Removal of Fine SiO₂ Composite Inclusions from 304 Stainless Steel Using Super-gravity

Lei GUO, Jintao GAO,* Chong LI and Zhancheng GUO

State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Xueyuan Road No. 30, Haidian District, Beijing, 100083 China.

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The super-gravity technique was used to remove the SiO₂ composite inclusions from 304 stainless steel. The effects of different super-gravity coefficients and super-gravity treatment time on the removal effect of inclusions were studied. It was found that the SiO₂-based composite inclusions floated up to the top of the sample after the super-gravity treatment, and the inclusions in the lower part of the sample were largely removed. The volume fraction and number density of inclusions presented a gradient distribution along the direction of the super-gravity, which became steeper with increasing gravity coefficient and treatment time. The total oxygen content at the bottom of the sample was reduced from 150 ppm to 93 ppm within 15 min of super-gravity treatment under the gravity coefficient of $G = 80$.

KEY WORDS: super-gravity; hige; inclusion; 304; stainless steel.

1. Introduction

The formation of nonmetallic inclusions is unavoidable in the steelmaking process.^{1,2)} Their existence destroys the uniform continuity of the steel matrix and has adverse effects on the mechanical properties and process properties of the steel.³⁾ Therefore, people have been researching and developing technology for the cleanliness of steel and the removal of inclusions. However, due to the details of the actual steelmaking operation and the influence of the removal kinetics of the product, some conventional removal methods such as electromagnetic stirring,⁴⁻⁷⁾ gas agitation,^{8,9)} slag washing,^{10,11)} filtration,^{12,13)} *et al.* are difficult to achieve ultimate removal for those nonmetallic inclusions in very small size and uniformly distributed. So some new purification methods need to be developed to remove the nonmetallic inclusions in steel more thoroughly.

The Hige technology,¹⁴⁻¹⁸⁾ or the so-called super-gravity technology, carried out in a rotating packed bed is a novel technology for process intensification. In the super-gravity field, the molecular diffusion and phase-to-phase mass transfer between molecules of different sizes are much faster than those under the normal gravity field. The gas-liquid, liquid-liquid, and liquid-solid phases can achieve rapid mobile contact in porous media or channels in the super-gravity field which is hundreds of times larger than the Earth's gravity field. Large shear forces and rapidly renewed phase interfaces, resulting in an increase in the phase-to-phase mass transfer rate of 1 to 3 orders of mag-

nitude compared to the conventional tower reactors.¹⁹⁾ The microscopic mixing, mass transfer and chemical reaction processes will be greatly enhanced, which helps to achieve the goals of energy conservation, consumption reduction, environmental protection, and process intensification. Super-gravity technology is one of the key technologies in process enhancement technology which has attracted people's attention.

The low temperature (below 473 K) super-gravity technology started earlier and has been able to be applied in many chemical fields.¹⁹⁻²²⁾ However, high temperature (above 673 K) super-gravity technology is difficult to study due to harsh conditions and is currently only used in limited fields such as centrifugal casting²³⁻²⁵⁾ or fabrication of functionally graded materials.²⁶⁻²⁸⁾ In recent years, our research group has carried out extensive research on the application of high temperature super-gravity technology in the field of high temperature metallurgy, including the efficient separation of valuable components in metallurgical slag,²⁹⁻³²⁾ the purification of metallurgy grade silicon for solar grade silicon,^{33,34)} the removal of inclusions from metal aluminum,³⁵⁻³⁷⁾ and the stepwise extraction of multiple metals in electronic waste *et al.*³⁸⁻⁴⁰⁾ The use of super-gravity technology to remove inclusions in steel requires a temperature of 1 873 K, which places high demands on the experimental setup. Our research group has realized the long-time super-gravity operation under high-temperature conditions by using microwave heating. C. Li *et al.*⁴¹⁾ studied the separation of fine Al₂O₃ inclusions from Al-deoxidized steel with super-gravity. It was found that up to 95.6% of the total oxygen content at the bottom of the sample (position of 5 cm) can be removed under the condition of gravity coef-

* Corresponding author: E-mail: jintao.gao@ustb.edu.cn
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ficient $G = 80$, and treatment time $t = 15$ minutes.

The 304 stainless steel is a kind of austenitic stainless steel which has good corrosion resistance and weldability, and good performance in hot and cold processing.⁴²⁾ It is extensively used in different fields like chemical engineering, construction, petroleum industry, decoration and so on. However, the presence of non-metallic inclusions seriously destroys the continuity of the stainless steel metal matrix, which not only has a great impact on the mechanical properties and corrosion resistance of the stainless steel but also causes great damage to the surface quality of the product.

Considering the difference in density between SiO_2 composite inclusions and 304 stainless steel, the super-gravity technology is introduced for the removal of SiO_2 composite inclusions in 304 stainless steel, expecting that the inclusions in 304 stainless steel can be reduced to the minimum value.

2. Experimental

2.1. Experimental Materials and Equipment

The steel used in the experiment is a 304 stainless steel product. The main chemical composition is shown in supplementary **Table 1**, and the oxygen content is as high as 190 ppm, indicating that there are a large number of oxide inclusions in the steel. After the steel sample was coarsely ground and polished, the morphology and distribution of the inclusions were observed under an electron microscope. As shown in **Figs. 1(a)–1(d)**, a large number of inclusions with rounded or irregular shapes were uniformly distributed in the steel, and the size was almost between $0.5\text{--}5\text{ }\mu\text{m}$. According to the energy dispersive spectrometer (EDS) analysis in **Fig. 1(e)**, the inclusion type is MnS, SiO_2 , MnO composite inclusion.

Table 1. The chemical composition of 304 stainless steel (mass%).

Cr	Ni	N	O
17.801	8.350	0.067	0.019

The equipment used in the experiment is a high-temperature rotary crucible super-gravity device which is heated by microwave energy. The diagram is shown in **Fig. 2**. It utilizes the advantages of enhanced mass transfer and enhanced phase separation generated by the super-gravity field and attempts to enrich the SiO_2 composite inclusions at one end of the sample. Then the steel is purified. The levels of centrifugal force are characterized by gravity coefficient which can be expressed as $G = \omega^2 R/g$. Where ω is the mold rotation rate ($\text{rad}\cdot\text{s}^{-1}$), R is the distance of samples from the axis (m), and g is the acceleration rate due to gravity ($\text{m}\cdot\text{s}^{-2}$). The inner and outer diameter of the crucible is 24 mm and 28 mm respectively. It should be noted that the centrifugal force will change with the position along the longitudinal direction of the sample. However, this variation of centrifugal force is ignored in the modeling work as the height of the samples was small. As the weights of the sample part and the counter part on the rotary arms were balanced very carefully in every trial, the rotating state was

Fig. 2. Schematic diagram of the super-gravity apparatus at working state: (1) centrifugal axis; (2) microwave generator; (3) temperature controlling system; (4) thermal couple; (5) protective cavity; (6) refractory mold with microwave absorbing material inside; (7) alumina crucible; (8) floating nonmetallic inclusions in molten liquid metal; (9) inclusions after super gravity treatment. (Online version in color.)

Fig. 1. Characterization of the inclusions in 304 stainless steel: (a) macro view, (b–d) individual inclusions, (e) EDS mapping of a typical inclusion. (Online version in color.)

kept very steady without any intense vibration. We think that when the rotating speed comes to the target value the liquid samples can be considered only in the super-gravity field and the convection in the molten metal can be ignored.

2.2. Sample Analysis and Testing

One of the two samples obtained by super-gravity was used to determine the distribution of the total oxygen content, and the sampling sites are shown in Fig. 3(b). The other sample was cut from the middle along the direction of super-gravity, and after grinding and polishing, the macroscopic photograph was taken by a digital camera for macroscopic characterization inside the steel sample. The distribution of inclusions at different locations was observed from the other half of the sample by scanning electron microscopy (SEM). The type of inclusions was analyzed by an energy dispersive spectrometer, and the inclusion size, number density and area fraction were statistically analyzed using the automatic inclusion analysis system (EVO-18INCOsteel).

3. Results and Discussion

3.1. Effect of Super-gravity Treatment Time

A 260 g 304 stainless steel was divided equally into two parts and placed inside two alumina crucibles. The alumina crucibles were then placed inside two protective graphite crucibles. The two samples were placed symmetrically in the thermal insulation material and then heated to 1 853 K under an argon gas environment. Temperature was held until the steel samples melted and then the centrifugal equipment was turned on immediately at a rotation speed of 800 rpm ($G = 80$). Then the influence of different treatment time

on the inclusions in the steel under the same gravity coefficient was investigated. The specific experimental scheme is shown in supplementary Table 2.

Figure 3 shows the macroscopic cross-sectional view of the samples after removal of SiO_2 composite inclusions in 304 stainless steel at different processing times for a gravity coefficient of $G = 80$. As shown in Fig. 3(a), there is no significant change in the profile of the steel sample under the gravity of $G = 80$ for 0 min (without super gravity treatment). But the upper part (>26 mm from the bottom) of the steel sample after 15 min of treatment under super-gravity ($G = 80$) shows significant defects as shown in Figs. 3(b)–3(c). It shows that a large number of holes are concentrated on the top, while the lower part (<26 mm) is smooth without any holes.

In order to further study the removal of SiO_2 composite inclusions, the microstructures were observed at four locations equidistant in the direction of super-gravity (Fig. 3(b)). The distribution of inclusions is shown in Figs. 3(A)–3(D) and 3(A')–3(D'). It can be seen from Figs. 3(A)–3(D) that the SiO_2 composite inclusions at different positions of the sample without super-gravity treatment are evenly distributed without any obvious segregation. After treatment for

Table 2. Experimental scheme with different treatment time.

No.	Gravity coefficient /G	Time/min	Temperature/K	Flow rate/L·min ⁻¹
(1)	80	0	1 853	1.5
(2)	80	1	1 853	1.5
(3)	80	5	1 853	1.5
(4)	80	15	1 853	1.5

Fig. 3. The morphology of (a) macroscopic cross-section without super gravity treatment; (b) macroscopic cross-section after 15 min of super-gravity treatment; (c) partial enlarged view of the top area after 15 min of super-gravity treatment; (A,B,C,D) different positions of samples without super gravity treatment; (A',B',C',D') different positions of samples after 15 min of super-gravity treatment. (Online version in color.)

15 min under super-gravity of $G = 80$, the number of SiO_2 composite inclusions at different positions of the steel sample was significantly reduced. The sizes of these inclusions were larger than inclusions formed without super-gravity treatment. Many large inclusions were segregated in the uppermost defect position (with many holes) of the steel sample. According to the EDS analysis shown in **Fig. 4**, the large inclusions are SiO_2 composite inclusions.

Although there is a density difference between the SiO_2 composite inclusions and the molten steel, due to various reasons such as viscosity and wettability, the inclusions cannot be removed in a short time under the normal gravity field. Therefore, these inclusions are evenly distributed in the steel. However, when a super-gravity field is applied, the super-gravity accelerates the floating speed of these inclusions and the removal step can be completed in a short time. The wettability is determined by the intermolecular forces between contacting solid and liquid phases and is dominant for the spreading ability of a liquid phase on the surface of a solid phase. In this research, the wettability of the liquid steel on the surface of inclusion particles will influence the adhesive force and the relative motion resistance between them, which will affect the separating process of the inclusions.

Inclusions of different sizes have different moving speeds, which causes the inclusions to collide and grow during the floating process. When the inclusions float up to the surface of the molten steel, they aggregate into larger inclusions. The MnS inclusions have a lower melting point. When the temperature is 1 873 K, they have already dissolved into the molten steel. Therefore, the super-gravity has no removal effect on Sulfur. As chromium oxide is formed by oxidation and it floats to the surface under the effect of super-gravity, Cr element appears in the inclusions.

In order to study the removal effect of SiO_2 composite inclusions in 304 stainless steel by super-gravity, the volume fraction and number density of inclusions were measured by the inclusion automatic scanning system every 1 cm along the direction of super-gravity. The results are shown in **Figs. 5(a), 5(b)**. It can be seen from the figure

that under normal gravity, the SiO_2 composite inclusions are evenly distributed, and there is no obvious gradient change in the inclusion volume fraction and the number density at each position of the sample. The average values of volume fraction and number density are about 0.4% and $1\,600\text{ mm}^{-2}$ respectively. When it is subjected to the super-gravity of $G = 80$, the volume fraction and the number density of inclusions in the sample show a significant gradient distribution, and the volume fraction and the number density of inclusions at the positions of 1 mm, 10 mm and 20 mm are significantly reduced compared with that with normal gravity. A large number of inclusions accumulate at the upper part after super gravity treatment with the maximum values of volume fraction and the number density occurring at the positions of 30 mm (upper part). However, due to the agglomeration and segregation of inclusions in the upper part, the total number is reduced. So the number density at the upper part (ex. 30 mm) is less than the corresponding value under normal gravity. With the gravity coefficient $G = 80$, $t = 15$ min, the volume fraction and the number density are about 5% and 120 mm^{-2} at the upper part (30 mm) in the sample, and the volume fraction in the lower part is close to 0.1%. The number density is close to 50 mm^{-2} and the slope of the curve decreases as the decrease of processing time.

Figure 5(c) shows the average size distribution of inclusions at different positions of the sample with different treatment times under the gravity coefficient of $G = 80$. It can be seen from the figure that under constant gravity, the size of SiO_2 composite inclusions does not change much along the normal gravity direction, reaching an average of $2\text{ }\mu\text{m}$. However, after super gravity treatment, the inclusion size is generally larger than that of normal gravity and displays a gradient distribution along the direction of gravity. The size of the inclusions at the upper part of the sample is significantly larger than that at the lower part, and longer treatment time corresponding to more obvious gradient distribution.

This result is also in accordance with the Stokes formula:

$$v = \frac{(\rho_L - \rho_P)d^2Gg}{18\eta} \dots\dots\dots (1)$$

Fig. 4. The EDS mapping of a large inclusion in uppermost part as shown in Fig. 3(D'). (Online version in color.)

Where v : the velocity of non-metallic inclusions in the direction of super-gravity ($\text{m}\cdot\text{s}^{-1}$); η : the viscosity of liquid steel ($\text{Pa}\cdot\text{s}$); d : the diameter of inclusions (m); G : the super-gravity coefficient (dimensionless); g : the acceleration rate due to gravity ($\text{m}\cdot\text{s}^{-2}$); ρ_L : the density of liquid steel ($\text{kg}\cdot\text{m}^{-3}$); ρ_P : the density of inclusions ($\text{kg}\cdot\text{m}^{-3}$). Due to the density difference between the SiO_2 composite inclusions and the molten steel, the SiO_2 composite inclusions migrate to the end of the sample under super-gravity. However, as shown by the Stokes formula, the migration rate of solid particles in the melt is proportional to the square of its diameter. The large inclusion particles move faster than small ones, they will collide and grow during migration, resulting in an increase of the average size of inclusions in the sample after the super-gravity treatment. As a large number of inclusions continue to migrate upward, the upper inclusions become larger and larger to form a gradient distribution of the size of the inclusions.

Figure 5(d) shows the analysis of total oxygen content at different positions of the samples treated under super-gravity of $G = 80$ with different processing time. Under normal gravity, the oxygen content at different positions in the sample is evenly distributed, and the average value is about 160 ppm. However, after the super-gravity treatment, the oxygen content in the middle and lower parts of the sample is significantly reduced, and the oxygen content in the upper part of the sample increases sharply. The total oxygen content forms a gradient along the direction of super-gravity, and as the processing time increases, the slope of the gradient distribution becomes larger. The reason is that the super-gravity plays a purifying role in this pro-

cess, and a large number of oxide inclusions float up to the upper part of the sample under the effect of super-gravity. According to the Stokes formula, the longer the treatment time is, the longer the migration distance of the inclusions is, thus the gradient distribution of oxygen content exists.

Table 3 shows the total oxygen content and removal rate at 5 mm from the bottom of the sample with different treatment time under the gravity coefficient of $G = 80$. The total oxygen removal rate was calculated with this equation:

$$R_r = \frac{\text{TO}_0 - \text{TO}_1}{\text{TO}_0} \times 100\% \quad (2)$$

where R_r is the removal rate (%), TO_0 is the total oxygen in the as-received material (mass%), TO_1 is the total oxygen in the samples after super gravity treatment (mass%). It can be seen from the supplementary Table 3 that after 15 min treatment under this gravity coefficient, the oxygen content was reduced from the original 150 ppm to 93 ppm at the lower part 5 mm from the bottom of the sample. And the removal rate reached 38%, indicating that the removal of

Table 3. Total oxygen content and removal rate at 5 mm from the bottom of the samples with different treatment time.

Treatment time/min	Total oxygen/ppm	Removal rate/%
0	150	—
1	98	34.7
5	96.5	35.7
15	93	38

Fig. 5. The (a) volume fraction (b) number density (c) average size of inclusions (d) total oxygen at different positions of the samples. (Online version in color.)

oxidized inclusions was significant. At the same time, the removal rate increases with the treatment time, showing a gradient distribution.

3.2. Effect of Super-gravity Coefficient

The experimental procedure was the same with section 3.1 except that the gravity coefficient was changed and the treatment time was fixed at 1 min. The specific experimental scheme is shown in supplementary **Table 4**.

Figures 6(a), 6(b) is the macroscopic cross-sectional view of the parallel sample obtained after 1 min of treatment under normal gravity and super-gravity of $G = 80$. The sample obtained under normal gravity is uniform and free of defects. After the super-gravity treatment, obvi-

Table 4. The experimental scheme of different gravity coefficients and same treatment time.

No.	Gravity coefficient /G	Time/min	Temperature/K	Gas flow rate/L·min ⁻¹
(1)	1	1	1 853	1.5
(2)	20	1	1 853	1.5
(3)	45	1	1 853	1.5
(4)	80	1	1 853	1.5

Fig. 6. The morphology of (a) macroscopic cross-section without super gravity treatment; (b) macroscopic cross-section after 1 min of super-gravity treatment ($G = 80$); (ABCD) different positions of samples after 1 min of super-gravity treatment ($G = 80$).

ous defects appeared in the upper part of the sample. In order to analyze the cause of defects and the distribution of inclusions after super gravity treatment, microscopic analysis was performed at different positions along the direction of super-gravity. The distribution of inclusions at different positions under normal gravity is the same as what is shown in Figs. 3(A)–3(D). It can be seen that the inclusions are uniformly distributed under normal gravity, and there is no obvious enrichment along the normal gravity direction. After the super-gravity treatment, as shown in Figs. 6(A)–6(D), the amount of inclusions in the lower part of the sample is significantly reduced, and a large amount of inclusions is concentrated in the uppermost part of the sample, and the size of inclusions is significantly increased due to collisions. The metal in the upper part with lots of inclusions does not solidify tightly and form void defects.

Figures 7(a), 7(b) shows the volume fraction and number density of SiO_2 composite inclusions at different positions along the super-gravity direction under different super gravity coefficients with the same processing time. It can be seen from the figure that under the normal gravity, the volume fraction and the number density of SiO_2 composite inclusions at various positions of the sample are uniformly distributed, and there is no obvious gradient distribution. As the super-gravity coefficient increases, the volume fraction and the number density of SiO_2 composite inclusions show gradient distribution in the direction of super-gravity. The volume fraction and the number density at the upper portion of the sample are larger than the values at the lower portion, and the slope becomes larger as the super-gravity coefficient increases.

Figure 7(c) shows the average size distribution of inclusions at different positions of the sample under different super gravity coefficients for 1 min. It can be seen from the figure that the average size of inclusions in the sample after super gravity treatment shows gradient distribution obviously along the direction of super-gravity. The average size of the inclusions in the upper part of the sample is significantly larger than the lower part of the sample, and the gradient distribution is more obvious as the gravity coefficient increases. At the same time, the inclusions after the super-gravity treatment are larger than the inclusions in the steel which have not been subjected to the super-gravity treatment, because the inclusions collide and aggregate due to their different migration speeds when moving up to the upper part.

Figure 7(d) shows the analysis of total oxygen content at different positions of the sample after 1 min of treatment under different gravity coefficients. Under the normal gravity, the oxygen content in different positions of the sample is evenly distributed, and the average value is about 160 ppm. In the sample subjected to super-gravity treatment, the oxygen content shows a growing trend from the lower part to the upper part, and the slope of the gradient increases with the increase of gravity coefficient. The reason is that the oxidized inclusions migrate to the upper part under the effect of super-gravity.

The oxygen content and removal rate at the position of 5 mm (from the bottom of the sample) after the super-gravity treatment are shown in supplementary **Table 5**. The oxygen content decreases with the increase of the gravity coef-

Fig. 7. The (a) volume fraction (b) number density (c) average size of inclusions (d) total oxygen at different positions of the samples. (Online version in color.)

Table 5. Total oxygen content and removal rate at 5 mm from the bottom of the samples with different gravity coefficients.

Gravity coefficient/G	Total oxygen/ppm	Removal rate/%
1	150	—
20	115	23.3
45	102	32
80	98	34.7

efficient, and the removal rate is correspondingly increased. When the gravity coefficient is $G = 80$, processing time is $t = 1$ min, the removal rate is 34.7%, indicating that the super-gravity has a certain effect on the removal of SiO_2 composite inclusions in 304 stainless steel.

3.3. Discussion

To consider the molten steel as a viscous liquid and the inclusions as hard spherical particles, then the motion behavior of the inclusions can be simulated with the law of Stokes. During super-gravity treatment, there are two significant forces act on each particle: the centrifugal force and a viscous drag force in the opposite direction. The balance between these two forces can be expressed as:^{43,44)}

$$m_p \frac{d^2x}{dt^2} = |\rho_p - \rho_m| \frac{4}{3} \pi \left(\frac{D_p}{2} \right)^3 Gg - 3\pi\eta D_p \frac{dx}{dt} \quad \text{..... (3)}$$

where dx/dt is the moving velocity ($\text{m}\cdot\text{s}^{-1}$), d^2x/dt^2 is the acceleration speed ($\text{m}\cdot\text{s}^{-2}$), ρ_p is the density of inclusion particles ($2600 \text{ kg}\cdot\text{m}^{-3}$), ρ_m is the density of molten metal ($7100 \text{ kg}\cdot\text{m}^{-3}$), D_p is the diameter of inclusions (m), G is

the super-gravity coefficient (dimensionless), g is the acceleration rate due to gravity ($9.8 \text{ m}\cdot\text{s}^{-2}$), η is the viscosity of liquid steel ($0.005 \text{ Pa}\cdot\text{s}$). The left term of Eq. (3) represents the buoyant force. The first term on the right side is the centrifugal force and the second on the right side is the viscous drag force. The moving direction of the particles is determined by the relative values of densities. In this study: $\rho_p < \rho_m$, so the particles move toward the opposite direction of the centrifugal force, and vice versa. The terms ρ_p , ρ_m , η and D_p in Eq. (3) are assumed to be time-independent, then Eq. (3) can be solved under the initial condition of $dx/dt = 0$ at $t = 0$. The solution is:

$$\frac{dx}{dt} = -\frac{|\rho_p - \rho_m| Gg D_p^2}{18\eta} = -\frac{\Delta\rho D_p^2 \omega^2 x}{18\eta} \quad \text{..... (4)}$$

where ω is the rotation rate ($\text{rad}\cdot\text{s}^{-1}$) and x is the distance of the particles from the centrifugal axis (m). As the moving direction of the inclusions is opposite to the centrifugal direction, a negative sign is added in Eq. (4). It shows that the moving velocity of the inclusion particles is proportional to the difference in density between inclusion particles and molten metal, to super-gravity coefficient and to the square of the particle diameter, and it is inversely proportional to the viscosity of the molten metal. It should be noted that the viscosity of the melt will increase with the increase in the number of particles in the melt, which can be expressed as:⁴⁵⁾

$$\eta = \frac{\eta_0}{\left(1 - \frac{V}{V_{\max}}\right)^{2.5}} \quad \text{..... (5)}$$

Where η_0 is the viscosity of the molten metal without particles, V is the particle volume fraction and $V_{\max}$ is the maximum packing fraction. Due to the tiny particle volume in the 304 stainless steel melt, the change of viscosity caused by inclusions is ignored in this study.

Assuming that ω is a constant, then the solution of Eq. (4) can be expressed as:

$$x = -ce^{\int \frac{\Delta \rho D_p^2 \omega^2}{18\eta} dt} = -ce^{\frac{\Delta \rho D_p^2 \omega^2}{18\eta} t} \dots \dots \dots (6)$$

Supposing that when $t = 0$, $x = x_0$, then $c = x_0$ and Eq. (6) is converted into:

$$x = -x_0 e^{\frac{\Delta \rho D_p^2 \omega^2}{18\eta} t} \dots \dots \dots (7)$$

then:

$$t = \frac{18\eta}{\Delta \rho D_p^2 \omega^2} \ln \frac{x_0}{x} = \frac{16\ 200\eta}{\Delta \rho D_p^2 \pi^2 N^2} \ln \frac{x_0}{x} \dots \dots \dots (8)$$

where N is the rotation speed ($\text{r} \cdot \text{min}^{-1}$). At initial state $x_0 = 0.11$ m, the particles move to the top of the sample $x = 0.08$ m. For the initial state, when $G = 20$, $N = 400$ $\text{r} \cdot \text{min}^{-1}$; $G = 45$, $N = 600$ $\text{r} \cdot \text{min}^{-1}$; $G = 80$, $N = 800$ $\text{r} \cdot \text{min}^{-1}$. Then the time for a particle of the diameter of D_p to move from the bottom to the top of the sample is: $t = 3.6 \times 10^{-9} \times D_p^{-2}$ ($G = 20$); $t = 1.6 \times 10^{-9} \times D_p^{-2}$ ($G = 45$); $t = 9.1 \times 10^{-10} \times D_p^{-2}$ ($G = 80$). Therefore, the required time for the SiO_2 composite inclusions with different sizes moving from the bottom to the top of the sample (3 cm) under gravity coefficients of $G = 20$, $G = 45$ and $G = 80$ is calculated by Eq. (8), and the results are shown in Fig. 8. The theoretical value of the floating time of the inclusions having a diameter of about $3\ \mu\text{m}$ is close to the actual value. For inclusions less than $1\ \mu\text{m}$ in diameter, it is difficult to achieve effective removal in a short time within the range of gravity coefficients used in this experiment ($G \leq 80$). There is a critical diameter value for the inclusions to move from the bottom to the top under a certain super-gravity coefficient and treating time. Thus, those inclusion particles above the critical diameter will quickly move to the top part and the left ones under the critical diameter will move very slowly, causing the little diameter gradient for the bottom part to the near top part of the sample.

Apparently the removal effect of the SiO_2 composite inclusions in 304 stainless steel is not as good as that of the fine Al_2O_3 inclusions in Al-deoxidized steel in terms of the total oxygen removal rate,⁴¹⁾ even though the density difference between inclusions and liquid metal for SiO_2 composite inclusions ($4\ 500\ \text{kg} \cdot \text{m}^{-3}$) is larger compared to that of the Al_2O_3 inclusions ($3\ 130\ \text{kg} \cdot \text{m}^{-3}$) and there is no big difference between their sizes. Moreover, according to the mathematical model, theoretically those inclusion particles above $3\ \mu\text{m}$ can complete the floating process (Fig. 8), whereas the critical diameter is a little larger in this study. Thus, we think there should be some other factors influencing the floating behavior of the inclusions which are not involved in the mathematical model established in this study. The most relevant factors as far as we know are the interface characteristic (such as wettability) and the shape of inclusions, which will affect the resistance force between inclusion particles and liquid metal besides the viscosity of

Fig. 8. The required time for the total floating procedure of inclusions with different diameters. (Online version in color.)

liquid metal.

4. Conclusions

In this paper, the research on the removal of SiO_2 composite inclusions within 304 stainless steel using super-gravity method was carried out, and the following main conclusions are drawn:

(1) The SiO_2 composite inclusions migrate to the upper part of the sample along the direction of super-gravity under super-gravity treatment, and the inclusions are obviously segregated and grown in the upper part; the inclusions are rare in the lower part, but the size of them becomes larger due to the collision during the migration process under super-gravity treatment. Since the MnS inclusions are dissolved in the molten steel at a high temperature, the super-gravity does not have a separation effect on them.

(2) The statistical analysis shows that the volume fraction, the number density and the average size of the SiO_2 composite inclusions exhibit a gradient distribution along the direction of super-gravity, and the slope of the gradient increases with the increase of the super-gravity coefficient and the treatment time. However, due to the accumulation of a large number of inclusions, the number density after the super-gravity treatment is smaller than that without super-gravity treatment. Under the super-gravity of $G = 80$, and treatment time of $t = 15$ min, the total oxygen content of the lower part of the sample is 93 ppm, and the removal rate is as high as 38%, indicating that the super-gravity has certain effects on the removal of SiO_2 composite inclusions in 304 stainless steel.

(3) The theoretical value of the floating time of the inclusions whose diameter is about $3\ \mu\text{m}$ is close to the actual value. For inclusions less than $1\ \mu\text{m}$ in diameter, it is difficult to achieve effective removal in a short time within the range of gravity coefficients used in this experiment ($G \leq 80$).

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