

Effects of Excitation Current on Levitation Force of Electromagnetic Levitation of Silicon-Iron Droplets

P Yan^{1,2}, G F Zhang^{1,2*}, B H Shi^{1,2}, W Zheng^{1,2}, Q Jiang^{1,2}, L Gao^{1,2}, Z Shi^{1,2}, Y D Yang^{1,3}

¹ Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Yunnan, Kunming, 650093, China

² Key Laboratory of Complex Iron Resources for Clean Metallurgy, Education Department of Yunnan Province, Yunnan, Kunming, 650093, China

³ Department of Materials Science and Engineering, University of Toronto, Toronto, Ontario, M5S3E4, Canada

E-mail: zgf@kmust.edu.cn

Abstract. In this paper, the relationship between the extraction current and the magnetic field had been discussed when the droplet was in the condition of vacuum electromagnetic levitation. The conclusion which the magnetic field was asymmetric could be simulated by finite element analysis in ANSYS software. Meanwhile, the shape of Silicon-Iron droplet was inferred as “up-wide and down-narrow” basing the magnetic field simulation results.

1. Introduction

As an advanced contactless melting technology, electromagnetic levitation has been widely applied to the research of new metallurgical technology[1-2]. At present, in order to reduce the production cost of solar grade silicon and develop new material preparation technology for environmental protection and energy saving, G F Zhang team of Kunming University of Science and Technology is researching the mechanism of simultaneous removal of phosphorus, boron and arsenic impurities in metallurgical grade silicon by electromagnetic levitation. However, the main difficulties in the study are as follows: (1) The electromagnetic levitation process is complex, the fluctuation of the suspended material easily leads to the experimental error, which affects the accuracy of the research results of the mechanism; (2) The impurity removal effect arousing by the transfer process inside the droplet is rather difficult to predict[3-5]. So, numerical simulation method[6] is used to simulate the levitation force of different conditions of silicon iron droplets under electromagnetic suspension in this paper. Meanwhile, the results would provide guidance for the experiment and mechanism of dephosphorization of metallurgical grade silicon and ferrosilicon alloy under the condition of electromagnetic suspension.

2. Research Methods and Theoretical Analysis

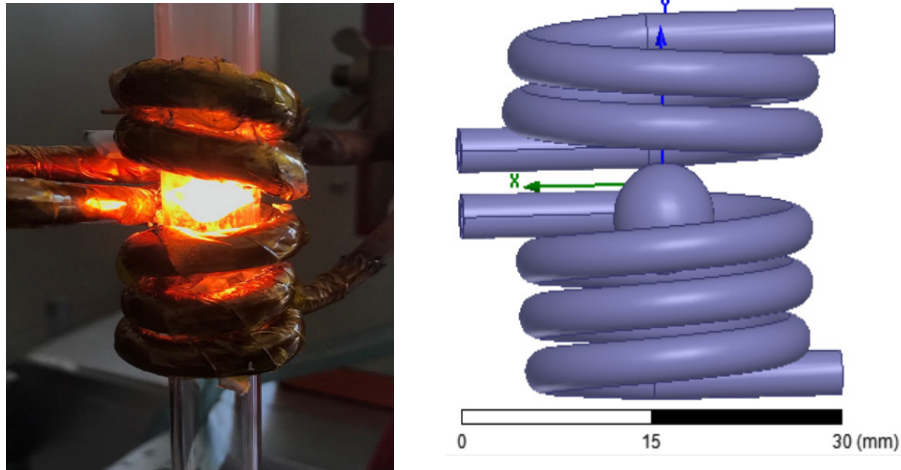
2.1 Simulated Calculation

In this paper, the Maxwell module of commercial finite element calculation software ANSYS 15.0 was used to research the electromagnetic force of electromagnetic levitation system by building the "Electromagnetic Induction Model". According to the actual measurement of electromagnetic



levitation equipment, an approximate geometric model of the electromagnetic suspension system was established. In order to simplify calculations, the droplet are approximated to spheres[7], and the coils are simplified as concentric circles with different declination. The centre of coordinate system selected by model is the droplet centre, and the positive direction of Y axis is the opposite direction of gravity.

The levitation system was shown in Figure 1 (a) and Figure 1 (b). The Figure 1 (a) is actual image of levitation system in working position. The Figure 1 (b) is model image of levitation system.



(a) EML equipment

(b) Levitation model of EML

Figure 1. Levitation model of EML equipment

2.2 Theoretical Analysis of Simulation Calculation

The theoretical formula involved in the process of model building were showed in above formulas. Electromagnetic field-Maxwell's electromagnetic equations were listed in formula (1) to formula (4)[8-9].

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}_s + \mathbf{J}_e + \mathbf{J}_v + \frac{\partial \mathbf{D}}{\partial t} \quad (1)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (3)$$

$$\nabla \cdot \mathbf{D} = \rho_1 \quad (4)$$

Calculation formula of transient electromagnetic force was showed in formula (5).

$$\mathbf{F} = \frac{1}{2} \int_{\text{vol}} \mathbf{N}^T (\mathbf{J}^* \times \mathbf{B}) d(\text{vol}) \quad (5)$$

Where $\mathbf{H}$ is magnetic field intensity vector, $\mathbf{J}$ is Total current density vector, $\mathbf{D}$ is electric flux density vector, t is time, $\mathbf{J}_s$ is applied source current density vector, $\mathbf{J}_e$ is induced eddy current density vector, $\mathbf{J}_v$ is velocity current density vector, $\mathbf{E}$ is electric field intensity vector, $\mathbf{B}$ is magnetic flux density vector, ρ_1 is electric charge density, $\mathbf{F}$ is levitation force, $\mathbf{N}$ is vector of shape functions, $\mathbf{J}^*$ is complex conjugate of $\mathbf{J}$.

2.3 Sample Property

The sample designed for the simulating computation in this paper is similar to the ferrosilicon (76Si-Fe) used in experimental research. Meanwhile, its electrical conductivity is 1820000 s/m, and density is 3.2 g/cm³. Meanwhile, the diameter of droplet was determined to 5.4 mm according to the actual experiment operation.

3. Results and discussions

Current is an important factor affecting electromagnetic force in the Maxwell equation set[10]. The acting force producing by levitation coil has closely relationship with its excitation current. So, the

bearing conditions of droplet in different current were discussed which the current frequency is set to 200 kHz. Then, the above images (Figure 2 to figure 5) were about the magnetic field strength and force density of droplet in different current (100A, 200A, 300A, 400A). The Figure 6 was showed the force of Y axis in different extraction current. The figure 10 was an actual picture about the levitation droplet.

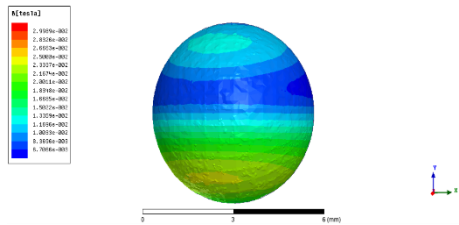


Figure 2. Magnetic field strength Simulation results in current of 400A

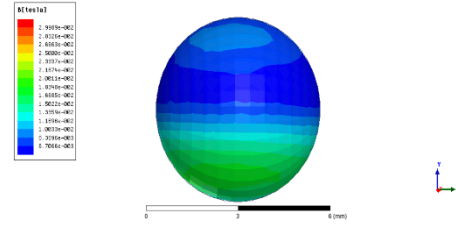


Figure 3. Magnetic field strength Simulation results in current of 300A

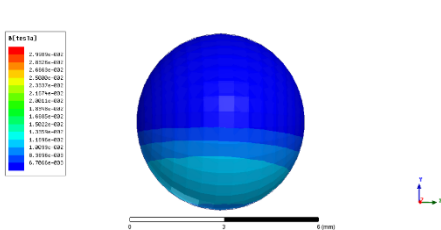


Figure 4. Magnetic field strength Simulation results in current of 200A

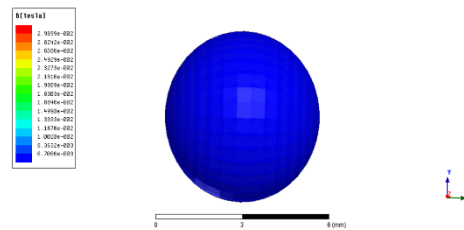


Figure 5. Magnetic field strength Simulation results in current of 100A

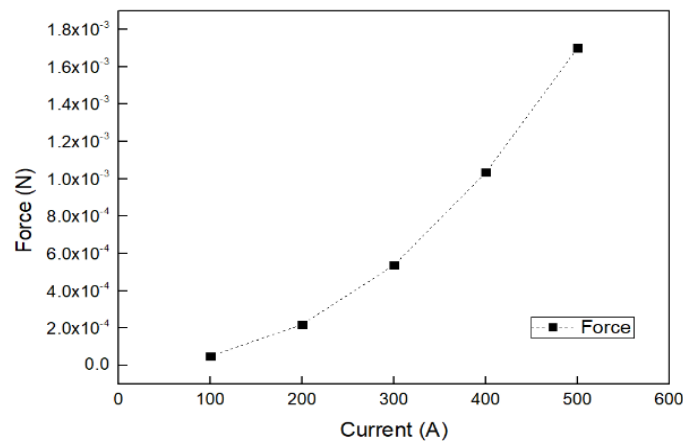


Figure 6. Calculation results about Levitation force in different current

As shown in Figure 2 to Figure 5, the excitation current has a lot to do with the magnetic field of the suspending droplet. Meanwhile, the magnetic field has much difference with the discussion in Y. Asakuma paper [11]. The magnetic field of droplet is unsymmetrical. The magnetic field strength of droplet's top is weaker than its bottom and the central section is weakest. Meanwhile, the formula 1 to formula 5 has stated that levitation force has intimate connection with extraction current. As shown in Figure 6, the intensity of magnetic field rose sharply with the increase of extraction current. Because the scale of force density in droplet's bottom is significantly greater than droplet's top and the direction of force is all toward the droplet center. So, the droplet in this coil would not be spherical when the ferrosilicon droplet was treated by vacuum electromagnetic levitation equipment.

4. Conclusions

(1) The Magnetic field distribution and Levitation force have positive correlation with the extraction current when the sample was treated by electromagnetic levitation equipment.

(2) The magnetic field distribution of droplet surface was asymmetrical and its tendency of magnetic field was “up-small and bottom-large”. Then, the shape of droplet was concluded to “up-wide and down-narrow”.

Acknowledgments

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