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Separation of electrically neutral non-metallic inclusions from molten steel by pulsed electric current

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Abstract

Effect of a pulsed electric current on the distribution of Al₂O₃ inclusions in liquid steel is explored; these inclusions ranged in size from microns to nanometres. When no electric current was applied the inclusions were randomly distributed in the steel. However, when an electric current was applied the inclusions were found in highly-populated regions near the various interfaces. Moreover, this process applies to a wide range of inclusion diameters, in contrast to conventional inclusion removal methods which tend to apply to larger (>20 µm) particles only. Consequently, the application of pulsed electric current provides a method of removing inclusions from the steel and thereby, improving the mechanical, physical and corrosion resistance properties of the steel.

Keywords: Pulsed electric current; Inclusion removal; Clean steel; Electrical conductivity.

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1. Introduction

It is widely recognized that, the defects, caused by non-metallic inclusions are detrimental to both the mechanical properties and the casting reliability of clean steels.¹ With the increasing demand for high-performance products, it is important to minimise the level of inclusions in steel melts. Therefore, it is necessary to control and improve the operating practices during the steel manufacturing process to improve the cleanness of the steel. Molten steel becomes contaminated with inclusions at various stages in the production route, e.g. during tap, ladle treatment, and during continuous casting. Large inclusions ($>10\ \mu\text{m}$) have a deleterious effect on the mechanical properties with toughness decreasing with increasing inclusion size. Fine dispersions ($< 10\ \mu\text{m}$) can be either helpful or harmful.^{2,3} However, the limit for acceptable inclusion size tends to decrease every year and inclusions of $2\ \mu\text{m}$ or less are required to the high performances expected. There have been efforts to apply various melt treatments in industries to extract inclusions from molten metals, including electromagnetic separation (utilizing the difference in the electrical conductivity between the particle and the melt, which induces a force driving the motion of particle in the melt under an applied external force field)⁴⁻⁸ and Ar bubbling⁹. These methods are generally applicable for elimination of inclusion particles above $20\ \mu\text{m}$ in diameter, and require significant energy consumption and cost.^{2,4-9} Removal of inclusions of less than $20\ \mu\text{m}$ may be accomplished by filtration using ceramic foam filters,¹⁰ but with limited (and controversial) filtration efficiency.¹¹ Inclusion levels can be reduced in steelmaking by careful manipulation of the inclusion chemistry (with Ca and Al) to produce a liquid inclusion which is easier to remove at steelmaking temperatures.¹² However, if calcium treatment is not controlled well, solid calcium aluminate and sulphide particles with higher melting points can be formed leading to a deterioration of mechanical properties.¹³ For these reasons, the development of a novel method to remove inclusions from the melts is important in green processing of steel.

Pulsed electric current, as an instantaneous high-energy input method with high efficiency and low energy consumption, has been developed to affect the microstructure of the metals. More importantly, pulsed electric current-based processing consumes significantly less electrical energy compared with electromagnetic-stirring. Thus pulsed electric current may be used to manipulate the transport of electrically-neutral non-metallic inclusions in a

conductive liquid with less energy consumption and high efficiency. Further, pulsed electric current can prevent Ohmic heating, whereas a large amount of Joule heat is produced by continuous electric current (AC or DC). Recently, inclusion removal has been reported by the present authors,¹⁴⁻¹⁶ however, the removal efficiency for the alumina need to be further clarified for the possible commercial operation.

In summary, the removal efficiency of inclusions in molten steel is still well below target and involves significant energy consumption and high cost. In this study an investigation has been carried out into how electric current induces inclusions to separate from molten steel. These results have enabled us to develop a novel clean steel green processing method.

2. Experimental Procedure

The investigated steel containing alumina inclusions was melted in a graphite crucible by an induction furnace. In order to apply the electric current into the liquid, a pair of steel bars was submerged into the liquid steel to act as the electrodes. The chemical compositions (wt.%) of both the investigated steel and the steel electrode were listed in **Table 1**. The electrode is 300 mm long, 5 mm wide and 5 mm high. The mass of the investigated steel is 300 g. In order to confirm the difference in melting point, the phase diagrams of both steels were calculated using Thermo-Calc software. From the calculated diagrams, the melting temperature of the liquid steel at 1469 °C is lower than that of the steel bar at 1520 °C. Therefore, it seems feasible that the electrode will remain solid in molten steel (the electrode will dissolve in the molten steel but it can still keep solid in short time) and this requires careful adjustment of the output power of the induction furnace. In order to determine the effect of electric current, two sets of experiments were carried out, one without electric current and the other with electric current. The experimental procedures were identical except for the application of electric current. The process and specimen dimensions are illustrated schematically in **Fig. 1**. The direction of the applied electric current, the current-induced magnetic field and the possible direction of migration of the particles are indicated in the figure. Pulsed electric current with square-wave form rather than continuous electric current (AC or DC) was applied to prevent Ohmic heating. The parameters of the experiment were given as: 1 Hz of frequency, 60 μ s of pulse duration, 1.6×10^6 A/m² of current density, and 8 minutes of

processing time. The average electric power in electric current pulse processing for a 300 g melt was 0.0012 Watts, which was much less than the power of a household fluorescent light. Furthermore, no skin effect was noted in the experimental analysis. Here, more than three experiments were performed to test its reproducibility. The pulsed electric current is also applied in the solidification process after the furnace is turned off.

The furnace-cooled samples were longitudinally sectioned and polished for metallographic examination. The composition of the inclusions in the steels was analyzed with a scanning electron microscope using a microscope equipped for energy-dispersive spectroscopy (SEM-EDS). The distribution of the inclusions across the sample was examined by automated inclusion analysis using field emission gun-scanning electron microscope (FEG-SEM). This technique combines the advantages of EDS with that of digital image analysis of backscattered electron micrographs. It provides fast measurements of composition, size and morphology for thousands of particles embedded in the steel matrix, giving a more statistically-sound inclusion size distribution in the sample compared with manual inclusion size measurements. The size resolution of the FEG-SEM is 500 nm, but in this experiment we only analyze inclusions larger than 1 μm because inclusions less than 1 μm are considered to be negligible for damage to the products in engineering. The collected data were analyzed and plotted using in-house developed MatVisual software.

3. Results and Discussion

Preliminary examination of the chemical composition and morphology of inclusions was carried out using SEM-EDS. A typical result is shown in **Fig. 2**; this indicates an alumina inclusion. The angular particle in the steel matrix, shown in **Fig. 2a**, was found by EDS to be rich in aluminium and oxygen (**Fig. 2b**). This indicates that the angular region consisted of an Al_2O_3 inclusion. Both the point analysis and line scanning show that all the inclusions, regardless of the size, are chemically homogenous and chemical segregation is absent. The relative proportion of the major elements varied slightly from inclusion to inclusion but the elements are distributed quite uniformly throughout the inclusion.

The number distributions of Al_2O_3 inclusions for both untreated- and treated- steels are compared in **Fig. 3a** and **b**. Here, individual Al_2O_3 features with their equivalent circular

diameter were recorded. In **Fig. 3**, the yellow dot represents the position of the inclusion. It can be clearly seen that the number of the particles in the interior of the treated-steel is much lower than those in the untreated-steel. It is strikingly obvious that the distribution of the inclusions has been greatly affected by the application of an electric current. **Fig. 4** shows the population distribution of the Al₂O₃ particles as a function of distance from the centre. The uncertainty in values of the inclusion number for each datum point is ± 3 . There are virtually no particles in the interior of the treated-steel. The particles have been pushed towards the surface and the population density is much greater near the surface. In contrast, the inclusions keep a random distribution through the steel in the untreated-steel.

The size of the inclusions for the untreated- and treated- steels is counted based on 389 individual Al₂O₃ features. The average size of the Al₂O₃ in the untreated steel is about 4.5 μm , which is similar to that in the treated-steel (2.2 μm). The maximum recorded size for particles was found to be proximately 11 μm . It seems that the electropulsing technique can separate particles $> 2 \mu\text{m}$ from the molten steel.

A numerical calculation has been performed by the present authors to investigate the particles separation from the liquids by electric current. **Fig. 5a** considers a spherical inclusion suspended at the position m in the molten steel. Let's assume that the electrical conductivity of the molten steel is 10^3 times larger than that of the inclusion. This assumption is applicable to this study, because the conductivities of the molten steel and Al₂O₃ above 1273K are $10^5 \Omega^{-1}\text{m}^{-1}$ and $10^{-2} \Omega^{-1}\text{m}^{-1}$,¹⁷⁻¹⁹ respectively. The free energy G associated with the electric current can be calculated by the following equation:¹⁴

$$G = -\frac{\mu}{8\pi} \int \frac{\vec{j}(r) \cdot \vec{j}(r')}{|r-r'|} dr dr'$$

where μ is the magnetic permeability, r and r' are two different positions in space, respectively. $\vec{j}(r)$ is the current density at position r .

Fig. 5b shows the change of the free energy when an inclusion moves from the centre of matrix toward the top surface. It is found that free energy decreases with the distance from the centre. From the thermodynamics, the system at lower free energy is more stable. It suggests that the inclusion tends to move from the position m to the position n , that is, the inclusions are expelled to the surface of the molten steel by electric current. Based on the calculation, the separation of inclusions in molten steel by electric current can be clarified. Here, in order to simplify the calculation we assume that inclusions are in a stagnant liquid, but in fact, molten steel is in a fluid state. In addition, in a strong convection environment, the inclusion removal can also be achieved by application of pulsed electric current, which shows pulsed electric current is effective for the purification of molten steel in a more complex environment. In the future, we will take the circulation into consideration to more precisely explain this separation mechanism.

As mentioned above, the inclusions were moved in molten steel by the application of an electric current; these inclusions were driven from the interior of the steel to the surface of the steel. More importantly, the electropulse technique works for inclusions with sizes less than 20 μm and thus has advantages over conventional techniques which can only effectively remove inclusions of $> 20 \mu\text{m}$. It is currently difficult to achieve these cleanliness standards with the conventional methods used for inclusion removal. For instance, the diameter of tyre wire steel is normally 150 μm . Thus an inclusion of 10 μm , can cause catastrophic failure in the wire. Thus, the production of such materials to meet special standards must rely on novel green processing techniques. Furthermore, this current-driven technique requires low power consumption; accordingly its production cost is low.

4. Conclusions

The size and number distribution of the alumina inclusions in steels have been determined for electropulsed steels and were then compared with data for blank samples where no pulse was applied. The removal efficiency of inclusions in molten steel was derived from a comparison of the solidified steels for the pulsed- and nonpulsed- samples. This is essential in the search for high-performance clean steel products.

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Figure and Table captions

Table 1 Chemical composition (wt.%) of investigated steel and steel electrode

Fig. 1 Experimental setup for pulsed electric current experiments. B is magnetic field, I is electric current, and v is the migration of the particle.

Fig. 2 SEM-EDS showing the type and shape of the inclusions. (a) The morphology of the Al_2O_3 inclusion, (b) The EDS pattern of Al_2O_3 inclusion.

Fig. 3 Automated inclusion analysis by FEG-SEM was applied to detect the distribution of Al_2O_3 inclusions in the untreated as-solidified steel and electric-current-treated steel. (a) Untreated as-solidified steel, (b) Electric-current-treated steel.

Fig. 4 Number distribution of inclusions in liquid metal without and with electric current treatment.

Fig. 5 (a) A spherical inclusion at the position m tends to be expelled toward position n by electric current; (b) Free energy change when the inclusion is located at different positions.

Table 1 Chemical compositions (wt.%) of investigated steel and steel electrode

Sample	C	Si	Mn	S	Cr	Ni	Cu	Fe
Steel	0.74	0.27	0.99	0.019	0.016	0.015	0.008	Bal.
Electrode	0.12	0.17	0.53	0.021	0.075	0.152	0.494	Bal.