Mechanism and simulation of droplet coalescence in molten steel

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Abstract: Droplet coalescence in liquid steel was carefully investigated through observations of the distribution pattern of inclusions in solidified steel samples. The process of droplet coalescence was slow, and the critical Weber number (\(We\)) was used to evaluate the coalescence or separation of droplets. The relationship between the collision parameter and the critical \(We\) indicated whether slow coalescence or bouncing of droplets occurred. The critical \(We\) was 5.5, which means that the droplets gradually coalesce when \(We \leq 5.5\), whereas they bounce when \(We > 5.5\). For the carbonate wire feeding into liquid steel, a mathematical model implementing a combined computational fluid dynamics (CFD)–discrete element method (DEM) approach was developed to simulate the movement and coalescence of variably sized droplets in a bottom-argon-blowing ladle. In the CFD model, the flow field was solved on the premise that the fluid was a continuous medium. Meanwhile, the droplets were dispersed in the DEM model, and the coalescence criterion of the particles was added to simulate the collision-coalescence process of the particles. The numerical simulation results and observations of inclusion coalescence in steel samples are consistent.

Keywords: mechanism; simulation; droplet; collision; coalescence; molten steel

1. Introduction

Particle aggregation is used to remove the inclusions generated during multiphase flow in molten steel \([1–3]\). During composite deoxidation, small droplets are formed in molten steel and polymerized inclusions along with droplets in excellent condition are washed away \([4–5]\). In addition, several class-D inclusions containing MnS are removed, facilitating droplet coalescence. Unlike the bubble removal of solid inclusions \([6–7]\), the droplets generated in molten steel combine with the solid and liquid inclusions and float on the slag. Thus, observing the input and output of droplets is difficult. The collision and coalescence of particles including the droplets are used to remove the inclusions in molten steel. Previous studies on sparse two-phase flow, i.e., where the volume fraction of particles in the dilute phase is \(\leq 10\%\), have mainly ignored the precondition of particle collision. Nevertheless, recent studies have shown that, even if the volume fraction of particles is only \(4 \times 10^{-4}\), particle collision cannot be ignored \([8–9]\). The conditions in the interior of the liquid steel cannot be observed at high temperatures. Therefore, numerical simulations of the dynamic behavior of particle motion, collision, aggregation, and coalescence in molten steel are critical.

In this study, we investigated the coalescence of droplets in liquid steel by observing the distribution patterns of inclusions in solid steel samples. Generally, the computational fluid dynamics (CFD) methods of numerical simulation of multiple phases include both Eulerian and Lagrangian methods. The former regards both the fluid and the particles as a continuum; the latter regards the fluid as a continuum and the particles as a discrete system. In the traditional sense, the Lagrangian method (including the Euler–Lagrangian method, the direct numerical simulation method, and the volume-of-fluid method) does not take into account the interactions among the particles or the effect of the particle volume fraction on the continuous phase. Because ignoring the collisions among particles is inappropriate, a numerical simulation should be carried out using, for example, the discrete element method (DEM). The DEM includes solving the Newton’s second law under the Lagrangian system, dynamically simulating each particle in the system, and assessing the interaction...
of particles under the effect of the fluid field as well as the exchange of mass, momentum, and energy among particles. Therefore, in the present work, a mathematical model based on a CFD + DEM approach was used to simulate the movement and coalescence of droplets of various sizes in a continuously bottom-argon-blown ladle. The simulation results indicate the capture and removal of inclusions. This study provides a theoretical basis for the production of clean steel.

2. Droplet coalescence in molten steel

2.1. Experimental procedure

A 60-t ladle furnace was used, and the molten steel was maintained at (1873 ± 10) K. The chemical composition (wt%) of ship plate steel is C 0.15, Si 0.32, Mn 1.45, P 0.021, S 0.018, and Al 0.030. The Si–Mn–Al–Fe alloy with a chemical composition (wt%) of Si 30, Mn 45, Al 10, and Fe 15 was added to the ladle to deoxygenate and produce a white slag, which was sampled every minute. We collected a steel sample 20 min after adjusting the chemical composition. The samples were rapidly cooled to room temperature to preserve their original high-temperature characteristics. The steel samples were cut, ground, and polished, and the inclusions were characterized using a metallographic microscope, a Philips Quanta 400 scanning electron microscope, and an Oxford INCA spectrometer.

2.2. Droplet coalescence

The number and morphology of inclusions are shown in Fig. 1. There are many inclusions at the beginning of deoxidation, and a majority of the inclusions had diameters between 5 and 50 μm. Inclusions greater than 10 μm were nearly nonexistent after 20 min. During deoxidation, early in the refining stage, the initial tiny inclusions rapidly aggregated and formed complex compounds of Si, Al, and Mn oxides and occasionally Ca or Ti oxides, which were homogeneously distributed and apparently liquid at steelmaking temperatures. The inclusions collided, grew, and floated prior to removal. After 20 min, few large oxide inclusions remained in the molten steel. The residual inclusions were mainly Al–Mg–O compounds, occasionally contained Si and Mn oxides, and spherical MnS.

An example of droplet polymerization is shown in Fig. 2. The energy-dispersive X-ray spectra corresponding to the three labeled areas in Fig. 2 are shown in Fig. 3.

The large inclusions in Fig. 1(a) have diameters of 32 and 53 μm and have nearly the same composition, i.e., O, Al, Si, Mn, and some Ti. The composition of the inclusions is plotted on the Al2O3–SiO2–MnO ternary phase diagram in Fig. 4. The projection of the composition of the inclusions in the Al2O3–SiO2–MnO ternary phase diagram and the 1873 and 1473 K isotherms are clearly observed. Because the melting point of these compounds is less than 1473 K, i.e., far below the steelmaking temperature of 1873 K, the inclusions generated by the deoxidation reaction are likely to be in the liquid state. Moreover, the circular outline of the inclusions...