

## Inclusion Removal from Molten Steel Using Electromagnetic Vibrating Force

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### Abstract

An electromagnetic vibrating force is a candidate of a micro-size inclusion removal method [1-5]. Especially, an A.C. magnetic field imposition has an advantage that it enables the inclusion removal and an induction heating of a molten steel in a tundish simultaneously [3-5]. However, appropriate system design and operating conditions for the simultaneous operation of the inclusion removal and the induction heating of the molten steel by the A.C. magnetic field imposition have not been clarified. Therefore, an inclusion removal time from the molten steel under the A.C. magnetic field imposition has been calculated in this study. And then, a minimum channel length for the inclusion removal and the molten steel temperature increase per unit channel length by the induction heating has been evaluated. The A.C. magnetic field frequency should be controlled within a certain frequency range in which the inclusion removal time becomes minimal. Furthermore, the channel length should be longer than the minimum channel length for the inclusion removal calculated by using the minimum inclusion removal time and an assumed maximum molten steel velocity in the channel. The molten steel temperature increase per unit channel length by the induction heating can be controlled by controlling the A.C. magnetic field frequency within the frequency range suitable for the inclusion removal. Especially, a high frequency condition in that frequency range is better for the efficient thermal supply in this calculation condition.

**Key words :** A.C. magnetic field; induction heating; inclusion removal

### Introduction

Demand for high quality steel has been extended in various industries for yield improvement, fabrication of long life time products and so on. Non-metallic inclusions such as alumina particles in the steel causes some troubles in some processes such as rolling and wire drawing, and decrease in fatigue strength of the final products. Therefore, fabrication of high-purity steel without the inclusions is one of important issue in the steel industry today. However, the inclusions formation resulting from control of the molten steel chemical component is inevitable. In general, the inclusions are removed from the molten steel using buoyancy force acting on them in the tundish and a continuous casting machine, and their rising velocity in the molten steel is proportional to the square of their diameter. Thus, removal of micro-size inclusions requires long operating time and it should be improved for high productivity of the high-purity steel. A vibrating electromagnetic force is a candidate of the micro-size inclusions removal method [1-5]. For example, cleanliness factor of the molten steel is improved by the A.C. magnetic field imposition using an induction heating system of the tundish [3]. By imposing the A.C. magnetic field on the molten steel flowing in a channel of the tundish for induction heating, the inclusions move towards the channel inner wall with vibrating motion by the electromagnetic force acting on them and are trapped on the channel inner wall [4]. This method has an advantage that the inclusion removal can be achieved simultaneously with preventing the temperature drop of the molten steel. The A.C. magnetic field with a commercial frequency, for example 50 Hz or 60 Hz in Japan, is generally used in the induction heating system. On the other hands, the authors carried out a numerical calculation of an inclusion motion in the molten steel under the A.C. magnetic field imposition and clarified presence of an optimum magnetic field frequency for the speedy inclusion removal [5]. However, for the simultaneous operation of the inclusion removal and the induction heating of the molten steel, the optimum channel design and operating conditions might be different. From the viewpoint of the inclusion removal, the channel length should be longer than a certain minimum channel length in which the inclusions should be attached to the channel inner wall before it reaches the channel exit. On the other hand, certain level of the heat supply is required from the viewpoint of the induction heating. Both the molten steel velocity in the channel and the A.C. magnetic field frequency are important parameters when the A.C. magnetic field magnitude is fixed.

In order to clarify guidelines of the channel design and the operating conditions, numerical calculation of the inclusion removal time from the molten steel under the A.C. magnetic field imposition based on electromagnetic field theory and fluid dynamics has been carried out at first. Then, the minimum channel length for the inclusion removal and the molten steel temperature increase per unit channel length by the induction heating has been evaluated.

### Calculations

Evaluation of the inclusion removal time from the molten steel under the A.C. magnetic field imposition was carried out, in which a couple of parallel horizontal A.C. magnetic fields with frequency of  $f$  and half amplitude of  $B_0$  are



simultaneously imposed on a horizontally infinite molten steel with vertical thickness of  $2w$  from its upper and bottom surfaces. The analytical system is same with the previous report [5]. Because  $x$ -axis is in horizontal direction and positive direction of  $y$ -axis is vertical upwind direction with the origin of on the center line of the molten steel thickness, the electromagnetic force acting on a spherical insulating inclusion in this molten steel has only  $y$  component, and its magnitude per unit volume of the inclusion  $F_m$  is given as follows [5];

$$F_m = F_p + F_v \quad (1)$$

$$F_p = C_1(\sinh 2\zeta - \sin 2\zeta) \quad (2)$$

$$F_v = C_1[C_2 \cos(4\pi ft + \alpha)] \quad (3)$$

$$C_1 = 3(B_0^2 \sqrt{R_\omega}) / [8\mu w ((\cosh \sqrt{2R_\omega} + \cos \sqrt{2R_\omega}))] \quad (4)$$

$$C_2 = \frac{\sqrt{(\cosh 4\zeta - \cos 4\zeta) [(\cosh \sqrt{2R_\omega} + \cos \sqrt{2R_\omega})^2 + \sinh^2 2\zeta \sin^2 2\zeta]}}{[\sqrt{2}(\cosh \sqrt{2R_\omega} + \cos \sqrt{2R_\omega})]} \quad (5)$$

$$\alpha = \frac{\pi}{4} - \arccos \left[ \frac{4 \sinh \zeta \cosh \sqrt{R_\omega/2} \cos \zeta \cos \sqrt{R_\omega/2} + \cosh \zeta \sinh \sqrt{R_\omega/2} \sin \zeta \sin \sqrt{R_\omega/2}}{2 \sqrt{(\cosh 2\zeta - \cos 2\zeta)(\cosh \sqrt{2R_\omega} + \cos \sqrt{2R_\omega})}} \right] \quad (6)$$

$$\zeta = (y - w) \sqrt{R_\omega/2} \quad (7)$$

$$R_\omega = 2\pi f \sigma \mu w^2 \quad (8)$$

where  $t$ ,  $\sigma$ , and  $\mu$  are time, electrical conductivity of the molten steel ( $7.2 \times 10^5 \text{ Sm}^{-1}$ ), and magnetic permeability of the molten steel ( $4\pi \times 10^{-7} \text{ Hm}^{-1}$ ), respectively. A shielding parameter  $R_\omega$  defined by Eq. (8) is a ratio of the penetration depth of the A.C. magnetic field to the half thickness of the molten steel  $w$ . The Eqs. (1) – (3) indicate that the electromagnetic force acting on the inclusion consists of a pinch force  $F_p$  in the direction from the molten steel center line to the molten steel surface and a vibrating force  $F_v$  with frequency of  $2f$ . An alumina inclusion with diameter of  $D$  and density of  $\rho_s$  ( $3880 \text{ kgm}^{-3}$ ) was set at  $y = 0$  as the initial condition. The driving forces of the inclusion are a buoyancy and the pinch forces toward the upper direction, and the vibrating force as illustrated in Fig.1. Using inclusion vertical velocity  $u$ , density of the molten steel  $\rho_f$  ( $6958 \text{ kgm}^{-3}$ ), and viscosity of the molten steel  $\eta$  ( $5.28 \times 10^{-3} \text{ Pa}\cdot\text{s}$ ), an equation of the inclusion motion in the vertical direction can be written as follows [5];

$$\frac{du}{dt} = \frac{1}{(\rho_s + \rho_f/2)} \left[ -\frac{18\eta}{D^2} u - \frac{9}{D} \sqrt{\frac{\rho_f \eta}{\pi}} \int_0^t \frac{du/ds}{\sqrt{t-s}} ds + g(\rho_f - \rho_s) + F_p + F_v \right] \quad (9)$$

where, first, second, and third terms in the right-hand side of the Eq. (9) are a drag force, a Basset force, and the buoyancy force, respectively. The inclusion behavior from the initial position ( $y = 0$ ) to the upper surface of the molten steel ( $y = w$ ) was computed by applying the fourth-order Runge-Kutta method for the inclusion with diameter  $D$  of  $100 \mu\text{m}$  in the molten steel with half thickness  $w$  of  $0.075 \text{ m}$  under the imposition of the magnetic field with half amplitude  $B_0$  of  $0.2 \text{ T}$ . And then, the inclusion removal time from the molten steel  $t_r$  was evaluated as total moving time of the inclusion from the initial inclusion position to the upper surface of the molten steel.

For evaluation of the minimum channel length for the inclusion removal and corresponding molten steel temperature increase per unit channel length by the induction heating, an induction heating channel model in which the A.C. magnetic field with frequency  $f$  and half amplitude  $B_0$  was imposed on a circular cross section channel of radius  $w$  and the molten steel flows in the axial direction with average velocity of  $u_f$  was adopted. The removal time of an inclusion  $t_r$  is obtained using the numerical calculation. Therefore, the minimum channel length for the inclusion removal  $L_{min}$  was evaluated by  $L_{min} = u_f t_r$ . The heating rate per unit channel length  $Q$  can be approximated as follows when the shielding parameter  $R_\omega$  given by the Eq. (8) is much larger than unity (when the A.C. magnetic field frequency  $f$  is much higher than  $31 \text{ Hz}$  in this case) [6].

$$Q \approx B_0^2 \pi w \sqrt{\pi f / \mu^3 \sigma} \quad (10)$$

Thermal balance equation of the molten steel in the channel can be written as follows;

$$Q = \rho_f C_p \Delta T \pi w^2 u_f \quad (11)$$

where,  $C_p$  is heat capacity of the molten steel ( $795 \text{ Jkg}^{-1}\text{K}^{-1}$ ) and  $\Delta T$  is the molten steel temperature increase per unit

channel length by the induction heating. From the Eqs. (10) and (11), the molten steel temperature increase per unit channel length  $\Delta T$  is given as follows.

$$\Delta T = B_0^2 \sqrt{\pi f / \mu^3 \sigma} / \rho_f C_p u_f w \quad (12)$$

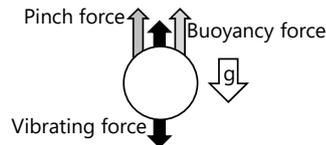


Fig. 1: Driving forces acting on the inclusion

### Results and discussions

Table 1 shows the numerically calculated inclusion removal time  $t_r$ . The inclusion removal time  $t_r$  becomes minimal when the A.C. magnetic field frequency falls in the range of 156 - 500 Hz. The reason for the presence of the minimal value  $t_r$  was discussed in the previous report [5] as follows. The rising velocity of the inclusion in the molten steel can be effectively promoted when the pinch force is larger than the buoyancy force. However, the pinch force becomes smaller than the buoyancy force in most of the region in the molten steel when the A.C. magnetic field frequency is excessive low or high, because the pinch force magnitude becomes small under the excessively low frequency condition and the penetration depth of the A.C. magnetic field becomes thin under the excessively high frequency condition. The region where the pinch force exceeds the buoyancy force becomes the largest when the A.C. magnetic field frequency falls in the range of 156 - 500 Hz in this calculation condition, and therefore the inclusion removal time  $t_r$  becomes minimal. For the speedy inclusion removal and minimization of the channel length, the A.C. magnetic field frequency should be controlled in this frequency range in which the inclusion removal time  $t_r$  becomes minimal. Because the inclusion removal time  $t_r$  is about 11.5 s with error of 4.3 % or less when the A.C. magnetic field frequency falls in the range of 156 - 500 Hz, the minimum channel length for the inclusion removal  $L_{min}$  when the inclusion removal time  $t_r$  is 11.5 s will be described below as a function of the molten steel velocity in the channel. And then, the molten steel temperature increase per unit channel length by the induction heating  $\Delta T$  of 156 - 500 Hz in the A.C. magnetic field frequency  $f$  will be also discussed.

Table 1: Inclusion removal time for various A.C. magnetic field frequency

A.C. magnetic field frequency $f$ [Hz]	5	50	156	313	500	5000
Inclusion removal time $t_r$ [s]	23.3	14.9	11.6	11.5	12.0	18.1

Figure 2 shows an effect of the molten steel velocity in the channel  $u_f$  on the minimum channel length for the inclusion removal  $L_{min}$  when the inclusion removal time  $t_r$  equals to 11.5 s. With increase in the molten steel velocity in the channel  $u_f$ , the minimum channel length for the inclusion removal  $L_{min}$  increases. In general, the molten steel velocity in the channel  $u_f$  is a function of the withdrawal speed in the continuous casting process for keeping certain casting temperature without consideration of the minimum channel length for the inclusion removal  $L_{min}$ . Thus, the inclusion removal effect of the A.C. magnetic field is not enough, when the minimum channel length for the inclusion removal  $L_{min}$  is longer than the length for the molten steel heating. From the viewpoint of the inclusion removal, the channel length should be longer than the minimum channel length for the inclusion removal  $L_{min}$  which is derived from the minimum inclusion removal time  $t_r$  and the maximum withdrawal speed in the continuous casting process. For example, the channel length should be longer than 1 m or more when the molten steel velocity  $u_f$  exceeds about  $0.1 \text{ ms}^{-1}$  (about  $0.7 \text{ ton} \cdot \text{min}^{-1}$  in flow rate in the channel) in this calculation condition.

Figure 3 shows the effects of the molten steel velocity  $u_f$  and the A.C. magnetic field frequency  $f$  with the range of 156 - 500 Hz on the molten steel temperature increase per unit channel length by the induction heating  $\Delta T$ . The molten steel temperature increase per unit channel length  $\Delta T$  decreases with increase in the molten steel velocity in the channel  $u_f$ . On the other hand, the molten steel temperature increase per unit channel length  $\Delta T$  increases with increase in the A.C. magnetic field frequency  $f$ . Therefore, the molten steel temperature increase per unit channel length  $\Delta T$  can be controlled by controlling the A.C. magnetic field frequency  $f$ . For example, when the molten steel velocity in the channel  $u_f$  is  $0 \text{ ms}^{-1}$ , the molten steel temperature increase per unit channel length  $\Delta T$  can be controlled from about 20 K (at 156 Hz) to about 36 K (at 500 Hz). And as shown in the Fig. 3, when the molten steel velocity in the channel  $u_f$  changes within the range from  $0.1 \text{ ms}^{-1}$  (about  $0.7 \text{ ton} \cdot \text{min}^{-1}$  in flow rate) to  $0.2 \text{ ms}^{-1}$  (about  $1.5 \text{ ton} \cdot \text{min}^{-1}$  in flow rate), the molten steel

temperature increase per unit channel length  $\Delta T$  can be kept a certain value of about 36 K by controlling the A.C. magnetic field frequency within the range from 156 Hz (at  $0.1 \text{ ms}^{-1}$ ) to 500 Hz (at  $0.2 \text{ ms}^{-1}$ ) in this calculation condition. Thus, a high frequency is better for thermal energy supply to the molten steel in the frequency range suitable for the inclusion removal. Above discussions provide some guidelines that (1) the magnetic field frequency  $f$  should be controlled within the certain frequency range in which the inclusion removal time becomes minimal, (2) the channel length should be longer than the minimum channel length for the inclusion removal  $L_{min}$  which is obtained from the minimal inclusion removal time and an assumed maximum molten steel velocity in the channel for industry, and (3) the molten steel temperature increase per unit channel length  $\Delta T$  can be controlled by controlling the magnetic field frequency  $f$ .

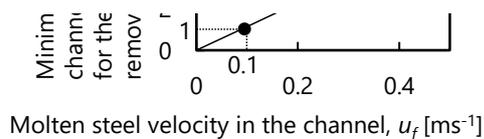


Fig. 2: Effect of the molten steel velocity in the channel on the minimum channel length for the inclusion removal

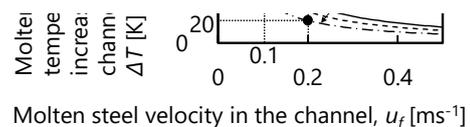


Fig. 3: Effects of the molten steel velocity in the channel and the A.C. magnetic field frequency on the molten steel temperature increase per unit channel length by the induction heating

## Conclusions

In order to clarify the guidelines of the channel design and operating conditions for the simultaneous operation of the inclusion removal and the induction heating of the molten steel by the A.C. magnetic field imposition, numerical calculation of the inclusion removal time from the molten steel under the A.C. magnetic field imposition, evaluation of the minimum channel length for the inclusion removal, and evaluation of the molten steel temperature increase per unit channel length by the induction heating were carried out. The results can be summarized as follows.

- (1) inclusion removal time becomes minimal when the A.C. magnetic field frequency falls in the range of 156–500 Hz under the assumptions that the A.C. magnetic field half amplitude  $B_0 = 0.2 \text{ T}$ , the channel radius  $w = 0.075 \text{ m}$ , and inclusion diameter  $D = 100 \text{ }\mu\text{m}$ . The A.C. magnetic field frequency  $f$  should be controlled in this frequency range to minimize the minimum channel length for the inclusion removal. In addition, the channel length should be longer than the minimum channel length for the inclusion removal which is calculated by using the minimal inclusion removal time and an assumed maximum molten steel velocity in the channel. The minimum channel length for the inclusion removal becomes 1 m or more when the molten steel velocity exceeds  $0.1 \text{ ms}^{-1}$  in this calculation condition.
- (2) The optimum frequency for the inclusion removal is a relatively wide range in comparison with that for the induction heating in this calculation condition. Thus, the operating frequency should be adjusted for optimum condition for the heat supply in the optimum frequency range of the inclusion removal.

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