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Analysis of Power Supply Heating Effect during High Temperature Experiments Based on the Electromagnetic Steel Teeming Technology

DOI 10.1515/htmp-2016-0163
Received July 25, 2016; accepted February 24, 2017

Abstract: For further lowering inclusions and improving the quality of steel, a new electromagnetic steel-teeming technology based on electromagnetic induction heating was proposed. To assess the proposed technology, an experimental platform that imitates the actual production condition of steelmakers was established. High temperature experiments were performed to investigate the melting length of Fe-C alloy under different power and frequency conditions. The heating effect was analyzed, and the method of magnetic shielding to reduce the power loss of power supply was put forward. The results show that when the power is 40 kW and frequency is 25 kHz, the melting length of the Fe-C alloy is 89.2 mm in 120 s, which meets the requirements of steel teeming. In addition, when magnetic shielding material is installed under the induction coil, the power loss is reduced by about 64 %, effectively improving the heating effect of power supply.

Keywords: clean steel, electromagnetic induction, industrial application, heating effect, power loss

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Introduction

In recent years, the improvement of steel cleanliness has been paid more attention. During the continuous casting process, nozzle sand is used as a filling material in the upper nozzle to accomplish successful steel teeming after opening the slide gate. However, industrial nozzle sand consists of metallic oxides and non-metallic oxides. When the slide gate is opened, nozzle sand drops into the tundish and this can reduce the cleanliness of molten steel. In addition, the automatic teeming of ladles also plays an important role in improving the steel cleanliness. The free opening rate is generally about 98 %. If the ladle cannot open automatically, the method of oxygen burning for nozzle sand is needed, which will further aggravate the pollution of molten steel [1, 2]. Two methods for avoiding nozzle sand contamination in the tundish have been proposed. The first involved blowing to reduce nozzle sand falling into the tundish, the second was a recovery device that aimed to collect nozzle sand. Although the above methods reduced nozzle sand mixed into the tundish by up to 80 %, they seriously affected the production rate, and even led to safety accidents [3, 4]. To avoid these problems, a new technology based on the principle of induction heating was proposed by Wang Qiang [5–7] et al. The Fe-C alloy particles having the same or similar composition to the liquid steel were employed instead of nozzle sand. After filling the ladle with high temperature molten steel, a sintering layer forms on the Fe-C alloy, blocking the molten steel. When the ladle is placed in the pouring position, all or part of the Fe-C alloy is melted by Joule heat generated by an induction coil at the bottom of the ladle, allowing the steel teeming to be completed smoothly. This method avoids using nozzle sand, improves steel cleanliness and allows the free opening rate to reach 100 %.

Because of the complexity of the ladle bottom structure, difficult measurement conditions and huge experimental cost, the numerical simulations have been used to analyze the heating effect of power supply [8, 9]. However, differences remain between numerical simulation results and industrial conditions. The working environment temperature of the coil is about 973 K during the electromagnetic induction steel-teeming process [9]. At high temperatures, the physical parameters of all materials are changed, and the normal operation of the induction coil and of the power supply is affected. Therefore, a high temperature experimental device is necessary, to perform experiments to validate the new steel teeming process. In this paper, the effect of the power and frequency of electricity supplied on heating effect of the Fe-C alloy was analyzed experimentally. To improve the heating efficiency and minimize power loss, the influence of magnetic shielding material between the coil and the ladle bottom shell was investigated.

Experimental

Experimental device

The principle of electromagnetic induction steel teeming technology is presented in Figure 1(a). The upper nozzle of the ladle is filled with Fe-C alloy particles and the induction coil is set in the nozzle brick around the upper nozzle. All or part of the Fe-C alloy particles are melted by induction heating. To imitate the actual condition at the bottom of the ladle during the electromagnetic steel-teeming process, a custom high temperature experimental device is used, as shown in Figure 1(b). Thermal insulation material of thickness 15.0 mm is placed around a steel barrel with inner diameter 1000.0 mm and height 800.0 mm. The induction coil, wound with thermal insulation material, is connected to the induction heating power supply 1# (rated power is 40 kW, and rated frequency is 30 kHz). The inside of the steel barrel is heated to simulate high temperature conditions. The steel sheet, thickness 10.0 mm, is set under the steel barrel and is considered the ladle bottom shell. The upper nozzle, inner diameter 55.0 mm, is placed in the center of the steel barrel. Refractory bricks are laid under the upper nozzle, and its thickness is equal to the distance between the coil and ladle bottom shell. The upper nozzle is filled with Fe-C alloy particles. The Fe-C alloy particles are cylindrical with diameter 2.0 mm and height 2.0 mm; the Fe-C alloy composition is shown in Table 1. Another induction coil wound around the upper nozzle is connected to the induction heating power supply 2# (rated power is 60 kW, and rated frequency is 40 kHz). This coil with inner diameter 250.0 mm and six turns consists of pure copper and stainless steel. A thermocouple is used to measure the environmental temperature inside the steel barrel.

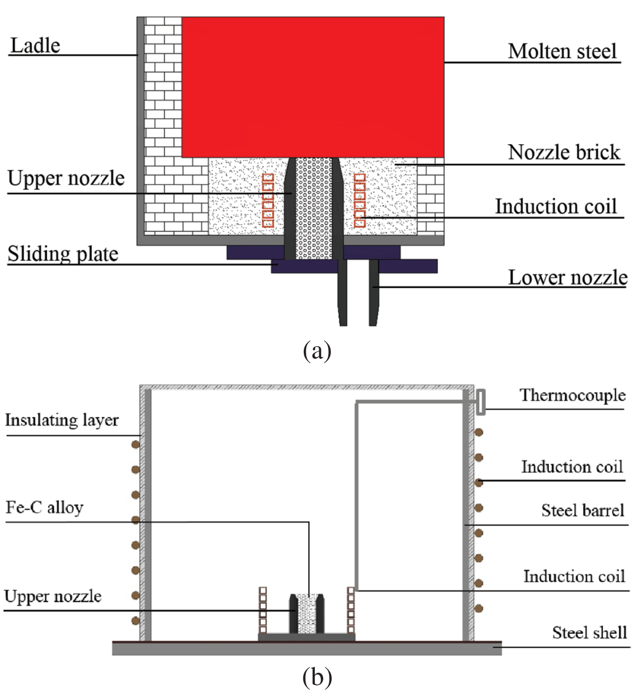

Figure 1: Schematic diagram of the electromagnetic induction heating steel teeming technology: (a) basic principle, (b) high temperature experimental device.

Experimental method

In the industrial experiments, Fe-C alloy is divided into four layers under the action of high temperature molten steel [10]: the melting layer, the liquid sintering layer, the solid sintering layer and the original layer. The original layer falls automatically after opening the slide gate. To compare the effect of different powers and frequencies on the heating effect of the Fe-C alloy, the melting length of the Fe-C alloy was investigated. In the high temperature experiments, the definition of melting length is the distance between the upper end and the non-melted original layer of Fe-C alloy within upper nozzle. When the melting length is at least 82.0 mm, steel teeming can be completed successfully [11].

During the high temperature experiments, the induction heating power supply 1# was switched on first to heat the air inside the steel barrel. When the thermocouple showed a temperature of 973 K, the power was reduced. The thermal insulation time was 30 min. Then power supply 1# was switched off and power supply 2# was switched on. The Fe-C alloy particles were heated for

Table 1: Components of the Fe-C alloy particles.

Fe-C alloy	C	Si	Mn	P	S	Cu	Ni
Components	0.07 ~ 0.13	0.17 ~ 0.37	0.35 ~ 0.65	≤ 0.035	≤ 0.035	≤ 0.25	≤ 0.25

120 s at different power and frequency conditions, and the melting length of the Fe-C alloy was measured each time. To improve the accuracy of the results, experiments were carried out in duplicate.

In addition, removing the steel barrel and installing magnetic shielding material with thickness 2.0 mm between the induction coil and the steel sheet was proposed to reduce the power loss of the power supply. After removing the Fe-C alloy, the power loss was analyzed with or without the steel barrel and with or without the magnetic shielding material.

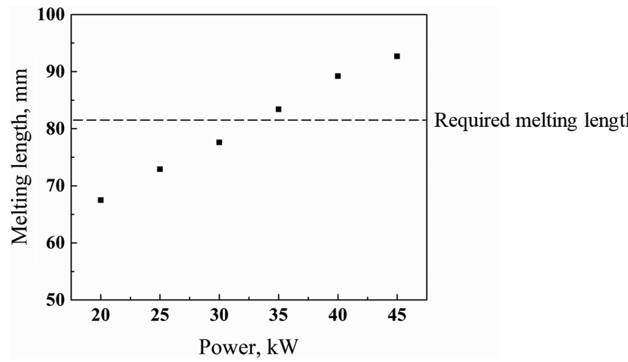

Figure 2: Effect of power on the melting length of the Fe-C alloy.

Results and discussion

Influence of different power supply parameters on heating efficiency

The induction heating power supply plays a vital role in industrial experiments of electromagnetic induction steel-teeming technology. Power and frequency are the main factors that affect the heating effect of the Fe-C alloy. To assess the effect of different parameters, the melting length of the Fe-C alloy was measured and compared at different powers and frequencies.

Effect of power on heating efficiency

To analyze the effect of power on the heating effect, the frequency was set to 25 kHz, and the power was set to 20 kW, 25 kW, 30 kW, 35 kW, 40 kW or 45 kW. The Fe-C alloy was heated for 120 s. After heating and cooling, the melting length of the Fe-C alloy was measured, and the results are shown in Figure 2.

It can be seen from the figure that the melting length of the Fe-C alloy increased linearly with increasing power. When the power was 35 kW, the melting length of the Fe-C alloy reached 83.4 mm, which meets the requirements. Owing to the limitations of the experimental apparatus, the power could not be increased above 45 kW. However, it can be predicted that the Fe-C alloy will melt more quickly at higher powers, allowing for a shorted heating time and maintaining a better production rate. To limit the experimental cost and improve the possibility of success, the selected power of the power supply is 40 kW, and the corresponding melting length of the Fe-C alloy is 89.2 mm.

Effect of frequency on heating efficiency

Similarly, to analyze the effect of frequency on the heating effect, the power was set to 40 kW, and the frequency was set to 15 kHz, 20 kHz, 25 kHz, 30 kHz, 35 kHz or 38 kHz. The Fe-C alloy was heated, and heating time is also 120 s. After heating and cooling, the melting length of the Fe-C alloy was measured, and the results are shown in Figure 3.

As the frequency increases, the melting length of the Fe-C alloy increases gradually. The melting length

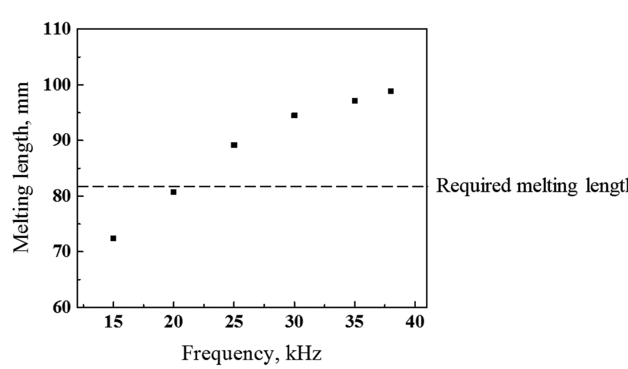

Figure 3: Effect of frequency on the melting length of the Fe-C alloy.

reached 89.2 mm when the power was 40 kW and the frequency was 25 kHz, which meets the industrial experimental requirements. However, the rate of increase in melting length decreases with increasing frequency. The main reason is, when the gap between Fe-C alloy and the induction coil is determined, the reactive power maintained in the gaps increases with the increasing of frequency. In addition, increasing the frequency of power supply increases the experimental cost substantially, so the selected frequency is 25 kHz.

The methods of decreasing power loss of power supply

During the high temperature experiments, the power loss of power supply was obvious. The heat loss on the steel barrel and the steel sheet was particularly apparent. In the industrial experiments, the average distance between the coil and the ladle side shell is 900.0 mm, and the distance is greater than that between the steel barrel and the coil. Thus, removing the steel barrel after the environment temperature reached 973 K was proposed. In addition, to reduce heating for steel sheet, based on the principle of magnetic shielding, installing the magnetic shielding material under the induction coil was proposed.

After removing the Fe-C alloy particles, when the currents were 160 A and 230 A, the power loss was investigated with or without the steel barrel. The results are shown in Figure 4. From Figure 4, it can be found that power loss decreased substantially without the steel barrel under the same current condition. When the current was 160 A and 230 A, the decrease in amplitude was 57.4 % and 57.5 %, respectively. In the experiments with the steel barrel, when the Fe-C alloy was heated by the induction coil, the steel barrel was also heated at the same time, greatly increasing the power loss. In contrast, during actual industrial experiments, the heating generated by the induction coil in the ladle side shell, and thus the resulting power loss, can be neglected.

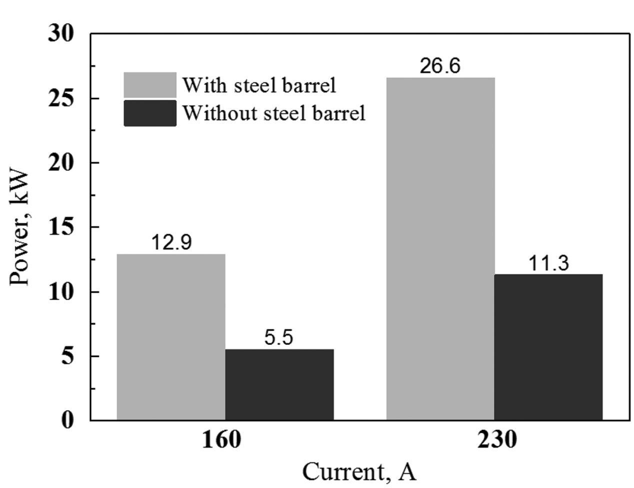

Figure 4: Power loss in different currents with or without the steel barrel.

Finally, when the current was 160 A and 230 A, the power loss was investigated with or without the magnetic shielding material. The results are shown in Figure 5. When the ambient temperature was 973 K, after removing the steel barrel and installing the magnetic shielding material, the power loss decreased substantially. When the current was 160 A and 230 A, the decrease in power loss was 64.4 % and 64.3 %, respectively. The magnetic shielding material has a shielding effect on the magnetic field. This can reduce the heating effect on the steel sheet dramatically, and improve the heating efficiency of the power supply. In industrial experiments, installing magnetic shielding material under the coil also can effectively reduce the temperature of the ladle bottom shell, and improve the safety and reliability of the electromagnetic induction steel teeming process.

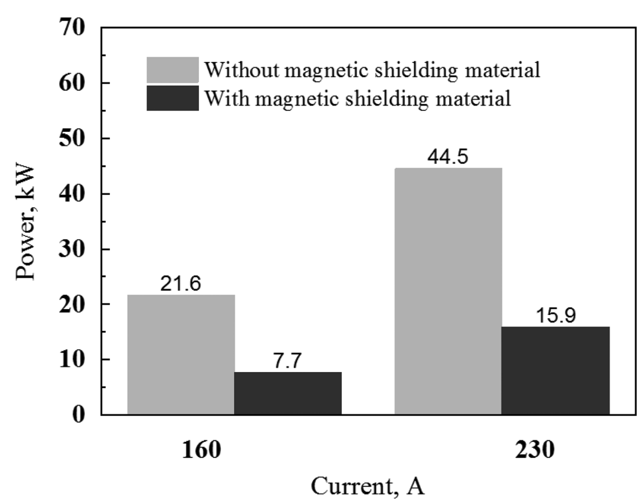

Figure 5: Power loss in different currents with or without the magnetic shielding material.

Conclusions

(1) The melting length of the Fe-C alloy can reach 89.2 mm when the power is 40 kW and the frequency is 25 kHz, which meets the requirements for the

electromagnetic induction heating steel-teeming technology.

(2) When the frequency is constant, the melting length increases linearly with increasing power. When the power is constant, the rate of increase in the melting length decreases gradually with increasing frequency. When the power and frequency are large enough, the heating time can be shortened to better maintain the production rate.

(3) After removing the Fe-C alloy, installing magnetic shielding material under the coil can reduce the power loss dramatically, by up to about 64 %. Therefore, the proposed method can improve the heating efficiency of the power supply. In actual industrial experiments, this magnetic shielding material can reduce the temperature of the ladle bottom shell, improving the safety and reliability of the electromagnetic induction steel-teeming technology.

Funding: This research was supported by the National Natural Science Foundation of China (Grant No. U1560207).

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