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Effect of low frequency electromagnetic field on casting crack during DC casting superhigh strength aluminum alloy ingots

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Abstract

Super high strength aluminum alloys are very important materials to the aerospace industries, however, cracks often occur during the DC casting process because of their high alloying element content. In this paper, a new low frequency electromagnetic casting (LFEC) process is used to study the possibility of eliminating casting cracks. The results show that a low frequency electromagnetic field eliminates cracks effectively. Under a low frequency electromagnetic field, temperature gradients in the mould are smaller, elements distributions are more uniform, sump depth is lower, and the grains are finer and have a more uniform spherical shape, so the internal stress in ingots is lower than that of ingots processed by conventional DC casting. The LFEC decreases the grain size, constituent size, and area fraction of grain boundary eutectics, which is helpful for thinning the liquid film between grains and improving high-temperature plasticity and strength. These factors improve the cracking resistance of the alloy. Decreasing internal stress and increasing cracking resistance eliminate cracks in DC cast ingots.

Keywords: Superhigh strength aluminum alloy; Low frequency electromagnetic field; DC casting; Casting crack; Internal stress; Cracking resistance

1. Introduction

Superhigh strength aluminum alloys are important materials to the aerospace industries, because of their low density, high strength, and good hot work ability. Demand in the aerospace industry for higher strength, higher toughness, and high corrosion resistance motivates continuing research on these alloys [1,2]. In general, increasing alloying element content will increase strength [3], but increased alloying element content makes it more difficult to cast the alloy. The 7000 series aluminum alloys are mainly cast by the direct-chill (DC) casting process. However, casting cracks are severe problems in this process, especially when casting large ingots with high alloying element content. Investigations on casting cracks have been reported in many previous studies [4–12]. These investigations have dealt primarily with the prediction and numerical simulation of casting cracks and with measures to control casting cracks, such as composition modification, decreased casting velocity, decreased cooling rate, and grains refinement. However, study on the effects of electromagnetic field on casting cracks has been limited [13,14]. The casting, refining and electromagnetic process (CREM) [15–18] can refine grains, decrease segregation, restrain casting cracks, and improve the surface quality of ingots. Based on this process, a new process, low frequency electromagnetic casting (LFEC) was developed by Cui and his colleagues [19–21], in which the low skin effect of low frequency electromagnetic field is used to control flow and temperature gradients. In this study, ingots of a new superhigh strength Al–Zn–Mg–Cu–Zr alloy were cast by LFEC, and the effects of low frequency electromagnetic field on casting cracks were discussed.

2. Experimental procedure

A new Al–Zn–Mg–Cu–Zr alloy with high alloying element content was cast. Table 1 shows the chemical composition of the alloy.

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Table 1
Chemical composition of the superhigh strength Al alloy

Elements	Composition (wt.%)
Zn	9.82
Mg	2.35
Cu	2.29
Zr	0.142
Fe	0.12
Si	0.08
Al	Balance

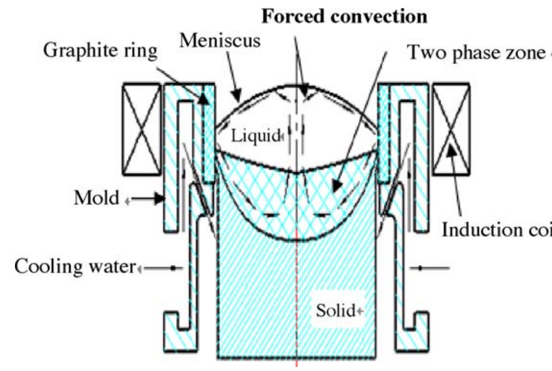

Fig. 1. Schematic diagram of LFEC process.

The alloy was melted in a 500 kW medium frequency induction furnace. When the temperature of the melt was 760 °C, the melt was degassed, slag was removed and refined, and the alloy was poured into a tundish. The Ø 200 mm ingots were produced by LFEC process at a melt temperature of 730 °C and a casting speed of 80 mm/min. The electromagnetic field was applied by an 80 turns water-cooled copper coil surrounding the stainless steel crystallizer. Casting was performed with a frequency of 25 Hz and 150 A current. A graphite ring with inside diameter of 204 mm, outside diameter of 216 mm and height of 30 mm was set in the crystallizer. Fig. 1 shows the schematic of the LFEC process.

The cast crack shapes were observed directly, and the fracture surfaces of cracks were examined using scanning electron microscopy (SEM). The microstructures were characterized by an optical microscope (Leica DMR) using standard optical metallography. The samples were cut from the ingots in the edge, 1/2 radius and center of the ingots respectively and were etched with mixed acid (2 ml HF, 3 ml HCl, 5 ml HNO_3 and 190 ml H_2O). The alloying element distribution was measured by chemical analysis. The temperature field and liquid metal sump shape were measured by thermocouples in a manner to be discussed in another article.

3. Experiment results

The high alloying element content makes it difficult to cast this alloy. All ingots DC cast without electromagnetic

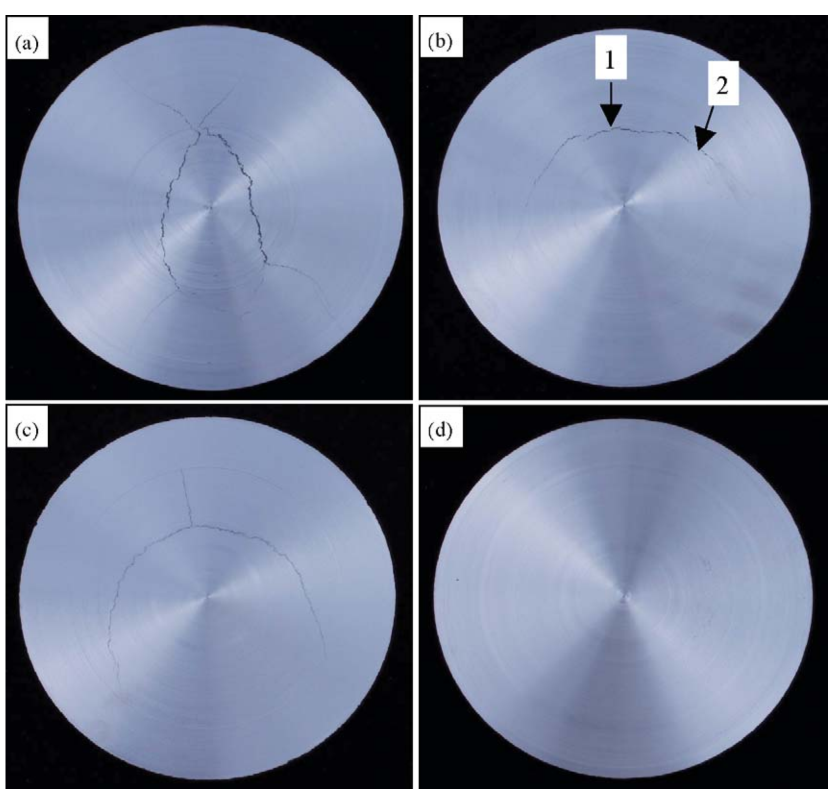

Fig. 2. Effect of low frequency electromagnetic field on the cracks of ingots: (a–c) DC cast ingots and (d) LFEC ingot. Locations marked “1” and “2” are the regions shown in the fractographs of Fig. 3.

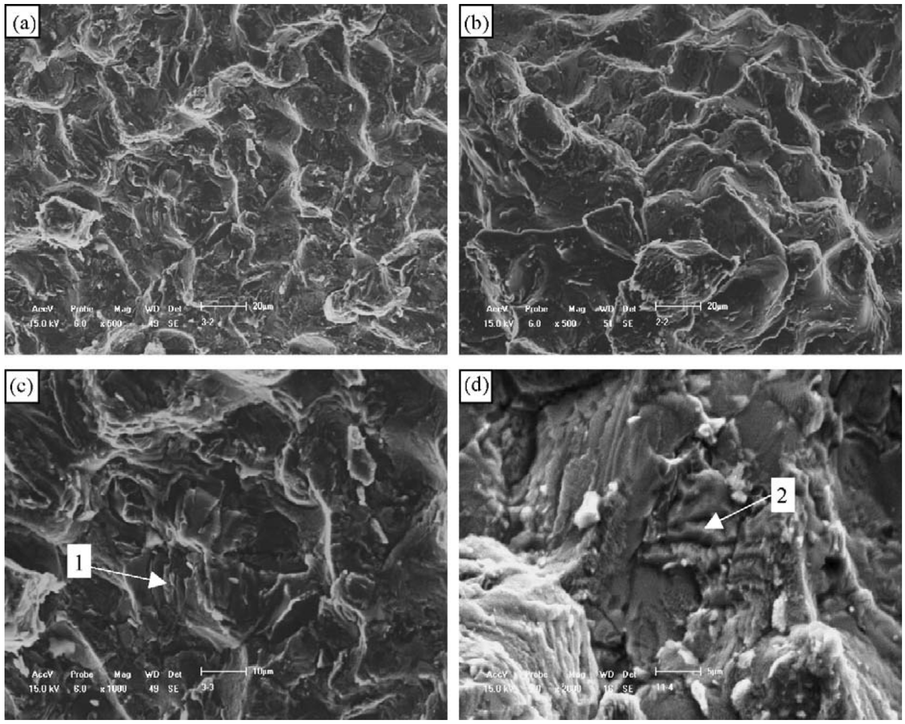

Fig. 3. Fracture surfaces of ingots.

field were cracked (Fig. 2), but no cracks were found in the ingots cast by the LFEC process. The cracks in the ingots cast without the electromagnetic field had three basic shapes: line-crossed cracks, arc-shaped cracks, and line-arc crossed cracks, which are shown in Fig. 2a–c, respectively.

The fracture surfaces of conventional DC cast ingots were examined using SEM. As shown in Fig. 3, the failure mode of the alloy was intergranular brittle fracture, and the failure was associated with crack propagation through the eutectic phases segregated at the grain boundaries. Fig. 3a and c are from point one in Fig. 2b and Fig. 3b and d are from point two in Fig. 2b.

The composition at selected locations was examined using SEM(EDX). The compositions of points 1 and 2 in Fig. 3c and d are listed as Table 2. Based on composition it is possible that the constituents are T(Al–Zn–Mg–Cu), which is brittle. It is clear that there are second cracks in the constituents, so a conclusion can be drawn that the constituents are crack initiators; cracks begin at these constituents, then propagate.

In general, for the new superhigh strength aluminum alloy, all ingots cast without electromagnetic field were cracked, and the cracks are intergranular brittle fractures. In contrast there were no cracks in the ingots cast by LFEC. Thus, we conclude that low frequency electromagnetic fields eliminate cracks in superhigh strength aluminum ingots of this alloy.

Table 2
Composition (wt.%) of the constituents at points labeled in Fig. 3

Point	Al	Zn	Mg	Cu
1	12.817	40.970	14.003	32.210
2	31.285	37.442	13.563	17.710

4. Discussions

Ingot contraction is unavoidable during DC casting. However, contraction of ingot is different for in different parts of the ingot because cooling rates vary with location. This in turn causes tensile stress in the center and compressive stress in the surface of the ingot [5]. If the tensile stress at the temperature near the solidus exceeds the strength of the alloy at the corresponding temperature, a hot crack will be generated. If the crack occurs at a temperature much lower than solidus, it is a cold crack. In these Al–Zn–Mg–Cu alloys, castings contain both hot cracks and cold cracks, and the cold cracks usually come from the hot cracks. To avoid both hot and cold cracks, it is important to reduce the internal stress and to improve the cracking resistance of the alloy. From the experiments reported here, we conclude that a low frequency electromagnetic field can eliminate cracks in superhigh strength aluminum alloy ingots by reducing internal stress and improving crack resistance.

4.1. Effect of LFEC on the internal stress

In the LFEC process, the alternating current generates a time varying magnetic field, B, which, in turn, gives rise to an induced current, J, in the melt. Therefore, the melt is subjected to electromagnetic body forces caused by the interaction of the induced current and magnetic field. The body forces contain a rotational component and a potential component [15]. The rotational component results in the forced convection shown in Fig. 1. The forced convection decreases the temperature gradients in the melt and the depth of sump, which makes solute distribution more uniform. It is clear that a lower temperature gradient in the melt and a flat liquid sump can decrease internal stress [22]. In addition, the uniformity of composition distribution and the resulting superior microstructures that result from LFEC are also helpful for reducing internal stress. Although, it is difficult to measure the internal stress during the process of DC casting, the temperature fields, composition distribution, liquid sump, and microstructures are easily measured. So, in order to analyse the effect of LFEC on the internal stress, the temperature fields and liquid sump depth in the mold, alloying element distribution, and microstructures of the ingots were measured.

4.1.1. *Effect of LFEC on temperature field*

Temperature gradient was measured using five thermocouples positioned along a radius about 15 mm under the meniscus inside the crystallizer. The liquid temperature gradients for LFEC and the conventional DC casting process are compared in Fig. 4. In the LFEC process, the temperature under the meniscus is more uniform and lower than that in conventional DC casting. The temperature difference from the center to the edge in the mold is smaller in LFEC (∼5 °C) than in conventional DC casting (∼45 °C). In conventional DC casting, the hottest liquid moves slowly from the ingot center toward the edge under the melt by convective flow.

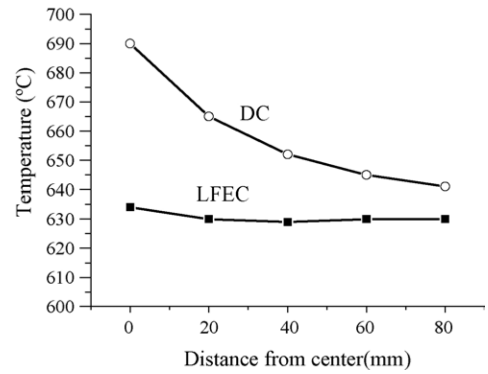

Fig. 4. Comparison of the temperature gradients 15 mm under the meniscus for conventional DC and LFEC casting processes.

However, in the LFEC process, the hottest liquid in the center of the ingot is carried to the ingot edge along the surface of the melt, and the cooler liquid at the edge of the ingot is carried into the center of the ingot rapidly by the electromagnetic force. This makes temperature distribution more uniform and acts to decrease the internal stress.

4.1.2. *Effect of LFEC on composition distribution*

The composition at different positions in the ingot was measured using chemical analysis. As shown in Fig. 5, both the inverse segregation in the surface and the difference of alloying element content are larger in the DC ingots than in the LFEC ingots. The element macro distribution in LFEC ingots is more uniform, which produces more uniform microstructures and properties. This also serves to reduce the internal stress.

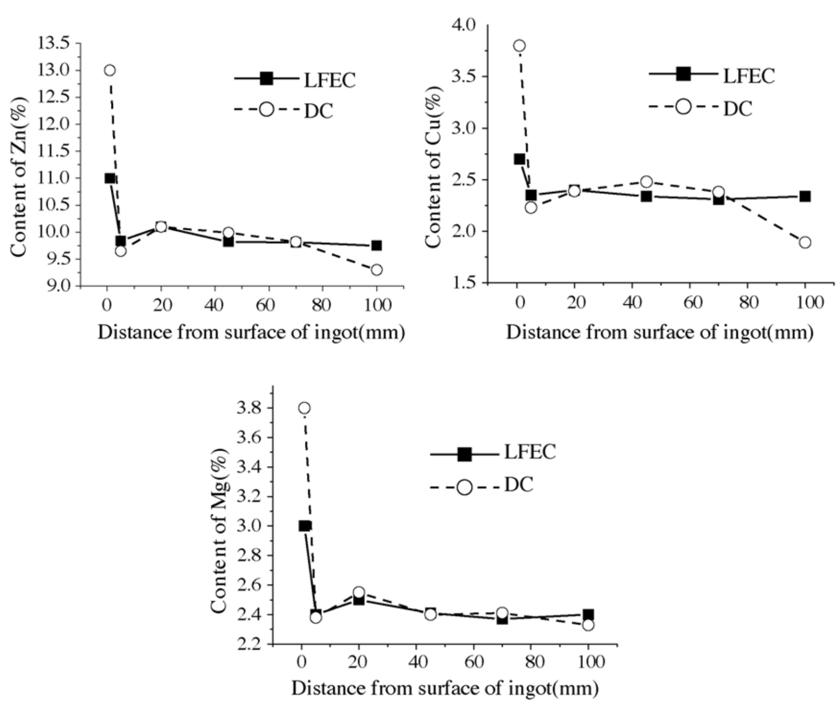

Fig. 5. The elements distribution along ingot radius.

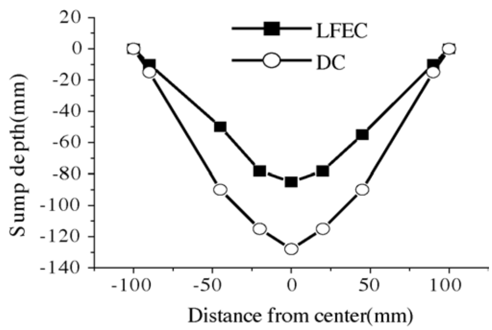

Fig. 6. The sump depth of LFEC and conventional DC process.

4.1.3. *Effect of LFEC on the sump depth*

Under a low frequency electromagnetic field, a forced convection is generated in liquid metals. The forced convection propels the cold melt near the mold wall to the center, and the overheat melt in the center moves toward the border. During this process, low frequency electromagnetic field not only makes the element distribution and temperature field more uniform but also reduces the sump depth. As shown in Fig. 6, the sump depth by LFEC is about 85 mm, while the sump depth by the conventional DC process is about 125 mm. Prior research shows that the deeper the liquid sump is, the greater the internal stress will be [22]. The LFEC process decreases the sump depth, so it can reduce the internal stress.

4.1.4. *Effect of LFEC on the microstructures*

In general, the microstructure of the LFEC ingots is much finer than the coarse microstructure of DC ingots. In the latter case, some grains are even visible with the naked eye.

Fig. 7a shows a dendritic microstructure near the surface of a DC ingot. Casting under an electromagnetic field of 25 Hz and 150 A, however, the microstructure near the ingots' surface is dominated by fine, uniform grains, as shown in Fig. 7d. Fig. 7b and e show the microstructures at the 1/2-radius area of the DC and LFEC ingots, respectively. It can be seen that in the DC ingot, the microstructure in the 1/2-radius area is characterized by coarse dendritic grains. On the other hand, in the LFEC ingot, the microstructure in the 1/2-radius area is finer, and grains are nearly spherical. Fig. 7c and f show the microstructures at the center of the DC and LFEC ingots, respectively. Fig. 7c shows a coarse microstructure at the center of the DC ingot. Fig. 7f shows that the microstructure at the LFEC ingot center is fine grained. So, the microstructures of LFEC ingot are fine and uniform. And the grains are nearly spherical throughout the ingots, which is helpful for reducing internal stress.

During solidification, spherical grains eliminate framework forming. Once frameworks form liquid complementarity is very difficult to achieve and linear contraction begins. Under a low frequency electromagnetic field, there is a forced convection in the melt during solidification and almost all grains are spherical. The spherical grains move along the convection direction, and they also spin because of a force moment at the grain from the electromagnetic force difference between the part near the centerline and the part far from the centerline. This is helpful for liquid compensating. So, the forced electromagnetic convection accelerates the liquid compensating, which result in the linear contraction beginning later than in the conventional DC process. Hence, the effectual crystallization interval becomes narrower, which result in less linear contraction and lower internal stress.

In general, the more uniform temperature gradient and elements distribution, lower sump depth, more uniform and finer microstructures and less linear contraction act collectively to lower the internal stress in ingots processed by LFEC. This in turn eliminates cracks in the LFEC ingots.

4.2. *Effect of LFEC on the crack resistance of the alloy*

4.2.1. *Refining effect of LFEC on microstructures*

As shown in Fig. 7, the microstructures of LFEC ingots are more uniform than that of conventional DC ingots, and

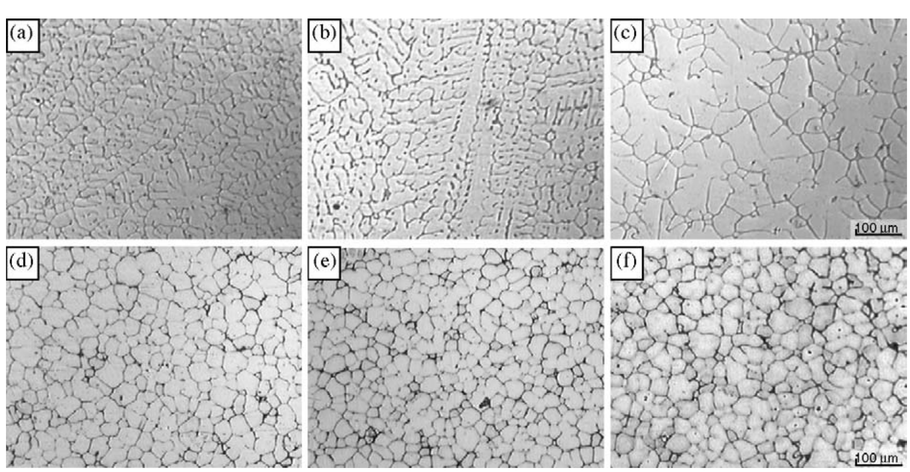

Fig. 7. Microstructures of DC and LFEC ingots: (a and d) edge (3 mm from surface); (b and e) 1/2 radius; (c and f) center; (a–c) DC; (d–f) LFEC.

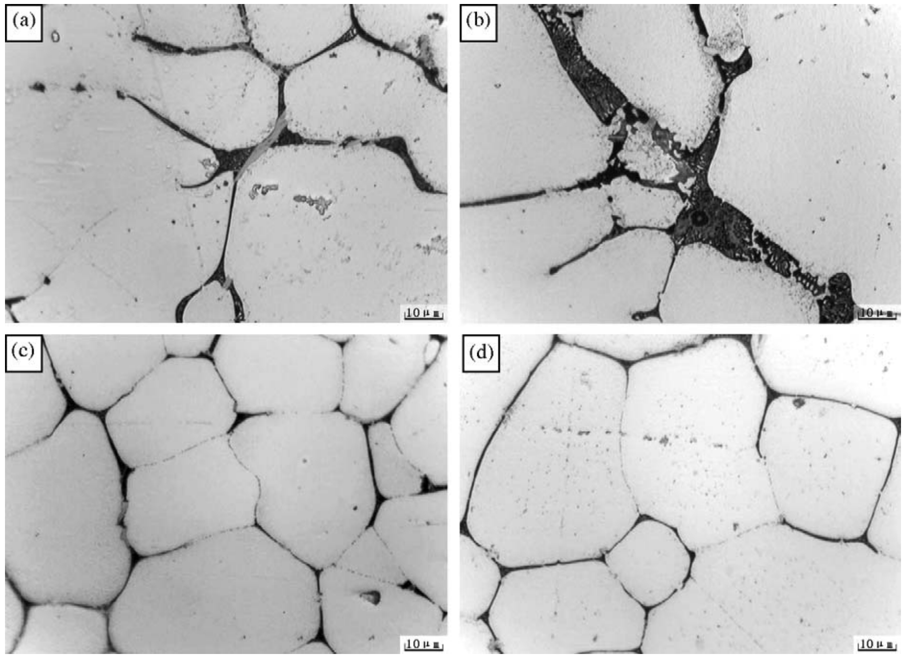

Fig. 8. The grain boundary state of LFEC and conventional DC casting ingots: (a) DC ingot border, (b) DC ingot center, (c) LFEC ingot border and (d) LFEC ingot center.

LFEC ingots have finer grain sizes near the ingot centers. The finer microstructure would be expected to improve high temperature and room temperature mechanical properties and hot tearing resistance [23].

Based on the liquid film theory, the thinner the liquid film becomes, the higher the strength of the alloy. Refining grains increases the total surface area of grains, which results in thinner liquid films, so the high temperature (near the solidus) strength and plasticity of LFEC ingots is higher than that of conventional DC ingots. Hence the ingot would have stronger crack resistance.

The room temperature as-cast mechanical properties were examined. The results are listed in Table 3. It is obvious that both the strength and the elongation of LFEC ingots are higher than those of DC ingots, which helps to improve crack resistance.

4.2.2. Effect of LFEC on the grain boundary structure

In high strength aluminum alloys, the phases in the grain boundaries are eutectic with a low melting point. Their influence on cracking is dependent of their amount and distribution. Brittle, coarse, low-melting phases at grain boundaries act to initiate cracks, so the effect of LFEC on the grain boundary structure is important. Fig. 8 shows that the eutectic structure in both the border Fig. 8c and center Fig. 8d of LFEC ingots is less than that of DC ingots. The measurements of our micrographs showed that the area fraction of eutectic structure was 10% at the center and near the surface of the DC ingots, but only 8% at both locations in LFEC ingots. The micrographs also showed that the constituent size of these phases is smaller in LEFC ingots than in DC ingots, which would be expected to reduce crack initiation. In summary, our findings show that LFEC decreased the grain size, constituent size, and area fraction of grain boundary eutectics. These changes would be expected to reduce crack initiation, decrease liquid film volume, and improve high temperature plasticity and strength, all of which should improve the crack resistance.

Table 3
As-cast mechanical property of the alloy

	UTS (MPa)	Elongation (%)
Conventional DC	213	0.2
LFEC	265	1.67

5. Conclusions

The results of these LFEC and conventional DC casting experiments lead to the following conclusions:

(1) During semi-continuous casting, the low frequency electromagnetic field eliminated cracks in ingots.
(2) Under low frequency electromagnetic field, the temperature gradient in the melt and the elements distribution in the ingot are more uniform; the sump depth is lower; and the microstructures have more uniform, spherical grains, which should make the internal stress lower than that of conventional DC process ingots.
(3) The LFEC process decreases the grain size, constituent size, and area fraction of grain boundary eutectics, which is helpful for thinning the liquid film and improving high temperature plasticity and strength. These factors are

expected to provide improved crack resistance in LFEC ingots vis-a-vis conventional DC ingots.

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References

[1] A. Heinz, A. Haszler, C. Keidel, S. Moldenhauer, R. Benedictus, W.S. Miller, Mater. Sci. Eng. A 280 (2000) 102–107.
[2] L. Chenggong, W. Shijie, D. Shenglong, Y. Shoujie, Chin. J. Nonferr. Met. (Special) 12 (2002) 14–21 (in Chinese).
[3] Y.L. Wu, F.H. Frose, A. Alvarez, C.G. Li, J. Liu, Mater. Des. 18 (1997) 211–215.
[4] Z. Xianshu, J. Junze, L. Zhi, Prog. Nat. Sci. 11 (12) (2001) 123–128.
[5] R.K. Paramatmuni, K.-M. Chang, B.S. Kang, X. Liu, Mater. Sci. Eng. A 379 (2004) 293–301.
[6] H. Nagaumi, T. Umeda, J. Light Met. 2 (2002) 161–167.
[7] D. Hao, F. Hengzhi, Rare Met. Mater. Eng. 29 (4) (2000) 228–230.
[8] Z. Xianshu, J. Junze, Acta Metall. Sin. 31 (11) (1995) 228–230 (in Chinese).
[9] P. Barral, P. Quintela, Comput. Meth. Appl. Mech. Eng. 178 (1999) 69–88.
[10] J. Du, B.S.J. Kang, K.M. Chang, J. Harris, Proceedings of Sessions, TMS Annual Meeting on Light Metals, Warrendale, Pennsylvania, 1998, pp. 1025–1030.
[11] J. Brobak Tor, G. Fjaer Hallvard, K. Jensen Einar, A. Mo, Light Met. (1991) 869–876.
[12] M.C. Flemings, AFS Trans. 77 (1969) 329–332.
[13] Z. Qin, C. Jianzhong, Z. Beijiang, Acta Metall. Sin. 39 (12) (2003) 1259–1263 (in Chinese).
[14] N. Zhiliang, X. Zhihui, L. Weizhong, C. Tianzhen, Chin. J. Nonferr. Met. 7 (1) (1997) 129–133 (in Chinese).
[15] C. Vives, Metall. Trans. 20B (1989) 623–629.
[16] C. Vives, Metall. Trans. 20B (1989) 631–643.
[17] C. Vives, Metall. Mater. Trans. 27B (1996) 445–455.
[18] C. Vives, Metall. Mater. Trans. 27B (1996) 457–464.
[19] Z. Beijiang, C. Jianzhong, L. Guimin, Z. Qin, B. Chunyan, Acta Metall. Sin. 38 (2) (2002) 215–218 (in Chinese).
[20] Z. Beijiang, C. Jianzhong, L. Guimin, Z. Qin, J. Northeastern Univ. (Nat. Sci.) 23 (10) (2002) 968–971 (in Chinese).
[21] D. Jie, C. Jianzhong, L. Xiaotao, Z. Zhihao, B. Weiping, Chin. J. Nonferr. Met. 13 (2003) 1494–1499 (in Chinese).
[22] Y. Wen, L. Shunyan, J. Process. Aluminum (China) 22 (1) (1999) 4–7 (in Chinese).
[23] V.D. Davies, Br. Foundryman 4 (1970) 93–101.