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Mould filling ability and microstructure of aluminum alloy under electromagnetic die casting ①

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[Abstract] In order to solve the mould filling problem of large thin-walled aluminum alloy castings effectively, a new casting technology called electromagnetic die casting has been developed. Emphasis has laid on studying the mould filling ability and microstructure under the mentioned method. The results show that the mould filling ability of A357 is increasing continually with the increasing of the input voltage, that is, the magnetic induction intensity. The pressure head of the molten metal increases from the lowest one at the input of the mould to the highest one at the end of the mould while in a conventional mould the pressure head depends invariably on the sprue height. Under electromagnetic die casting, the grains of A357 alloy are refined, and the pattern of eutectic silicon of alloy changes from rough plate to smooth strip.

[Key words] cast aluminum alloy; magnetohydrodynamics; electromagnetic die casting; mould filling ability; microstructure

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1 INTRODUCTION

Cast aluminum alloys are widely used in aerospace, aeronautics, automobiles, mechanical manufacturing industries, etc., due to their desirable features such as low density, high specific strength. With the development of modern industries and new casting technologies, the demand for aluminum alloy castings has been increased, especially, with required features such as large sized, thin-walled, integrality[1,2]. However, the large radiating area and high solidification velocity of thin walled castings reduce the mould filling ability of melt greatly, hence it is necessary to apply special mould filling technologies[3]. Up to now, there exist several methods to produce large thin-walled and integral aluminum alloy castings including sequence crystallization casting, low-pressure casting, counter-pressure casting, squeeze casting, die casting and permanent mould casting, etc. But reasons of large equipment investment or complication processing make them limited application[4, 5].

Recently, a kind of method based on magnetohydrodynamics has been widely used in various metallurgical processes which can be utilized to carry out non-contact stirring, transporting and shape controlling of melt[6~9]. However, few results deal with the availability of such method in use of casting large and integral thin-walled aluminum alloy have been reported.

A357 alloy is one of the alloys in Al-Si-Mg system, which has excellent casting performance, eminent mechanical properties and rust-resisting capabilities[10] make it widely used in industries, especially in the aeronautics and aerospace industries[11~13]. When liquid alloy solidifies under electromagnetic die casting method, it is affected by the strong stirring of electromagnetic forces, which will make the structure of alloy change than that without the effect of electromagnetic forces.

With regard to development of casting technology for producing large thin-walled light alloy castings, the mould filling ability of alloy is the fundamental aspect. Therefore, in the present study, the mould filling ability and microstructure of aluminum alloy under so called electromagnetic die casting method has been investigated and discussed under different conditions including input voltage, pouring temperature, mould preheating temperature and moulding materials.

2 EXPERIMENTAL

2.1 Brief introduction to experimental apparatus

Fig. 1 shows a schematic drawing of apparatus used in the experiment. The experimental apparatus consists of an inductor, voltage transformer, magnetic-matrix switch and MHD-mould. A permanent mould in which the cavity having length of 570 mm, width of 140 mm and thickness of 3 mm and a gypsum mould, having cavity length of 550 mm, width of 160 mm and thickness of 2 and 5 mm have

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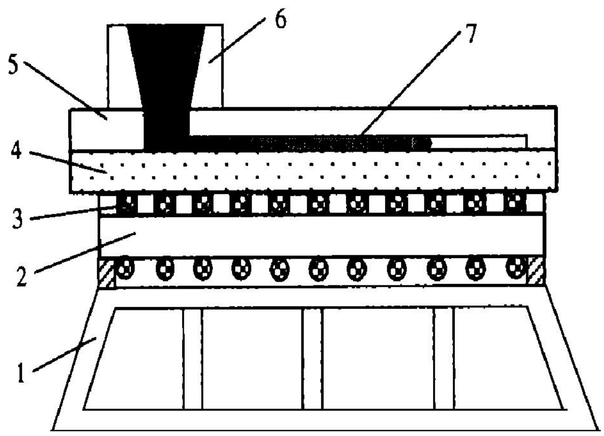

Fig. 1 Schematic diagram of electromagnetic die casting method
1 —Support; 2 —Iron core; 3 —Coil; 4 —Bottom half mould; 5 —Top half mould; 6 —Pouring gate; 7 —Casting

been used. The fundamental operating principle of this method can be described as follows. A mould of special design is employed, called magneto-hydrodynamic mould (abbr. MHD-mould) is placed on the inductor of a linear motor. When molten metal is pouring into the mould, the top half mould of MHD-mould which is made of ferromagnetic material (here steel used) and non-ferromagnetic materials (melt) compose a composite secondary pole. In this secondary pole, steel is mainly used for conducting magnetism, while melt for conducting electricity. Thus the whole secondary pole can be supposed to consist of infinite paralleling set conducting bars, then, the inductor supplied with an alternating current generates a variable magnetic field in the molten metal that, in turn, gives rise to an induced current. While three-phase current varies with time, the air-gap field will move along a line in the order of A, B, C, A and B. By the interaction between the eddy current and the air-gap magnetic field which is doing a line motion, the molten metal is subject to a pushing force which is in the state of relatively longitudinal motion between steel plate and inductor. And then, the melt will fill the mould under the effect of electromagnetic propulsive forces.

2.2 Comparison experiments on filling ability of alloy A357

The alloy used in experiments is namely A357 alloy, which is composed of high purity aluminum (≥99.9%), silicon (≥99.7%), pure magnesium (≥99.95%) and Al-3.37Be (impurity content is less than 0.39%) master alloy. Comparison experiments are carried out between castings solidified under the effect of electromagnetic field and castings solidified without any effect of electromagnetic field trying to clarify the effect of electromagnetic field upon the filling ability of the alloy.

To study the effect of the variation of the electromagnetic force on the filling ability of the molten metal, castings are made under different input voltages. Because the variations in input voltage result in the variations of the strength of the magnetic field which leads to the variations in the inductive force in the molten metal.

Besides the different input voltages in the inductor, the comparative effects of pouring temperature and preheating temperature of mould are also investigated.

2.3 Microstructure observation

The samples for microstructure observation were taken from the end away from pouring gate of plate castings of A357 alloy produced under the electromagnetic die cast method. Model Olympus BH2 Optical Microscope and model S-570 Scanning Electro-microscope were employed.

3 RESULTS

3.1 Filling ability of A357 alloy

Fig. 2 shows the influence of mould materials on

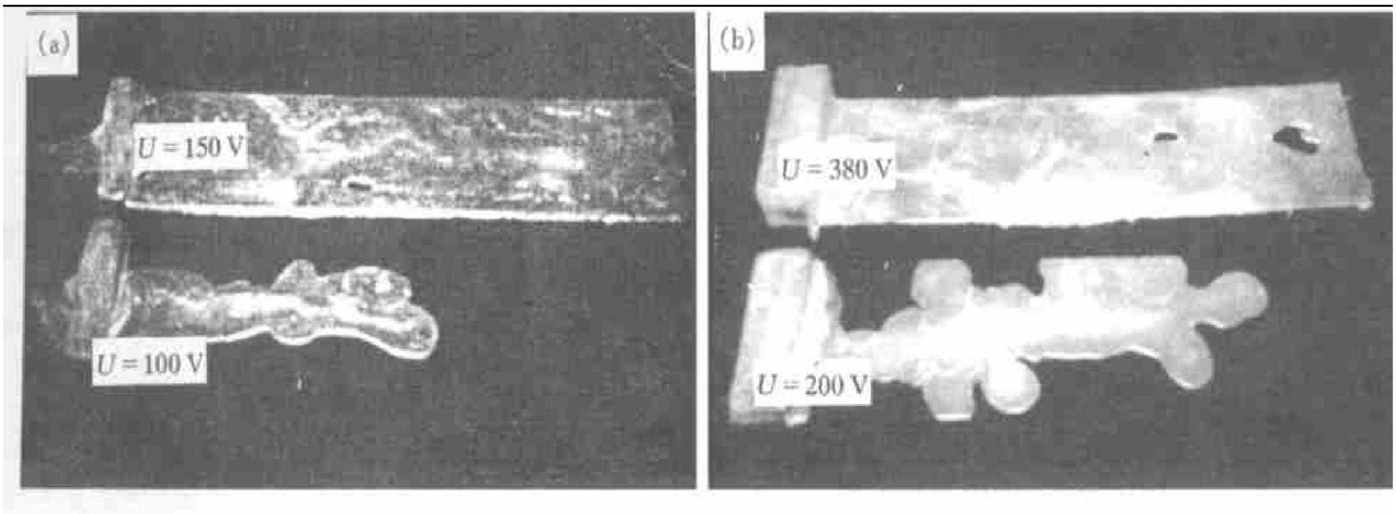

Fig. 2 Influence of mould materials on filling ability of A357 alloy under electromagnetic die casting
(a) —In permanent mould; (b) —In gypsum mould

the filling ability of plate castings that solidified under electromagnetic die casting method. In which Fig. 2(a) is in the permanent mould under the condition of input voltages as 100, 150 V respectively with the pouring temperature of 700 ℃; Fig. 2(b) shows the castings solidified in the gypsum mould under the condition of input voltages as 200, 380 V respectively with the same pouring temperature as above.

Fig. 3(a) shows the castings solidified in the permanent mould without the effect of electromagnetic field, pouring temperature is 660, 700, 740 ℃ respectively. The input voltage is kept to be a constant and then the pouring temperature is changed to certify the influence of the pouring temperature upon the filling ability under the effect of electromagnetic field. In these experiments the input voltage was set to be 380 V, pouring temperatures were 660, 700 and 740 ℃ respectively. Fig. 3(b) is used to compare with Fig. 3(a).

In order to get a quantitative comparison of the experimental results mentioned above, some histogram figures are obtained as shown in Fig. 4 to indicate the relationship between mould filling ability of A357 alloy and mould materials, pouring tempera-

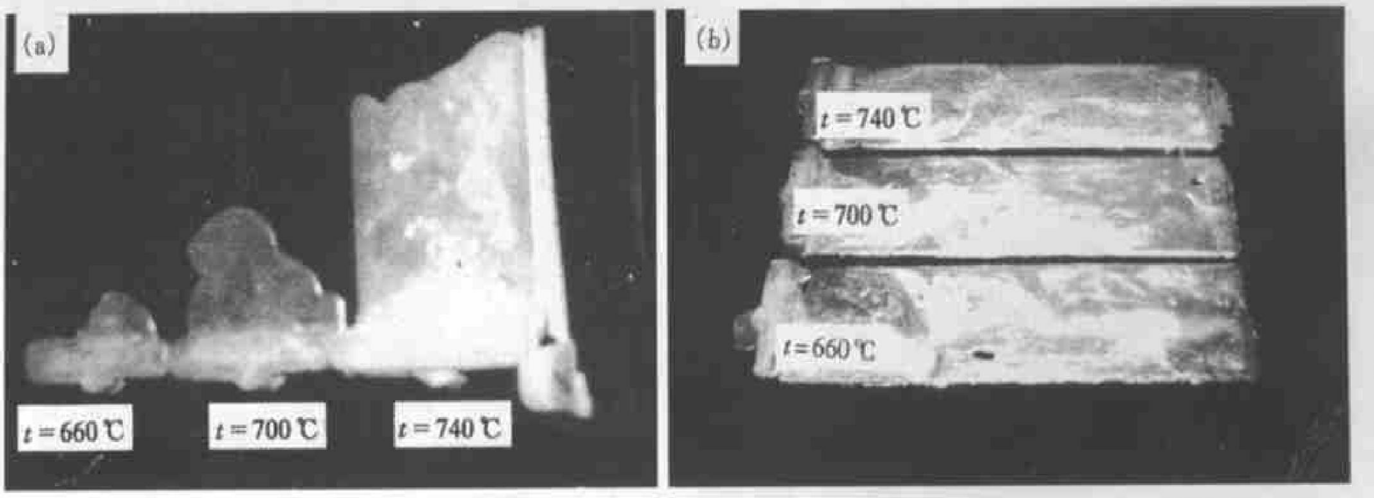

Fig. 3 Influence of pouring temperature on filling ability of A357 alloy in permanent mould with or without presence of electromagnetic
(a) —Without presence of electromagnetic field; (b) —With presence of electromagnetic field

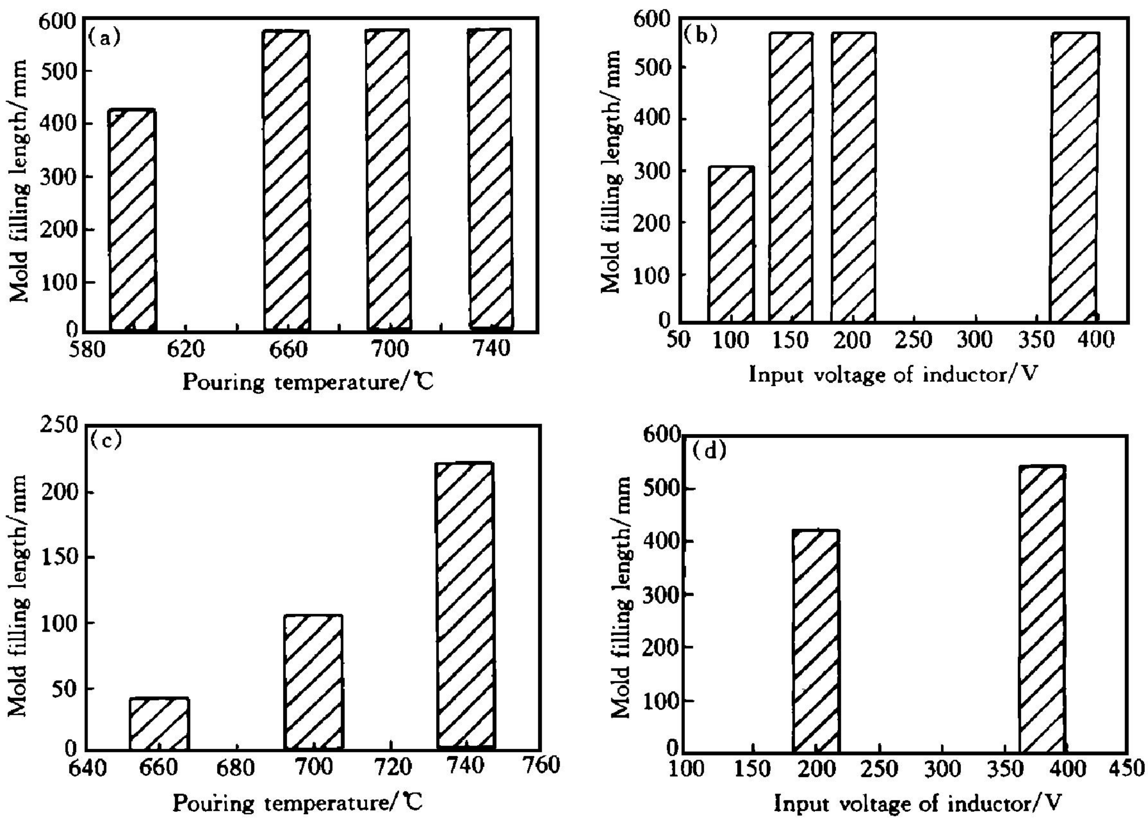

Fig. 4 Relationships between filling length of A357 alloy and pouring temperature and input voltage of inductor, respectively
(a) —With the presence of electromagnetic field; (b) —In permanent mould;
(c) —Without the presence of electromagnetic field; (d) —In gypsum mould

ture, and input voltage of the inductor, respectively. Fig. 4(a) shows the filling length is 425 mm when pouring temperature is 600 ℃, while as the pouring temperature is above 660 ℃, the mould cavity is fully filled. Fig. 4(b) shows: when pouring temperature is equal to 700 ℃, the filling length is 310 mm with input voltage to be 100 V. With the increase of input voltage, the filling ability of the melt increases also, when input voltage is larger than 150 V, the whole channel is filled. As shown in Fig. 4(c) when pouring temperature is 700 ℃, the filling length of the melt is 105 mm only. It means that the filling length decreases greatly without the effect of electromagnetic field. And in gypsum mould with thickness of 2 mm (shown in Fig. 4(d)), when input voltage is 200 V, the filling length of the melt is 423 mm. The most mould cavity is just filled when input voltage is equal to 380 V.

From the above figures, under the electromagnetic die casting condition, the filling ability of molten metal is greatly enhanced. The melt in the permanent mould can fill the full length of the cavity whenever input voltage is larger than 150 V.

3.2 Microstructures of plate castings

The effect of electromagnetic field on the grain size and shape of A357 alloy under different input voltages in inductor is shown in Fig. 5. When there is no presence of electromagnetic field, the grains in Fig. 5(a) have large size and sharp corner. Under the presence of electromagnetic field, the grains in Figs. 5(b) and (c) exhibit refinement and corner rounded. This is due to the electromagnetic force which induces oscillating motion act uniformly throughout the whole channel. As shown in Figs. 5(b) and (c), with the increase of input voltage, the size of grains decreases.

The morphologies of eutectic silicon phase are shown in Fig. 6.

The eutectic silicon in the alloy appears in the form of acicular and tabular (shown as Fig. 6(a)). On the surface of the acicular eutectic silicon, there are twin grooves and few tabular branches in the rib of acicular. It is shown in Fig. 6(b), when the input voltage is 200 V, the eutectic silicon appears as the form of fibers which has smaller size and more smooth surface than that of the silicon without the effect of electromagnetic field. When the input voltage is set to 380 V, the eutectic silicon in Fig. 6(c) is smaller than that in Fig. 6(d), the morphology of eutectic silicon varies with the change of pouring temperature, in this respect, low superheat is favored.

4 DISCUSSION

The filling ability of the molten metal is a complex property affected by the fluidity of metals and external factors such as mould properties, structure of casting. The fluidity of metals is affected by factors including solidification mode, superheat, and pressure head, mould coatings and metal treatments[14].

A357 alloy is solidified in the form of dendritic crystal. When molten metal is poured into the mould cavity, solidification begins to occur at the mould wall near the channel entrance. But due to the narrow solidification range, the liquid metal continues to flow through the center of the channel, those grains grow inwardly, gradually reducing the flow until the solid interfaces infringe upon each other, choking off and stopping the flow. In conventional casting methods,

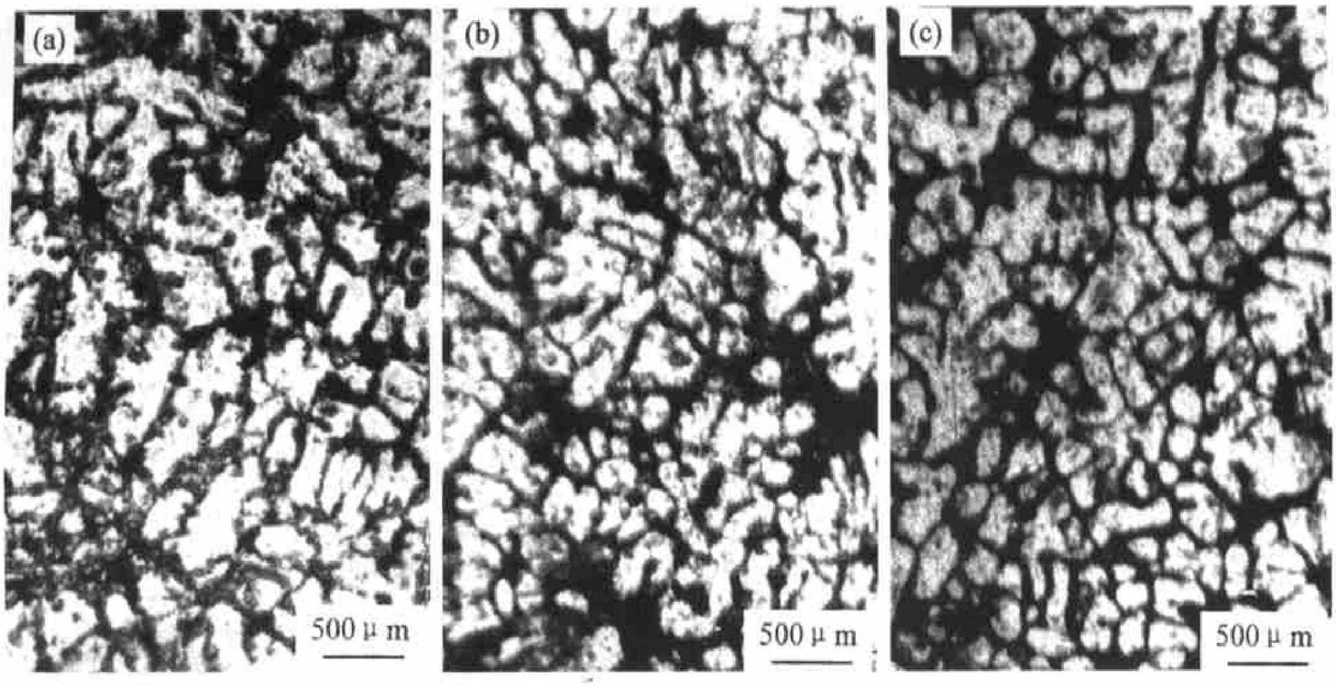

Fig. 5 Optical microstructures of A357 as-cast alloy
(a) —With no effect of electromagnetic field; (b) —Input voltage is 150 V; (c) —Input voltage is 380 V

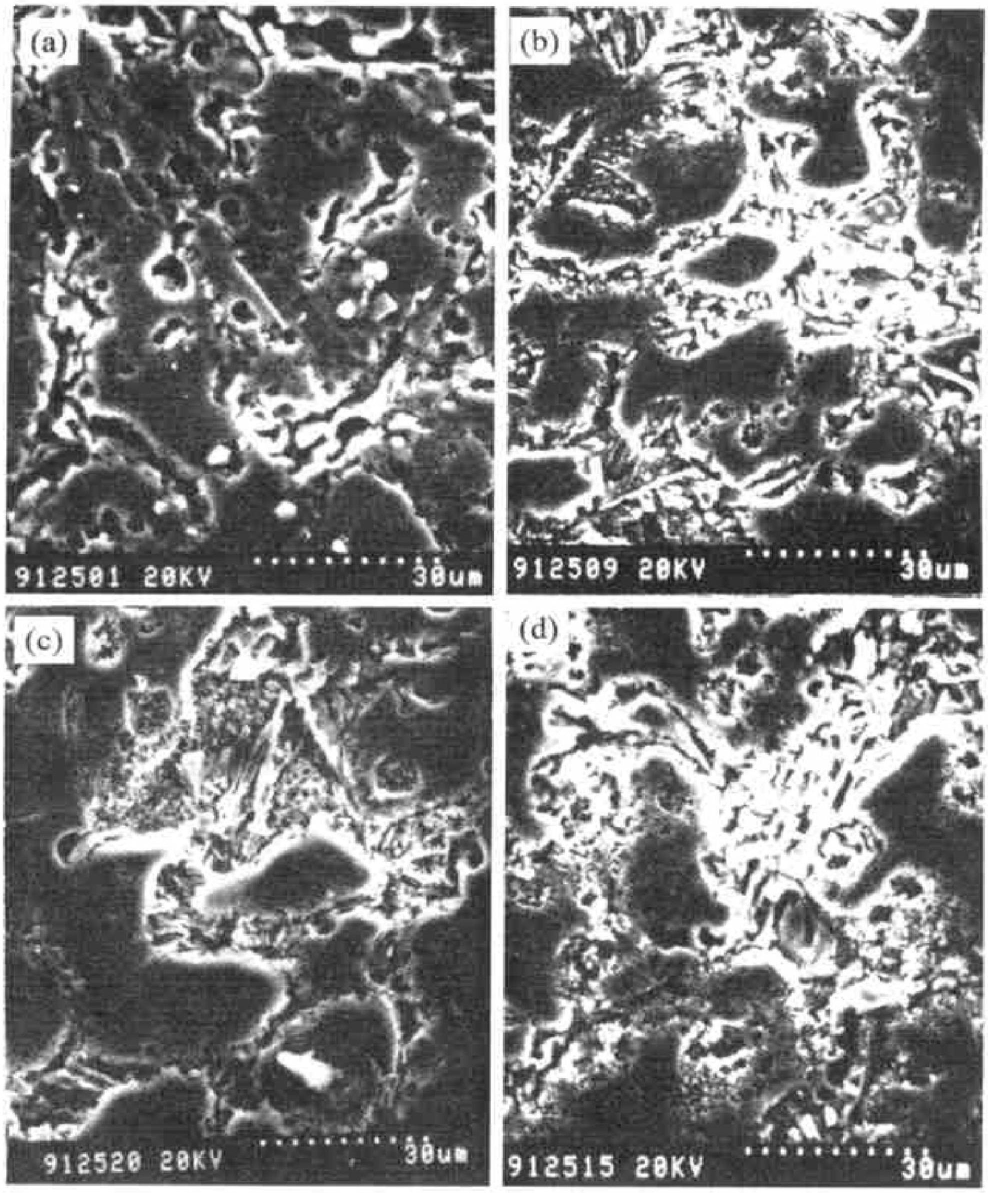

Fig. 6 Morphologies of eutectic silicon phase in castings made under different conditions
(a) —With no effect of electromagnetic field, pouring temperature 700 ℃;
(b) —Input voltage 200 V, pouring temperature 700 ℃;
(c) —Input voltage 380 V, pouring temperature 660 ℃; (d) —Input voltage 380 V, pouring temperature 740 ℃

the crystalline growth velocity is larger than the flow velocity of the molten metal when the molten metal is poured into the narrow mould cavity, so the molten metal cannot fill the whole mould cavity.

But in present method, the fluidity of the melt is enhanced with the increase of input voltage in the inductor. With the effect of electromagnetic field, the mould filling process of molten metal is different from those in other casting methods such as other pressure casting methods. It possesses the characteristic of applying electromagnetic forces directly in molten metal. During the process of pouring, with the movement of molten metal front along the horizontal direction of the mould cavity, the electromagnetic forces applied on molten metal increase continuously, which leads to the increase of resultant forces.

Then, some parameters include amplitude value (J_{om}), flux density (B), penetration depth (δ), action force (F) and filling pressure head (h) which describe the characteristic of electromagnetic die casting can be conduced as follow.

Firstly it is provided that the molten metal fills the whole entrance end of mould cavity when mould filling initiates, and the electromagnetic force propels molten metal forward. Then, to a certain specific cross-section, it can be assumed that equal volume of flow pass through per unit of time, which satisfied the fluid continuity conditions.

Here, amplitude value (J_{om}) of the molten metal in the electromagnetic field in the vertical direction of mould cavity can be given as Eqn. (1)[15]:

$$J_{om} = \frac{\sqrt{2} m w U}{K_1 K_2 P \tau \delta_e R} \tag{1}$$

where m is number of phase, w is number of coil,

U is input voltage in inductor, R is coil resistance of inductor, K_1 and K_2 are Carter's coefficient respectively, P is number of poles of inductor, τ is the pole pitch, and δ_e is depth of electromagnetic air gap.

The flux density of inductor in the horizontal direction of the mould cavity can be described as Eqn. (2)[15]:

$$B = \frac{\pi\rho}{\tau\omega} J_{om} e^{(-ay)} \sin(\omega t - ay + \lambda x) \quad (2)$$

where ρ is electrical resistance of molten alloy, λ is electromagnetic wavelength, a is coefficient, and ω is angel frequency of current.

Then, depth of penetration of magnetic flux in the molten alloy can be calculated by Eqn. (3):

$$\delta = \sqrt{\frac{\rho}{\pi\mu f}} \quad (3)$$

where μ is vacuum magnetic conductivity and f is frequency of current.

According to the estimated value of depth of magnetic flux penetration in A357 alloy is about 11.7 mm[11], thus, for castings with thickness of 3 or 5 mm, the effect of magnetic forces can reach any part of the castings during mould filling process.

The electromagnetic force along the horizontal direction of the mould can be described as Eqn. (4)[16]:

$$F_x = B_\Delta^2 f \tau k S L \delta \Delta K_{oc} \quad (4)$$

where F_x is the electromagnetic propelling force, B_Δ is the mean value of magnetic field imposed on the melt, f is the industrial frequency, τ is the pole pitch, k is the electrical conductivity, S is the slip ratio, and L, δ, Δ are the length, width and thickness of the casting, respectively, and K_{oc} is the spread factor.

Then, the filling pressure can be described as Eqn. (5):

$$P = \frac{F_x}{\delta\Delta} = B_\Delta^2 \tau f k S L K_{oc} \quad (5)$$

So, the pressure head imposed on the melt can be described as Eqn. (6):

$$h = \frac{P}{\rho g} \quad (6)$$

From the above equations, with the increase of the input voltage of inductor, the strength of the magnetic induction increases, so the pressure head increases, the velocity of the molten metal is accelerated in a very short time.

Theoretically, it can also be learnt that pressure head along the horizontal direction of the mould differs not only in quantity but also in its nature depending on electromagnetic field presence and absence. The pressure head of molten metal in electromagnetic die casting method increases from the lowest one at the entrance to the highest one at the end of the mould. While in a conventional casting method, it must be inevitably high at the entrance of mould and depends on the sprue height or outer pressure. So, in electromagnetic die casting method, the filling velocity of molten metal is increasing all the time along the mould cavity. It means that a high initial aluminum alloy front, filling flow velocity and its subsequent increase are favorable prerequisites for obtaining thin-walled castings.

Under the effect of electromagnetic field, the liquid metal could be inductively stirred. With the effect of the periodic current, the inductor generates a variable magnetic field in the melt, which, in turn gives rise to an induced current in the melt, then the melt is subject to electromagnetic body forces[17]. It causes the dendrites to be stirred violently, and at last, the dendrites are clashed to fragments. And the melt flow forward continuously carrying away the fragments and dispersing them in a slightly under-cooled melt. Under these conditions, the crystallization takes place simultaneously in most of the mould cavity, which results in the appearance of fine-grain structure. Because of electromagnetic stirring of the melt, according to the intensity of stirring, the grain structures of castings change from columnar-dendritic to equiaxed dendritic or globular.

The flow of melt during the mould filling process belongs to turbulent flow. With the increment of input voltage in inductor, the stirring effect of electromagnetic forces on the flow melt is enlarged, which leads to the relatively homogeneous temperature field and solute field in the melt. Then, the tips of Si phases are partly dissolved or their growth is delayed, which leads to the lack of characteristic of facet growth of crystal, the increment of the thickness of flat and the internal condensation of tips and brims, and growing into fiber.

5 CONCLUSIONS

The mould filling ability of A357 alloy is increasing continually with the increasing of the input voltage in inductor under electromagnetic die casting. The increase of pouring temperature leads to the improvement of mould filling ability. But the effect of pouring temperature on mould filling ability is weaker than that of input voltage. The mould filling ability of A357 alloy is larger in permanent mould than in gypsum mould under the same conditions.

Under the method of electromagnetic die casting, the grain size, shape and eutectic silicon of A357 alloy is much different from that with conventional casting methods. With the increase of input voltage in inductor, crystal grains of castings are refined, and dendrites in castings have the trend to convert to equiaxial crystal. As for the eutectic silicon in castings, it is observed that the shape of silicon phase became round. Under the mentioned method, eutectic silicon changes from rough flat to coral then to smooth strip along with the increase of input voltage in inductor.

[REFERENCES]

[1] Campbell. Thin wall castings [J]. Material Science and Technology, 1988, 14(3): 194-204.

[2] DING Hong-sheng, GUO Jing-jie, JIA Jun. Mould-filling ability of A357 alloy under travelling electromagnetic field [J]. Special Casting and Nonferrous Alloys, (in Chinese), 1999(2): 5-6.

[3] GAO Yi-xi, ZHANG Zhan. Develop trends and key technological problems for producing large thin-walled complicate aluminum precision castings [J]. Special Castings and Nonferrous Alloys, (in Chinese), 1992(1): 24-26.

[4] YE Rong-mao, WANG Hui-guang, TIAN Jing, et al. Development and features of casting technology for thin-walled precision casting of nonferrous alloys [J]. Special Casting and Nonferrous Alloys, (in Chinese), 1995(2): 33-34.

[5] DING Hong-sheng, GUO Jing-jie, JIA Jun. Present situation and development trend of production technology for special casting and nonferrous alloy in China [J]. Foundry, (in Chinese), 1999, (Supplement): 43-48.

[6] CHEN Xi-shen, JIA Jun. Effects of Electromagnetic Field on the Process of Alloy Melting and Crystallization of Castings [R]. Assemble of research reports in aerial material, Vol. 1. Research Group of Aerial Materials, (in Chinese). 1964. 64-72.

[7] HAN Zhi-cheng. Application and research of magneto-hydrodynamics in the production of metallurgy [J]. Foreign Iron and Steel, (in Chinese), 1992(11): 1-2.

[8] BAI Bing-zhong. Application of linear motor in electromagnetic stirring of molten metal [J]. Foreign Iron and Steel, (in Chinese), 1992(11): 79-84.

[9] DENG Kang, REN Zhong-ming, JIANG Guo-chang. Theoretical and experimental analysis of continuous casting with soft-contact moulded [J]. Trans Nonferrous Metal Soc China, 2000, 10(3): 314-319.

[10] ZHU Han-liang, GUO Jing-jie, JIA Jun. Aging characteristics and deformation mechanism of Al-Si-Mg casting alloy [J]. The Chinese Journal of Nonferrous Metals, (in Chinese), 1997, 7(1): 143-146.

[11] Knol R. Aluminum's growing role in motor vehicles [A]. 8th International Light Metals Congress [C]. Leoben: GMBH, 1987. 200-205.

[12] ASM International Handbook Committee. Metals Handbook (10th Edition), Vol. 2: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials [M]. Ohio: ASM International, 1990. 166-167.

[13] Smith F W. Structure and Properties of Engineering Alloys [M]. New York: McGrawHill Inc, 1993. 26.

[14] Tirykioglu M, Askeland D R, Ramsay C W. Fluidity of 319 and A356: an experimental design approach [J]. AFS Transactions, 1994, 102: 17-25.

[15] Yamamura S. Theory of Linear Induction Motors [M]. New York: John Wiley & Sons, 1972. 24-78.

[16] DING Zhi-gang. Micro & Special Linear Motors and their Control, (in Chinese) [M]. Hangzhou: Zhejiang University Press, 1987. 36.

[17] Charles V. Effects of forced electromagnetic vibrations during the solidification of aluminum alloys. Part 1: Solidification in the presence of crossed alternating electric fields and stationary magnetic fields [J]. Metallurgical and Materials Transactions, 1996, 27B(6): 445-455.

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