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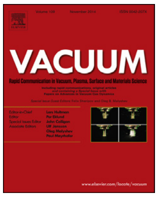

Rapid communication

Degassing of aluminum alloys *via* the electromagnetic directional solidification

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ABSTRACT

A new route for degassing of molten aluminum alloys has been developed *via* the electromagnetic directional solidification. We evaluated the degassing feasibility and mechanism for the formation and evolution of the porosity. As expected, it enabled the migration of porosity to the upper end instead of the distribution in the whole sample. Furthermore, we investigated the effects of various pull-down rates, *i.e.*, solidification rates on the degassing efficiency, porosity area fraction, and microstructure of alloys, *etc*. Clearly, the experimental results show that with the reducing of pull-down rates, the degassing efficiency increases and the porosity area fraction decreases, respectively. The lowest porosity area fraction is down to 0.08% under the 5 μm/s pull-down rate. Simultaneously, there are almost no porosity and other defects in the lower part of the final product. In conclusion, it offers an alternative method for degassing and possesses potential applications in aeronautic and space industry.

Porosity, which exists in almost all aluminum alloy castings [1], is detrimental to their mechanical properties and pressure-tightness [2]. It is widely recognized that the occurrence of porosity attributes to two main aspects, *viz*., (i) the shrinkage caused by the reduction of volume during the solidification; (ii) the solubility of gasses is different due to the phase distinction, namely, it has a remarkable decrease in solid phase compared with liquid phase [3]. Actually, hydrogen is considered to be the only significant gas dissolved in molten aluminum [4,5]. Thus, the elimination of the hydrogen in molten aluminum is crucial for producing high quality castings.

Several approaches have been explored for degassing in the past few decades, including re-melting degassing [3], vacuum degassing [6–8], ultrasonic degassing [9–12], and spray degassing [13,14], as well as, rotary impeller degassing with nitrogen, argon or a mixture of the inert gasses and chlorine as a purge gas [15–17], additionally, tablet degassing by hexachloroethane (C_2Cl_6) and so on [18,19]. Nonetheless, these established degassing methods have been demonstrated to be effective to various degrees in refining aluminum melt, they can cause environmental problems due to the usage of chlorine, or require a large amount of investment and special equipment. Up to now, to the best of our knowledge, no information is available for degassing of aluminum alloys *via* the electromagnetic directional solidification.

Hence, for developing a clean and environmentally friendly degassing route, we design herein a strategy for degassing of molten aluminum alloys under electromagnetic field with directional solidification. Moreover, we have verified the degassing feasibility and mechanism for the formation and evolution of porosity, the effects of various pull-down rates on the degassing efficiency, porosity area fraction, and microstructure of alloys. The optimal degassing conditions for the fabrication of high quality aluminum alloys have been obtained. It is our belief that we put forward an alternative method and a new concept for degassing which has potential applications in aeronautic castings.

The near eutectic Al-12.6%Si casting alloys were used in this investigation and prepared by the mixture of metallurgical grade silicon powder and pure aluminum powder. The main chemical compositions of pure aluminum were listed in Table 1. Initially, the

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Table 1
Chemical compositions of pure aluminum (%).

Element	Al	Si	Fe	Cu	N	Others
wt.%	99.00	0.30	0.60	0.05	0.01	≈0.04

alloys were held in a graphite crucible and placed in the middle of coil zone of a 60 kW high frequency induction furnace. Then heated the samples until they were completely molten at about 1073 K for 1 h. The temperature of the melt was measured by infrared thermometers and controlled within an accuracy of ±30–50 K. After melting, the samples were pulled down by the pulling system, the pull-down rates were controlled at 5–25 μm/s, and the pulling distance was 12 cm from the initial place. The argon was constantly poured through the quartz tube to prevent the melt from being oxidized. The schematic diagram of the experimental equipment was shown in Fig. 1.

Then, the alloys solidified continuously from bottom to top due to the natural cooling accompanied by pulling down. When the solidification completed, the samples were cut open along the longitudinal section to evaluate the degassing effect. The volume of the bubble cavity and the porosity area fraction of the product were measured quantitatively by injecting water and using an image analyzer. The samples were polished using standard metallographic techniques, the macro and micro structures of solidified samples were respectively photographed and observed by Sony digital camera and Olympus PME3 light optical microscope (LOM) along with a KAPPA image analyzer.

Firstly, we explored the degassing feasibility of electromagnetic directional solidification. The vertical cross-sections of samples solidified in different conditions were shown in Fig. 2. Initially, the solidification was performed under the condition of the electromagnetic stirring, and the bubbles generated from bottom to top across the sample [Fig. 2(a)]. Afterward, the directional solidification was took place by the addition of pulling down, this condition led the bubbles only distributed at the top of the samples [Fig. 2(b)]. From the experimental results above, we can conclude that when the downward directional solidification was absent, the bubbles were very difficult to be removed from the Al–Si melt owing to the large viscosity of the alloy melt. On the other hand, to pull down the sample at a certain rate, the temperature gradient was formed. What's more, the production of the solubility variation went with the formation of the temperature gradient. The solubility variation can be elucidated as follows: in general, the region with a higher temperature usually has a higher solubility of the bubbles [4], and *vice versa*. Accordingly, the bubbles which located in the lower temperature region would transfer to the higher temperature area, *i.e.*, the movement of the bubbles always intended to the higher solubility region. It proves that using electromagnetic directional solidification can be a good method for bubbles' directional movement and enrichment.

Based on the experimental results, we established a model to explain the degassing mechanism of electromagnetic directional solidification which was shown in Fig. 3. It is well known that most of the hydrogen atoms dissolved in molten aluminum come from the dissociation of water vapor at the surface of the liquid aluminum according to the reaction [20,21]: $2Al_{(l)}+3H_2O_{(g)} = Al_2O_{3(s)}+6H$. At the beginning, under the effect of electromagnetic stirring, the hydrogen atoms are fully released into the melt, and tiny cavitation bubbles which have smaller internal pressure are produced, they satisfy the formation conditions [22,23]:

$$p_{H_2} > p_{\text{outside}} = p_{\text{at}} + p_{\text{m}} + \frac{2\sigma}{R_{\text{b}}} \tag{1}$$

where p_{H_2} is the hydrogen pressure inside the bubble, kPa; p_{outside} is the external pressure outside the bubble, kPa; p_{at} is gas pressure above the molten alloy, kPa; p_{m} is the static pressure of the molten alloy column on the bubble, kPa;

$$p_{\text{m}} = 0.1h\gamma \tag{2}$$

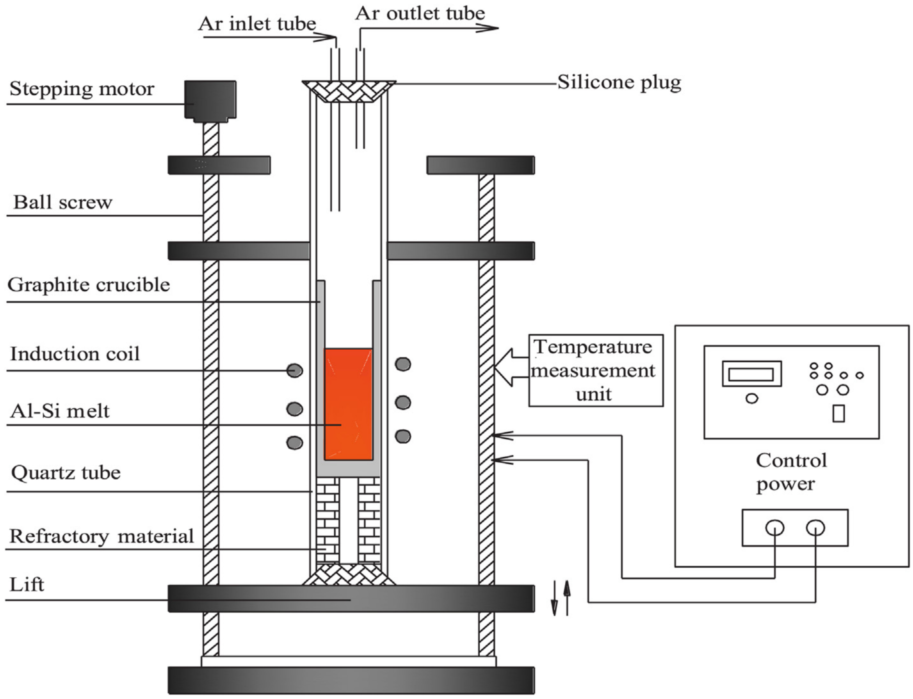

Fig. 1. The schematic diagram of the equipment.