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Removal of SiC particles from solar grade silicon melts by imposition of high frequency magnetic field

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Abstract: Non-metallic particles and metallic impurities present in the feedstock affect the electrical and mechanical properties of high quality silicon which is used in critical applications such as photovoltaic solar cells and electronic devices. SiC particles strongly deteriorate the mechanical properties of photovoltaic cells and cause shunting problem. Therefore, these particles should be removed from silicon before solar cells are fabricated from this material. Separation of non-metallic particles from liquid metals by imposing an electromagnetic field was identified as an enhanced technology to produce ultra pure metals. Application of this method for removal of SiC particles from metallurgical grade silicon (MG-Si) was presented. Numerical methods based on a combination of classical models for inclusion removal and computational fluid dynamics (CFD) were developed to calculate the particle concentration and separation efficiency from the melt. In order to check efficiency of the method, several experiments were done using an induction furnace. The experimental results show that this method can be effectively applied to purifying silicon melts from the non-metallic inclusions. The results are in a good agreement with the predictions made by the model.

Key words: SiC particle; electromagnetic separation; solar grade silicon (SoG-Si); photovoltaic cells; computational fluid dynamics (CFD); non-metallic particles; metallic impurities

1 Introduction

Carbothermic reduction of quartz in submerged arc furnaces is the established process in order to produce metallurgical grade silicon (MG-Si). The liquid silicon produced at temperatures around 2000 °C contains dissolved carbon. After tapping the melt from the furnace, additional SiC particles will be formed, as the solubility of carbon in liquid silicon decreases with falling the temperature [1].

One of the important applications of silicon is in making of photovoltaic solar cells. Existence of SiC particles in the solidified silicon can cause shunting in the solar cells as well as affecting the mechanical properties of the cells. Therefore, these inclusion particles must be removed from the silicon melt before solar cells are fabricated.

Electromagnetic processing of materials (EPM) has been widely applied to the continuous casting of steel like electromagnetic stirring and electromagnetic braking for the purpose of clean steel production [2]. Recently, effective separation methods of non-metallic inclusions from liquid steel have been more searched because of the strong demand for higher cleanliness of steel products. Concerning nonferrous metals like aluminium and copper, the situation is the same. Especially for recycling of aluminium, fine inclusions from molten scrap must be removed. Electromagnetic (EM) separation based on the works done by LEENOV and KOLIN [3] and MARTY and ALEMANY [4], is one of the most promising methods for inclusion removal. Various methods have been proposed to generate EM forces in liquid metals: imposition of alternating current [5], simultaneous imposition of alternating current and AC magnetic field [6,7] and imposition of AC magnetic field [8−10].

It is well known that silicon has a quite low electrical conductivity (σ_s=5×10^4 S/m) in the solid phase. However, liquid silicon has an electrical conductivity of σ_m=1.23×10^6 S/m, which is approximately twenty five times more than the solid conductivity [11]. Such high electrical conductivity of the silicon melt makes it possible to remove the nonconductive inclusions from the melt using electromagnetic separation method. In the

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current research, the feasibility of electromagnetic separation method for removal of SiC particles from silicon melt is studied.

2 Principle of electromagnetic separation

According to Leenov-Kolin's theory [3], when a uniform electromagnetic force is applied to a liquid metal, the metal is compressed by the electromagnetic force and a pressure gradient is generated in the metal. The nonconductive particles in the liquid metal receive only pressure because they do not experience the electromagnetic force. This phenomenon is simply shown in Fig. 1.

LEENOV and KOLIN [3] derived a theoretical expression of the force acting on a single sphere suspended in liquid metal in the case that the electrical conductivities of the sphere (σ_p) and liquid (σ_L) are different. The equation is

$$\boldsymbol{F}_p = -\frac{3}{2}\cdot\frac{\sigma_L - \sigma_p}{2\sigma_L + \sigma_p} V_p \boldsymbol{F} \tag{1}$$

where $\boldsymbol{F}_p$ is the separation force acting on a sphere; V_P is the volume of the sphere and $\boldsymbol{F}$ is the electromagnetic force (EMF) given by:

$$\boldsymbol{F} = |\boldsymbol{J}\times\boldsymbol{B}| \tag{2}$$

where $\boldsymbol{J}$ is the induced current density; $\boldsymbol{B}$ is the magnetic flux density.

This separation force does not include the effect of fluid flow around the spherical particle because the viscous force cancels out totally on the sphere. As the inclusion particles are nonconductive compared with the liquid metal in general, σ_p is zero in Eq. (1) and the following equation is obtained:

$$\boldsymbol{F}_p = -\frac{3}{4}\cdot\frac{\pi d_p^3}{6}\boldsymbol{F} \tag{3}$$

where d_p is the particle diameter.

In the case where the AC magnetic field is imposed alone, the induced electromagnetic force should be restricted in a skin depth given by the following equation:

$$\delta = \frac{1}{\sqrt{\pi f \mu_L \sigma_L}} \tag{4}$$

where μ_L is the relative liquid permeability.

The skin depth becomes thin with increasing the frequency, *f*. In order to enhance the separation, the mean convection velocity and turbulent dissipation are effective to carry particles from the bulk of liquid to the vicinity of the wall, where a strong electromagnetic force captures them. Using the physical properties of the silicon melt (Table 1) and frequency of the induction furnace (Table 2), the skin depth δ is equal to about 4.33 mm.

Table 1 Physical properties of silicon melt and SiC particles [11,12]

Material	Density/ ($kg\cdot m^{-3}$)	Electrical conductivity/ ($S\cdot m^{-1}$)	Viscosity/ ($Pa\cdot s^{-1}$)	Melting point/°C
Silicon (melt)	2560	1.23×10^6	0.00075	1415
SiC	3185	0.0001−1	−	2735

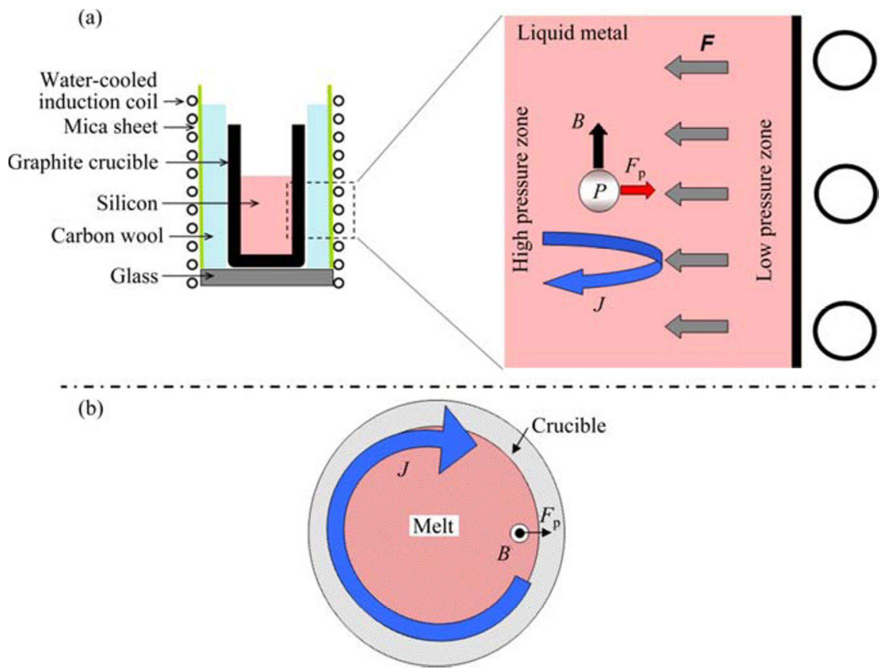

Fig. 1 Graphical presentation of principle behind electromagnetic separation of nonconductive inclusions from liquid metals (a) and electromagnetic forces inserted on particle in cross section of melt (b)