Microstructures and constituents of super-high strength aluminum alloy ingots made through LFEC process

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Abstract: Ingots of a new super-high strength Al-Zn-Mg-Cu-Zr alloy were produced respectively by low frequency electromagnetic casting (LFEC) and by conventional direct chill (DC) casting process. Microstructure and constituents of the ingots were studied. The results indicated that the LFEC process significantly refines microstructure and constituents of the alloy, and to some extent, decreases the area (or volume) fraction of constituents and eutectic structure precipitated at grain boundaries. But, no difference in the type of constituents was observed between LFEC and DC ingots. The results also showed LFEC process can improve the as-cast mechanical properties.

Keywords: Al-Zn-Mg-Cu-Zr alloy; low frequency electromagnetic field; DC casting; microstructure; constituent

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Ultrahigh strength aluminum alloys are extensively used in aircraft structure applications, because of their low density, super-high strength, and good hot work ability. With the development of aerospace industry, products with higher strength and better combination property are needed [1, 2]. To meet the increasing demands of the aerospace industry, super-high strength aluminum alloy should be further developed. Increasing the content of alloying elements is a way to improve strength [3]. However, increasing element concentration may cause serious grain boundary segregation, leading to the formation of additional eutectic phases and coarse constituents at the grain boundaries. The coarse structures may not only cause hot cracking during casting but also decrease strength, ductibility, fracture toughness and fatigue strength after heat treatment [4-8]. In order to obtain good combination property the possible coarse constituents have to be minimized. The effects of cooling rate and alloy composition on the phase formation during solidification have been reported in many previous studies [9, 10]. However, reports about the effects of electromagnetic field on microstructures and related constituents are limited. A new technique, the Low Frequency Electromagnetic Casting process (LFEC) was developed by professor CUI *et al* [11-13]. In the present study, ingots (ϕ 200 mm) of a new superhigh strength A1-Zn-Mg-Cu-Zr alloy were produced with the LFEC and DC processes, and the microstructure and constituents of the ingots were investigated.

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1 Experimental procedure

A new super-high strength Al-9.82Zn-2.35Mg-2.29Cu- 0.142Zr (wt-%) alloy was proposed and used as the experimental material. In this case, Fe and Si are considered as impurities. The alloy was melted in a 500 kW medium frequency induction furnace. While held at the temperature of 760℃, the melt was degassed, slag removed and refined, then it was poured into a tundish. ϕ 200 mm diameter ingots were produced in both LFEC and conventional DC processes with melt temperature of 730℃, and casting speed at 80 mm/min. The electromagnetic field was generated by an 80-turn water-cooled copper coil which surrounded a stainless steel mold. During the casting process, the frequency and the current intensity were fixed at 25 Hz and 150A, respectively. A graphite ring with a dimension of 204 mm inner diameter, 216 mm outer diameter and 30 mm height was set in the mold. Figure 1 shows the schematic of the LFEC process.

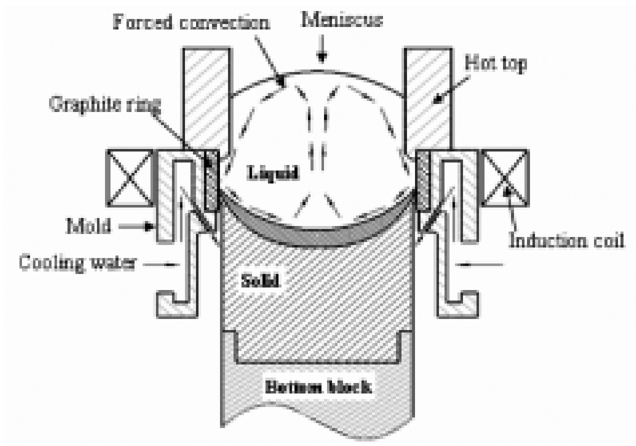


Fig.1 Schematic diagram of LFEC process

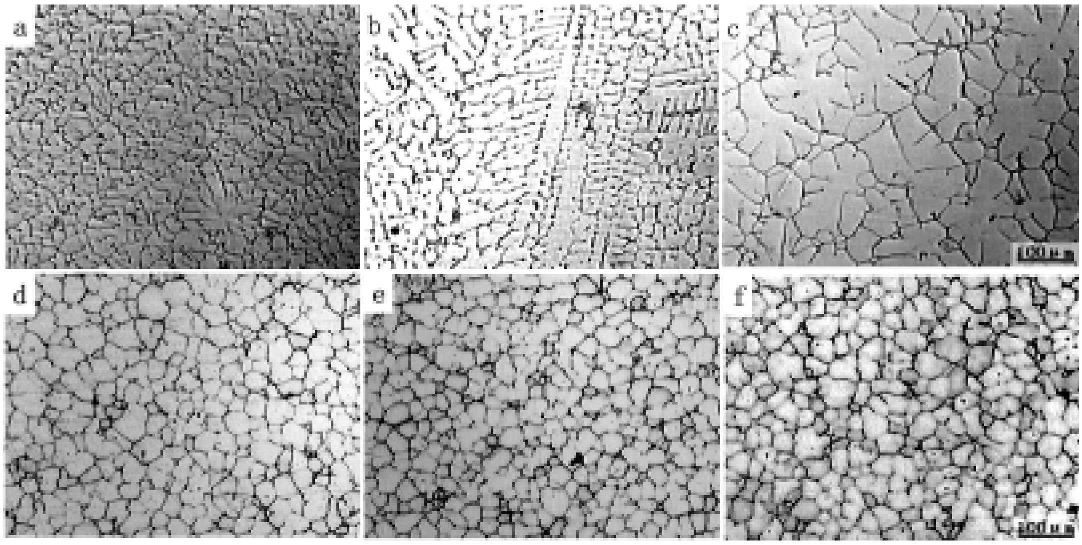
Cubic samples with 15 mm side length were obtained respectively at the OD (outer diameter), 1/2 radius and center areas of the slice cut from the ingot. The samples were ground, polished and then etched with dilute Keller's reagent (2 mL HF, 3 mL HCl, 5 mL HNO_3 and 190 mL H_2O). Microstructures of these samples were examined under optical microscope, while constituents were analyzed by X-ray diffraction instrument.

2 Results and discussions

2.1 The microstructures of DC and LFEC ingots

Figure 2(a, b, and c) show the microstructures of the specimens taken respectively at the OD, the 1/2 radius and the center of a DC ingot. Obviously, the microstructures transitioned from fine dendritic structure at the OD area to coarse dendritic structure at the1/2 radius and to coarse equiaxed grain structure at the center of the ingot. The corresponding microstructure of LFEC ingot is dominated by very fine and uniform equiaxed grains as shown in Fig.2(d, e and f). Clearly, the microstructure of LFEC ingot consists of almost solely global (or equiaxed) or near global grains which is much finer and more uniform than the microstructure in the produced DC ingot.

During the LFEC process, forced convection is generated in the melt. The forced convection accelerates nuclei formation near



(a), (d) edge (3 mm from surface); (b), (e) 1/2 radius; (c), (f) center;
(a), (b), (c) DC; (d), (e), (f) LFEC

Fig.2 Microstructures of DC and LFEC ingots

the mold, and moves them from mold to the center, resulting in higher nucleation density and more uniform distribution. Flemings [14] studied the break of secondary dendritic arms and block nucleation, and concluded that the break of secondary dendritic arms boosts nucleation sites. Under electromagnetic field, dendrite arms are broken by the forced convection, and the transformation from broken blocks into nuclei is increased. In addition, during LFEC process the melt temperature is uniform and it can be controlled to little lower than the liquidus (temperature), which helps to form many crystal nuclei throughout the melt and to reduce the remelting of nuclei caused by local overheating. That is to say, the LFEC process increases the effective nuclei in the melt. Therefore, the microstructures of LFEC ingots is much finer than that of DC ingot.

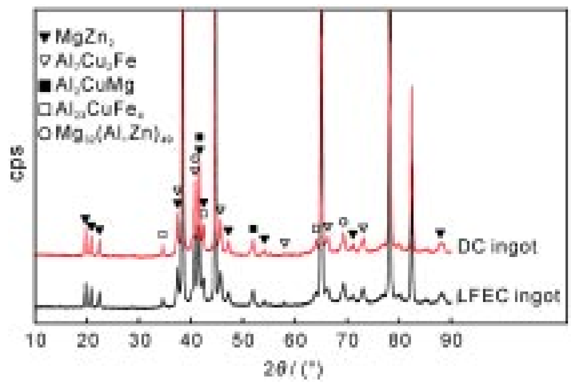


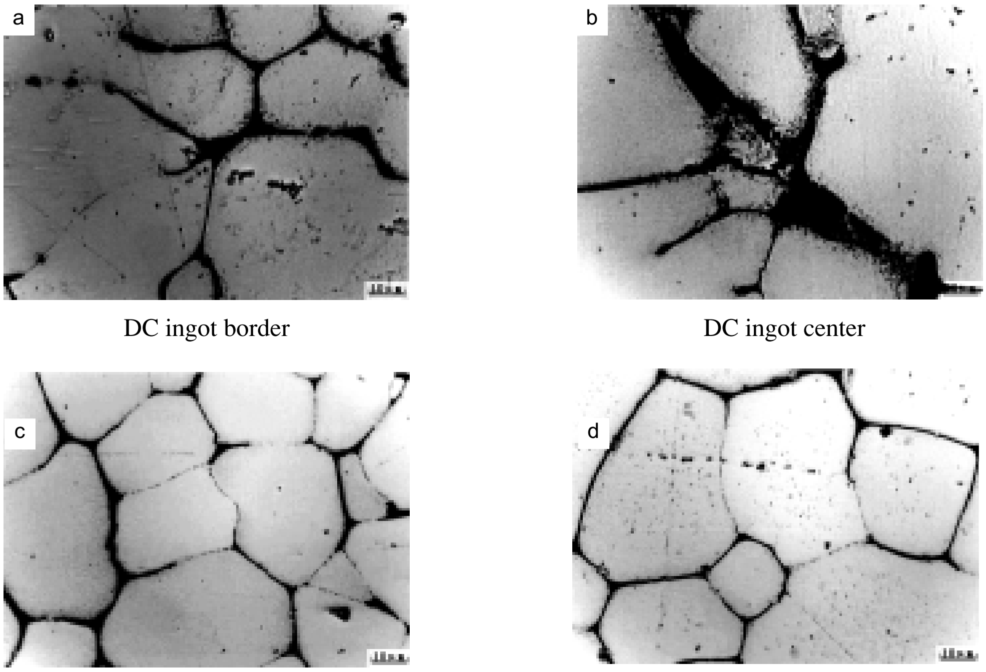
Fig.3 XRD graph of LFEC and DC ingots

2.2 The major constituents of the new super-high strength aluminum alloy

Constituents of the ingots were analyzed by means of X-ray diffraction. The results are shown in Fig.3. No difference was found in the type of constituents between LFEC and DC ingots. The main constituents of this new superhigh strength aluminum alloy include α(Al), $MgZn_2$, $CuMgA1_2$, $Mg_{32}(A1, Zn)_{49}$ and $A1_7Cu_2Fe$.

Although effects of electromagnetic field on the type of constituents were not observed, effects of LFEC on area fraction and size of constituents are very obvious. As shown in Fig.4 (a, b) for the DC ingot, the eutectic phases segregated at grain boundaries are coarse and continuous. The eutectic phases near the outer surface (or border) of the ingot are thinner than those in the center, which is due likely to the thermal effect, higher cooling rate at the outer layer and lower cooling rate in the center of the ingot. As shown in Fig.4(c, d) for the LFEC ingot the eutectic phases segregated at grain boundaries are more uniform, thinner and smaller than those of DC ingot, which is helpful to improve as-cast strength and plasticity of the alloy.

As discussed above, the microstructure of LFEC ingot is much



a DC ingot border

b DC ingot center

c LFEC ingot border

d LFEC ingot center

Fig.4 The grain boundary's states of LFEC and conventional DC casting ingots

finer than that of DC ingot. In general, the finer the microstructure, the lower content and smaller size of the constituents and eutectic structure [9, 15]. It was also shown that the electromagnetic field can improve alloying element content inside the grains [16]. Hence, LFEC can lower the content and reduce size of constituents and eutectic structure.

2.3 The as-cast mechanical properties of ingots

The mechanical properties of all the samples were tested at room temperature. As shown in Fig.5, the as-cast fracture strength and percentage elongation of LFEC ingots are higher than that of DC ingots, which results from finer constituents and finer microstructures of LFEC ingots.

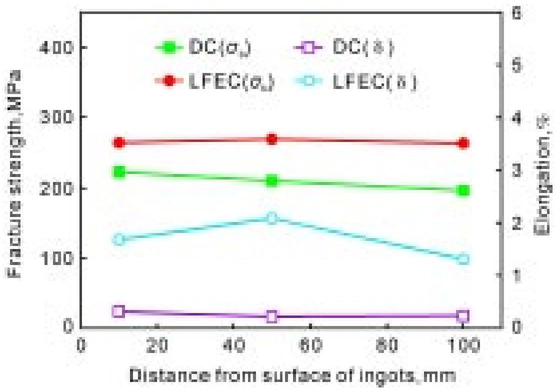


Fig.5 Fracture strength and percentage elongation of DC and LFEC ϕ 200 mm ingots

3 Conclusions

(1) The microstructure of the LFEC new super-high strength Al-Zn-Mg-Cu-Zr alloy presents fine equiaxed grain structure throughout the ingot (from the border to the center), which is much finer and more uniform than that of DC ingot.

(2) According to X-ray diffraction phase analysis, the constituents of the new superhigh strength aluminum alloy mainly include α(Al), $MgZn_2$, $CuMgA1_2$, $Mg_{32}(A1, Zn)_{49}$, and $A1_7Cu_2Fe$. LFEC process showed no effect on constituent type.

(3) The LFEC process, to some extent, decreases the area fraction of constituents and eutectic structure at grain boundary and reduces the constituent size.

(4) For the newly proposed super-high strength Al-Zn-Mg-Cu alloy, the as-cast mechanical properties of LFEC ingot are much higher and more uniform than that of DC ingot.

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