. Li, Z. H. Jiang, M. F. Jiang, J. W. Wang and W. B. Gu: J. Iron Steel Res. Int., 10 (2003), 13.
7) S. B. Lee, J. H. Choi, S. M. Jung, H. L. Lee and P. Rhee: Metall. Mater. Trans. B, 36 (2005), 414.
8) M. Van Ende, M. Guo, J. Proost, B. Blanpain and P. Wollants: ISIJ Int., 50 (2010), 1552.
9) O. S. Bobkova and V. V. Barsegyan: Metallurgist, 50 (2006), 463.
10) O. K. Tokovoi, V. I. Khyakkinen, A. I. Zorin and V. V. Obrezkov: Metallurgist, 59 (2015), 44.
11) O. I. Nokhrina, V. P. Komshukov and V. I. Dmitrienko: Metallurgist, 48 (2004), 264.
12) H. Gaye, D. Huin and P. V. Riboud: Metall. Mater. Trans. B, 31 (2000), 905.
13) H. Ono-Nakazato, K. Taguchi, R. Maruo and T. Usui: ISIJ Int., 47 (2007), 365.
14) A. N. Conejo and D. E. Hernandez: Mater. Manuf. Process., 21 (2006), 796.
15) O. D. Brovko, Y. A. Bublikov, I. V. Mezhebovskii, S. N. Podgorny, G. A. Polyakov, A. S. Popov, A. V. Rabinovich and Y. V. Sadovnik: Russ. Metall., 2013 (2013), 952.
16) X. Ai, Y. Bao, W. Jiang, J. Liu, P. Li and T. Li: Int. J. Miner. Metall. Mater., 17 (2010), 17.
17) J. Wei and H. Hu: Steel Res. Int., 77 (2006), 32.
18) H. Sun and J. Zhang: ISIJ Int., 51 (2011), 1657.