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Effect of Temperature on Dephosphorization of Ferrosilicon using Electromagnetic Levitation Technology under Vacuum

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Abstract. Electromagnetic levitation (EML) is a novel contact-less process which avoids the contaminant from the crucible at high temperature. EML is also praised for providing great kinetics condition. The technology plays a very good role in the dephosphorization of ferrosilicon for the photovoltaic industry. In this research, the influence of the magnetic field on the temperature field under levitated conditions is studied. Building the coupling model of magnetic field and temperature field. The research uncovered that the magnetic field where the specimens are changed corresponding to the shape of specimens. The range of the temperature of the temperature field where the specimens does not vary a lot. It's due to the Joule heat generated by electromagnetic stirring inside the sample, which makes the temperature uniform. Based on this, the effect of temperature on dephosphorization is researched. The experimental researches have shown that when the levitated ferrosilicon alloy (24% Fe-76% Si) is placed in the flow of argon-hydrogen gas, the phosphorus removal increases with both time and temperature. Upon approaching the equilibrium time point, the reaction becomes mass transfer limited in the liquid phase. It's observed that an equilibrium time point exists at approximately 45 minutes, for which the concentration of phosphorus remains constant, independent of increasing refining time. Higher processing temperature results in lower final [P] content, with a 72% rate of removal achieved after 40 minutes of levitation at 1720°C.

1. Introduction

Recently, the photoelectric conversion rate of solar grade silicon in the market is not high, which is mainly due to the relatively high content of phosphorus and boron in solar grade silicon. The existence of these two elements affects the efficiency of photoelectric conversion efficiency seriously[1]. The researchers found that electromagnetic levitation melting technology has some advantages in refining[3-7]. Moreover, under vacuum conditions, phosphorus and boron in ferrosilicon can be reduced to relatively low levels[1, 2]. It's friendly to the environment during the entire process at the same time. There are few reports on the research of the refining metals by the technology of electromagnetic levitation refining under vacuum conditions. In this research, the phosphorus in ferrosilicon can be reduced to a certain extent by levitation refining method, and it is found that temperature control is very important for the dephosphorization effect of ferrosilicon.

2. Research method

2.1 Model establishment and verification

Specimens of different shapes are selected to perform levitation refining under the same parameter conditions. Based on this, the simulation results of magnetic fields and temperature fields are analyzed using commercial software such as Ansoft Maxwell and Ansys Fluent. The formula for establishing a simulation model for suspended samples is shown in equation (1).

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=(\frac{a}{b}\times r)^2 \quad (1)$$

The five groups of data are substituted into equation (1) for modeling. Specific data are shown in Table 1. Among them, b is the value of the major axis for the Y axis of the coordinate axis, and a is the value of the minor axis for the X axis of the coordinate axis.

Table 1. Detailed model data

Sample No.	No.1	No.2	No.3	No.4	No.5
a	3	4	4	5	6
b	3	5	6	4	4

Putting the above five models into the previously established coil model. Add the excitation current to 220A, and add the frequency to 320kHz. The specific coupling method is shown in Table 2 below.

Table 2. Coupling method of magnetic field and temperature field

Data parameters inputted	Maxwell magnetic field calculation	Fluent temperature field calculation
Collection parameters of coil Power parameters Sample parameters	Maxwell equations Induced current Induced magnetic field Magnetic field distribution	Joule fever Navier-Stokes equation Temperature field distribution

In this research, the simulation results of the magnetic field and temperature field coupling model are verified. The source of heat and momentum inside the droplet are provided by an experimentally validated "electromagnetic induction" model[8,9]. Compared this simulation result with that of Spain et al.[10] it can be seen that the distribution of the internal flow field of the droplet is relatively close, and the maximum flow rate inside the droplet is within the same order of magnitude.

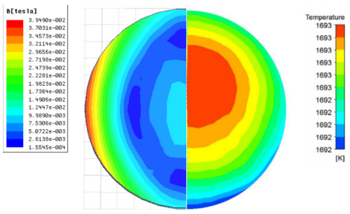
2.2 Experimental route

The dephosphorization of ferrosilicon (24%Fe-76%Si) is studied in detail by using electromagnetic levitation refining method. Determining the best experimental parameters and revealing the influence of temperature on the dephosphorization effect of ferrosilicon. During the experiment, the levitation chamber is filled with high-purity argon—high-purity hydrogen gas to make it into a vacuum state, and the entire experiment is conducted to keep the gas mixture filled the entire levitation chamber.

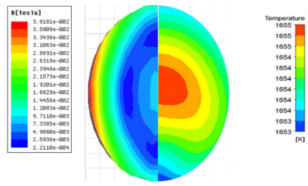
3. Results and analysis

3.1 Simulation results and analysis

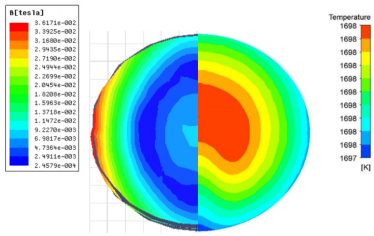
The results of Maxwell magnetic field simulation and workbench temperature field simulation of five groups samples are shown in Figure 1(a)-(e) below, where the left pictures show the magnetic field cloud diagram and its magnetic field range, and the right pictures show the temperature field cloud diagram and its temperature range.



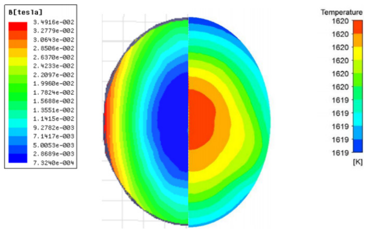
(a) No.1 samples



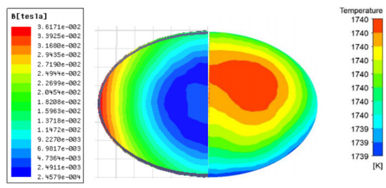
(b) No.2 samples



(c) No.3 samples



(d) No.4 samples



(e) No.5 samples

Figure 1. Coupling simulation results of magnetic field and temperature field of sample

It can be seen from Figure 1 that due to the effect of skin effect, the magnetic field gradually decreases from the boundary of the specimen to the interior of the specimen, while the temperature field is just the opposite, showing a trend of decreasing from the inside to the outside. From the temperature range, it can be seen that the temperature gradient of the temperature field of the sample is small, only differing by about 1K (1℃). For the reason that, the influence of temperature gradient on the magnetic field and other parameters of the suspended environment of the sample can be ignored under normal conditions. And the influence of temperature on the dephosphorization effect of ferrosilicon is ruled out, which makes the experimental study easier and smoother.

3.2 Experimental results and analysis

Experimenting on the basis of simulations. Figure 2 shows results for the phosphorus removal rate ([P]t/P]i]), where [P]t denotes the phosphorus concentration at time t, and [P]i represents the initial phosphorus concentration of the alloy. The data presented shows the increase in phosphorus removal rate with temperature. The removal of phosphorus increases with both time and temperature. Upon approaching the equilibrium time point, the reaction becomes mass transfer limited in the liquid phase. It is observed that an equilibrium time point exists at approximately 45 minutes, for which the concentration of phosphorus remains constant, independent of increasing refining time. Higher processing temperature results in lower final [P] content, with a 72% rate of removal achieved after 40 minutes of levitation at 1720° C. With the continual and increased mass transport of P to the interface, the chemical reaction limited regime, which involves the transition of P to adsorbed and gaseous states, is eventually reached.

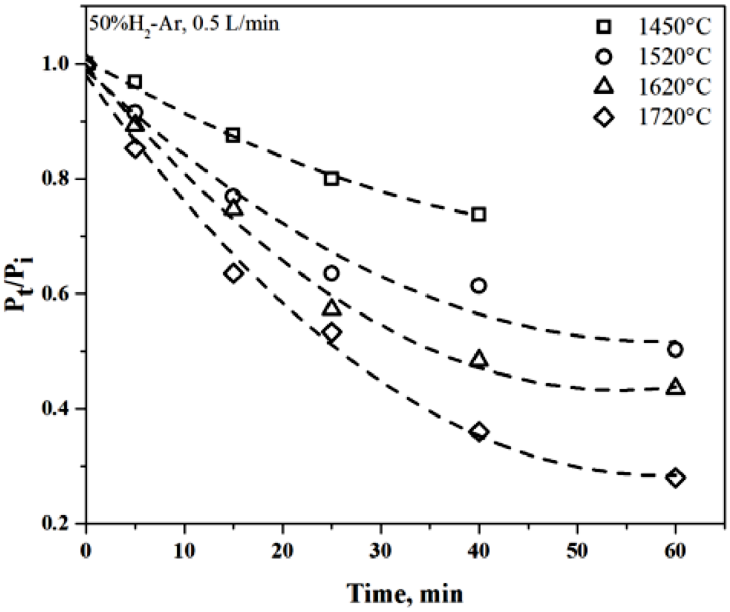


Figure 2. Effect of time and temperature on dephosphorization

4 Conclusions

(1) Through simulation studies, it is found that due to the effect of skin effect, the magnetic field gradually decreases from the boundary of the droplet to the interior of the sample, while the temperature field is the opposite, showing a trend of decreasing from the inside to the outside. It can be seen from the temperature range that the temperature gradient of the temperature field of the sample is small, which is due to the electromagnetic stirring inside the droplet to generate Joule heat and evenly distribute it. Therefore, the influence of temperature gradient on the magnetic field and other levitation environment parameters of the sample can be ignored under normal conditions.

(2) The experimental researches have shown that when the suspended ferrosilicon alloy (24% Fe-76% Si) is placed in the flow of argon-hydrogen gas, the phosphorus removal increases with both time and temperature. Upon approaching the equilibrium time point, the reaction becomes mass transfer limited in the liquid phase. It's observed that an equilibrium time point exists at approximately 45 minutes, for which the concentration of phosphorus remains constant, independent of increasing refining time. Higher processing temperature results in lower final [P] content, with a 72% rate of removal achieved after 40 minutes of levitation at 1720℃.

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