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Aggregation Kinetics of Inclusions in Swirling Flow Tundish for Continuous Casting

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Abstract: The mechanism of inclusion aggregation in liquid steel in swirling flow tundish is analyzed by applying the theory of flocculation which was developed in the field of colloid engineering. The gas bridge forces due to the micro bubbles on hydrophobic inclusion surfaces were responsible for the inclusion collision and agglomeration, which can avoid the aggregation to breakup. The quantity of micro bubbles on hydrophobic inclusion particle is more than that on hydrophilic one. The trend of forming gas bridges between micro bubbles on particles is strong in the course of collision. The liquid film on hydrophobic particles is easy to break during collision process. Hydrophobic particles are liable to aggregate in collision. According to the analysis of forces on a nonmetallic inclusion particle in swirling chamber, the chance of inclusion collision and aggregation can be improved by the centripetal force. Hydrophobic particles in water are liable to aggregate in collision. Hydrophilic particles in water are dispersed although collision happens. The wettability can be changed by changing solid-liquid interface tension. The nonmetallic inclusion removal in swirling flow tundish is studied. The result shows that under certain turbulent conditions, the particle concentration and the wettability between particles and liquid steel are the main factors to induce collision and aggregation.

Key words: collision; aggregation; wettability; inclusion; swirling chamber; continuous casting tundish

Nonmetallic inclusions generated from deoxidation treatments and other processes degrade the comprehensive mechanical property of steels. In recent decades, removal of inclusion is desired in steel industries to achieve higher cleanliness of steel products[1]. Several methods have been proposed for separating inclusion particles from liquid steel: floatation, bubbling and centrifugal separation[2]. The centrifugal flow tundish[3] (CFT) and the swirling flow tundish[4] (SFT) have been developed in recent years. For both of them, the effective means of removing inclusions is to promote collision and coalescence of the inclusion particles under centripetal force by increasing inclusion sizes and improving average residence time.

SFT is equipped with a swirling chamber (SC) to produce rotational motion of liquid steel, which can achieve similar metallurgical effects as CFT without extra electromagnetic field. Because of the introduction of the swirling chamber, the fierce turbulence in the swirling chamber can cause great dissipation of mechanical energy, and at the same time, enhance the collision and coalescence of inclusions from small particles to big ones. To clarify the agglomeration behavior, a lot of studies have been made now[1-2]. Inclusion particles in liquid steel are known to be agglomerated by collision. The enlarged particles become easy to be removed from liquid steel. Therefore, it is quite important to understand the phenomenon of aggregation in detail. Aggregation of hydrophilic particles in stirred liquid media can be considered as a relatively well-understood process in spite of the variety and complexity of its aspects[5]. Good models exist in particular for representing the physicochemical interactions between aggregates and for predicting the collision rates and their efficiency[6]. Aggregation of solid particles in non-wetting media is less known, at least on certain

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aspects. A large number of experimental works indeed have definitely proved the existence of strong long range (20−200 nm) attractive forces between hydrophobic surfaces in water[7].

In this study, the respective mechanisms of inclusion aggregation between hydrophobic particles and hydrophilic particles are analyzed. The motion of nonmetallic inclusion in swirling chamber is studied. Considering the centripetal aggregation of inclusion particles in swirling chamber, the inclusion removal of plastic particles in a swirling flow tundish has been made in a water model experiments.

1 Theoretical Analysis of Inclusion Particles Removal in Swirling Flow Tundish

1.1 Inclusion particles aggregation in liquid steel

Fig. 1 shows the two types of different configurations of gas-solid-liquid phases. Because of the different properties of hydrophobic and hydrophilic particles, the contact angle of hydrophobic solid in liquid medium is large than 90°. The contact angle of hydrophilic solid in liquid medium is small than 90°.

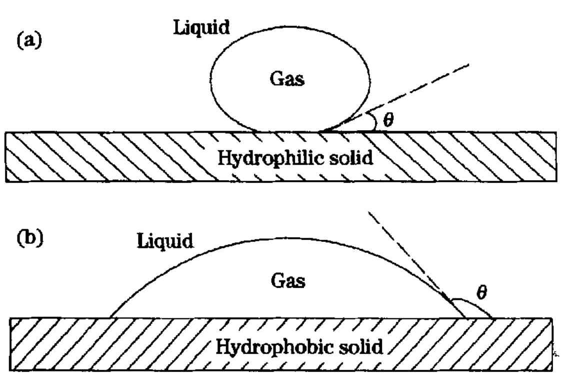

Fig. 1 Two statuses of three-phase configuration

The presence of bubbles changes the interaction between solid and liquid. For the inclusion in liquid steel system, such as alumina oxide (S), liquid steel (L) and gas (G), the respective interfacial tensions at the operating temperature of 2000 K are: $\gamma_{SG}=0.65\ J/m^2$, $\gamma_{SL}=1.96\ J/m^2$, $\gamma_{LG}=1.70\ J/m^2$[7]. Equilibrium of the contact line between the three phases gas-liquid-solid imposes the Young relation

$$\gamma_{SG}-\gamma_{SL}=\gamma_{LG}\cos\theta \qquad (1)$$

In this case, $\theta=140°$. The contact angle is greater than 90°; as expected, it is the non-wetting. As proved by several experiments and model, before two hydrophobic particles come in contact, most of their pores are full of gas or vapor which covers at least partially their external surface[7]. Solid particles are linked by gaseous bridges, which may pre-exist prior to the aggregate formation[8].

Fig. 2 shows different particle surfaces with adsorbed micro bubbles in liquid media. Because of the three-phase configuration (Fig. 1), the same size bubbles in different solid surfaces have different contact angles, and the contact area is different. The area of hydrophobic particle is larger than that of the hydrophilic one. So the attraction effect between hydrophobic particle and micro bubbles is greater than the attraction effect between hydrophilic particle and micro bubbles. The bubbles adhered in hydrophilic solid is liable to get into the liquid. The number of micro bubbles adhered on hydrophobic solid is more than that on hydrophilic solid.

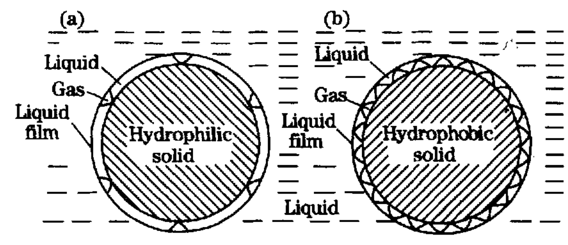

Fig. 2 Different particle surfaces adsorbed micro bubbles in liquid media

It is well known that inclusion particles in liquid media collide due to the Brownian motion, the differences in floating velocity, the turbulence of flow, and other similar factors. When two hydrophobic particles get close to collision, the micro bubbles on particle surface merge into a gas bridge between the two particles. The authors propose that the formation of such a gas bridge is the driving force leading to the rupture of liquid film covering the solid particle. ELI[9] considers there is an attraction force called Bjekness force between two bubbles pulsating in an inviscid liquid. Fig. 3 shows the formation of gas bridges and rupture of liquid film between solid surfaces coated with micro bubbles. Fig. 3 (a) shows that two hydrophobic particles with micro bubbles on their surfaces get close to collision. Fig. 3 (b) shows the attraction capillary force caused by forming and growing of gas bridges. Fig. 3 (c) shows the rupture of liquid film and particles aggregation. The presence of gas bridges between the particles strengthens the stability of aggregates.

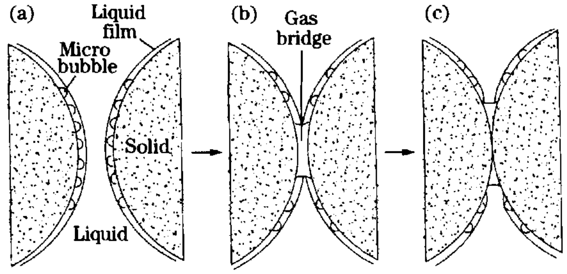

Fig. 3 Formation of gas bridge and rupture of liquid film between solid surfaces coated with micro bubbles

1.2 Analyses of nonmetallic inclusion separation

In the swirling flow tundish, the improvement on inclusion separation and removal can be expected from two parts mainly: 1) inclusions concentrate into the center of the swirling chamber under the centripetal force and then collide and aggregate into bigger ones; 2) inclusions float up onto the metal/slag interface in the very slow velocity field behind the dam and weir.

Because of the density of inclusion (3700 kg/m^3) is smaller than that of molten steel (7100 kg/m^3), the inclusions in the swirling chamber will concentrate into the center area under the centripetal force. The forces on a particle in the swirling flow chamber are shown in Fig. 4. Since the three-dimensional turbulence flow is very complicate in the swirling chamber, the forces acting on inclusion particles are hard to calculate precisely. Here, for simplification, only a simple model for this phenomenon is given. The force balance in radial direction is given by the following equation where the movement of the particle

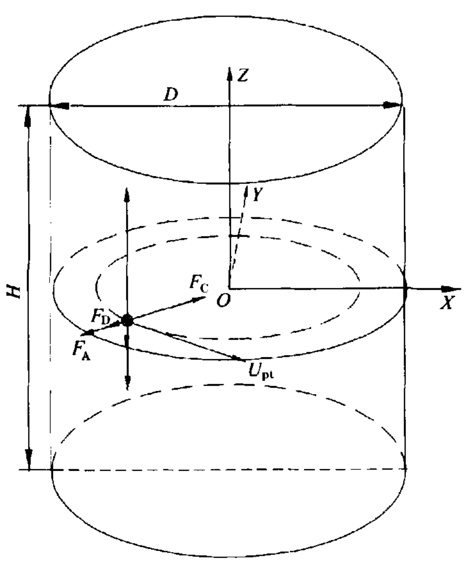

Fig. 4 Schematic of forces on an inclusion particle

is assumed in Stokes regime ($R_{ep}<1$). The force in axis direction is not analyzed.

Stokes drag force F_D on particle is produced when relative movement exists between particle and liquid steel.

The centrifugal force F_A under the effect of tangential acceleration goes against centripetal movement of inclusion particles.

Since pressure gradient exists in radical direction of swirling chamber, inclusion particles move towards center of swirling chamber under centripetal force F_C. This is the main reason that the inclusions can move to the center of swirling chamber and aggregate into a bigger ones under the centripetal force field. Meanwhile, the turbulent kinetic energy confinement in the entry zone is favorable for the aggregation and floatation of inclusions.

The combination of the above forces gives:

$$F=F_C-F_A-F_D \tag{2}$$

The final equation:

$$\frac{\pi}{6}d^3\rho_p\frac{du_{pr}}{dt}=\frac{\pi}{6}d^3(\rho_s-\rho_p)\frac{u_{pt}^2}{r}-3\pi\mu d(u_{pr}-u_{sr}) \tag{3}$$

where, ρ_s is density of steel; ρ_p is density of particle; u_{pr} is velocity of particle in radius direction; u_{pt} is velocity of particle in tangential direction; and u_{sr} is velocity of steel in radius direction.

Eqn. (3) shows that there is a significant force on inclusion toward the center of the swirling chamber, especially for inclusions of big diameter and small density.

2 Water Model Experiment

2.1 Similarity principle

In water model experiment, geometrical similarity and dynamic similarity between the model and the prototype were required. For the dynamic similarity, *Re* number and *Fr* number in the model should be equivalent to those in the prototype, respectively. As the flow of liquid steel within the tundish is severely turbulent, the *Re* number can meet the requirement naturally. Thus, only the *Fr* in the model should be equal to that in the prototype, that is,

$$(Fr)_m=(Fr)_p \text{ or } u_m^2/gl_m=u_p^2/gl_p \tag{4}$$

where, m is model type; p is prototype. The geometrical similarity scale factor of the single-strand tundish λ is 1 : 2.5. According to similarity principle, the geometric parameter, velocity and volumetric flow rate ratios can be obtained.

2.2 Inclusion simulant

The nonmetallic inclusions in molten steel are lighter than molten steel and thus, rise up to the surface of the molten steel. For the inclusion with the size range existing in tundish, inclusion and molten steel have the same horizontal velocity. It may be assumed that the inclusions rise with the Stokes' velocity:

$$u_{inc}=\frac{(\rho_f-\rho_{inc})gd_{inc}^2}{18\mu} \tag{5}$$

where μ is viscosity of the molten steel.

For satisfying the similarity of inclusion floatation rate and hence for proper simulation, it is necessary that particles' trajectories should be similar to the inclusions in molten steel, and this demands the horizontal and floating velocity ratios should be the same in model and prototype[10].

$$\frac{u_p}{u_{inc}}=\frac{u_w}{u_{steel}} \tag{6}$$

The kinematic viscosities of water at room temperature and that of steel at 1600 ℃ are nearly the same. According to Eqn. (4) and Eqn. (5), the simulant particles should meet the following requirement for different scale factors.

$$\frac{d_p}{d_{inc}}=\lambda^{0.25}\left[\frac{1-\rho_{inc}/\rho_{steel}}{1-\rho_p/\rho_{water}}\right]^{0.5} \tag{7}$$

Two types of tundish are designed. They are the tundish with dam, weir and turbulence inhibitor and the other tundish with dam, weir and swirling chamber. The single strand swirling flow tundish is shown in Fig. 5, where L_1 is 1800 mm; L_2 is 1665 mm; W_1 is 610 mm; W_2 is 480 mm; H is 420 mm; H_{sc} is 90 − 260 mm; D_{sc} is 170 − 320 mm; Φ is 30 mm. The swirling chamber is shown in Fig. 6.

2.3 Experimental methods

The Al_2O_3 inclusions in liquid steel were simulated in the experiment. High density polypropylene particles are used as inclusions. The wetting angle between polypropylene and water is 118°[11]. Polypropylene particles of 96−120 μm, 120−160 μm in

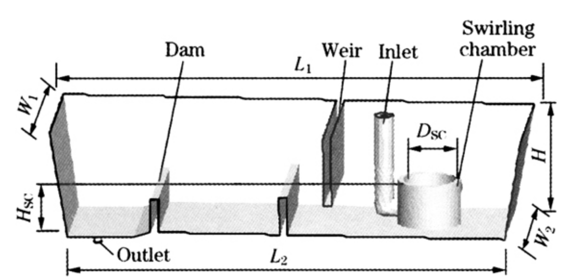

Fig. 5 Single strand swirling flow tundish configuration

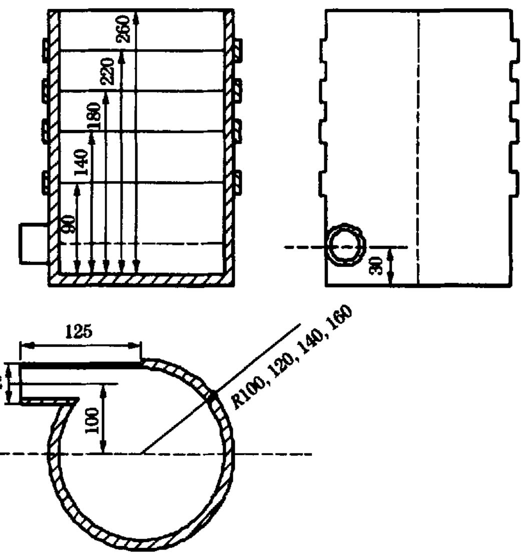

Fig. 6 Schematic of cylindrical swirling chamber

diameter are obtained by sieving. Its density is 0.912 g/cm³, measured with Micromeritics Accupyc 1330 True Densimeter. According to Eqn. (7), inclusions of 51 − 64 μm, 64 − 86 μm in diameter in liquid steel can be simulated. 2 g, 40 g polypropylene particles dipped with ethanol solution is added to the inlet pipe by injector once for all and time is recorded immediately. Based on the tundish RTD experiments and experience, the experimental time is set as 12 min. The polypropylene particles collected from the outlet are weighed with Sartorius electrobalance after drying. The floatation rate of inclusion is calculated by Eqn. (8).

$$\eta=\frac{W_{in}-W_{out}}{W_{in}}\times 100\% \tag{8}$$

where, W_{in} is quality of particle for inlet; W_{out} is quality of particle for outlet.

3 Experimental Results and Discussion

Particles of 120−160 μm, 120−160 μm in diameter used in water modeling are to simulate the inclusions of 51−64 μm, 64−86 μm in diameter in liquid steel. Fig. 7 shows the inclusion floatation rates with different quantity added in the inlet pipe of tundish equipped with swirling chamber of height 140 mm and diameter 280 mm. The inclusion particles floatation rate enhanced with increasing concentration of inlet initially. The floatation rate with 40 g inclusion particles addition is higher than that with 2 g addition. With a swirling chamber in the tundish, the function of turbulence inhibiting pouring pad can

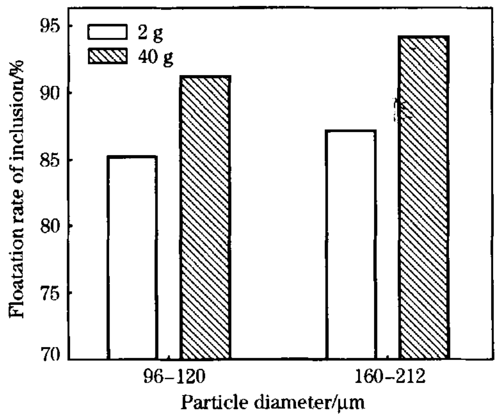

Fig. 7 Variation of inclusion floatation rate with particle size and quantity

be fully realized. It improves the flow field of tundish and promotes inclusion floatation, coalescence and removal. Especially, it shows very distinct effect of improving inclusion floatation rate with high mass concentration. According to Cai and Zhang[12], the initial inclusion number density is high particularly for small inclusion. In high temperature condition, the interaction of particles in liquid steel is strong and the chances for collision and aggregation between inclusions are good. Hence, in order to meet the condition of inclusion particles collision and aggregation, the initial inclusion number should be to some extent.

The morphology of floating course of different types of particles in water. Polypropylene particles aggregated, while hollow Al_2O_3 particles dispersed in water. Polypropylene particles dispersed in water when ethanol was added. Polypropylene particles are hydrophobic, whose surfaces are non-wetting. Hollow Al_2O_3 particles are hydrophilic, whose surfaces are wetting. When two hydrophobic particles get close to collision, the micro bubbles on particle surfaces merge into a gas bridge, which is the driving force leading to the rupture of liquid film covering the solid particle. That may be a long-range attraction process. The hydrophobic particles are thus liable to aggregate at collision. The micro bubbles on hydrophilic particle surface are not effective action by forming gas bridges, so the long-rang attraction process is neglected. Hydrophobic particles dispersed when ethanol or other surface active agent is added. The surface active agent changes the liquid interface tension, and the wettability is changed. Hydrophobic particles in liquid become wetting.

4 Conclusions

1) The inclusion floatation rate can be enhanced by increasing collision and aggregation. The wettability is a key factor for inclusion aggregation. Hydrophobic particles are liable to aggregate in collision.

2) The aggregation driving force of hydrophobic particles is the gas bridges between particles with micro bubbles on their surfaces.

3) Collision and aggregation phenomena exist in the course of inclusion removal in swirling flow tundish, which is favorable to increasing inclusion removal.

4) The inclusion removal in swirling chamber is governed by centripetal force, collision and aggregation. Big size inclusions are limited by centripetal effect, while small size inclusions are limited by collision and aggregation.

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