

# Effect of electromagnetic vibration on the microstructure of direct chill cast Al-Zn-Mg-Cu alloy

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**Abstract.** An electromagnetic vibration was achieved by the combined application of an alternating magnetic field and a stationary magnetic field during direct chill (DC) casting process. The ingots with 200 mm in diameter were prepared under the influence of electromagnetic vibration. The effect of electromagnetic vibration on the microstructure of an Al-Zn-Mg-Cu alloy was studied. The results showed that electromagnetic vibration has a significant effect on the solidification behaviour, under the influence of electromagnetic vibration during DC casting process, the microstructure is significantly refined and the uniformity of microstructure is evidently improved. This paper introduces the DC casting technology with the application of electromagnetic vibration, presents these results and gives corresponding discussions.

## 1. Introduction

Al-Zn-Mg-Cu alloys with ultra-high strength and good comprehensive performance are widely used in many industrial sectors including aerospace, defence, and sports equipment. DC casting process for aluminum alloys has been developed for about eighty years since it was invented in 1930s and is still the important method to produce ingot of high strength Al-Zn-Mg-Cu alloys. However, it is difficult to produce high quality ingots of Al-Zn-Mg-Cu alloys because casting defects such as hot tearing, cold crack, macrosegregation, porosity often occurs during casting process due to their high content of alloy elements, high strength and low ductility [1]. It is accepted that fine and uniform equiaxed grain structure of DC cast billet can improve mechanical properties, refine cast defects, decrease the sensitivity to hot tearing, result in a good surface finish, and enhance deformability and castability. Intensive development work on developing DC casting process has taken place over the last 30 years [2] to refine microstructure, reduce casting defects.

Grain refinement by grain refiners is an important and effective approach for refining microstructure [3, 4]. Although grain refinement of aluminium alloys has attracted intensive research the search for new and effective methods for grain refinement still continues. The application of external physical fields including intensive melt shearing [5] and electromagnetic field [6] during solidification process have attracted more intensive attention.

Fan and his co-workers [7] have found that intensive melt shearing provided by a twin-screw mechanism has a significant grain refining effect on both aluminium and magnesium alloys. Based on the similar principle, a new technology with simpler equipment (a rotor-stator high shear device) for intensive melt shearing was developed [8] and was used in the DC casting process [9].



The application of electromagnetic field in the DC casting process is also an effective method to control microstructure. Electromagnetic casting [10] developed in the early 1970s is perhaps the earliest application of electromagnetic field in DC casting of aluminium alloys. Refined microstructure and improved mechanical properties of 2024 aluminium alloy has been achieved by EMC process [11, 12]. Based on EMC, a CREM process was developed by Vives [13], which slightly modified the conventional DC casting mould and applied the industrial frequency alternating current to generate alternating magnetic field through a coil around the mould. Different electromagnetic fields such as high magnetic field [14, 15], rotating electromagnetic field [16, 17], travelling magnetic field [18] have been studied to refine microstructure.

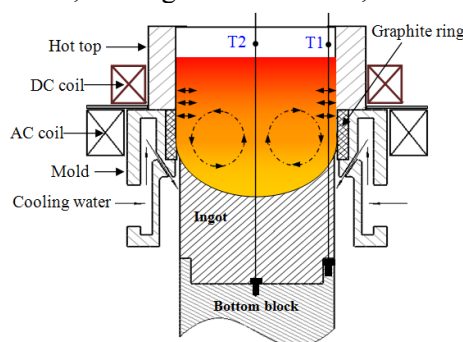
Based on EMC and CREM, a low frequency electromagnetic casting (LFEC) process was developed recently by Cui and his colleagues [19, 20] in which the low frequency electromagnetic field was used to control the fluid flow and temperature field. Recently, based on the work of Vives [21], a low frequency electromagnetic vibration casting (LFEVC) was achieved by the combined application of an alternating magnetic field and a stationary magnetic field during direct chill (DC) casting process. The stationary magnetic field was achieved by a coil with application of direct current. The alternating magnetic field was achieved by a coil with application of alternating current.

In the present work, the electromagnetic vibration in the DC casting process was introduced and its effect on the microstructure of an Al-Zn-Mg-Cu alloy was studied.

## 2. Experimental procedure

Al-(9.5-10)Zn-(2.0-2.5)Mg-(2.0-2.3)Cu-(0.12-0.15)Zr (all in wt.%) aluminium alloy was used in the present work. The measured solidus and liquidus of the alloy are 470 °C and 632 °C, respectively. The pure aluminum was melted in a 500 kW medium frequency induction furnace. Pure Cu, Zn, Mg and Al-Zr master alloy were added to the melted aluminum at 750 °C. Then the alloy melt was transferred into a resistance furnace. The melt was degassed by  $C_2Cl_6$  in the resistance furnace, and then was poured into DC casting mould through a launder. The experimental equipment for the LFEVC process is schematically illustrated in figure 1.

A 100 turn induction coil was arranged outside the hot-top to provide the stationary magnetic field. An 80 turn induction coil was arranged outside the mould to provide the alternating magnetic field. Billets in diameter of 200 mm were cast by the conventional DC casting and the LFEVC process, respectively, under following conditions: casting temperature (melt temperature in the furnace), 730-740 °C; casting speed, 80 mm/min; cooling water flow rate, 70 L/min.



**Figure 1.** Schematic of LFEVC process.

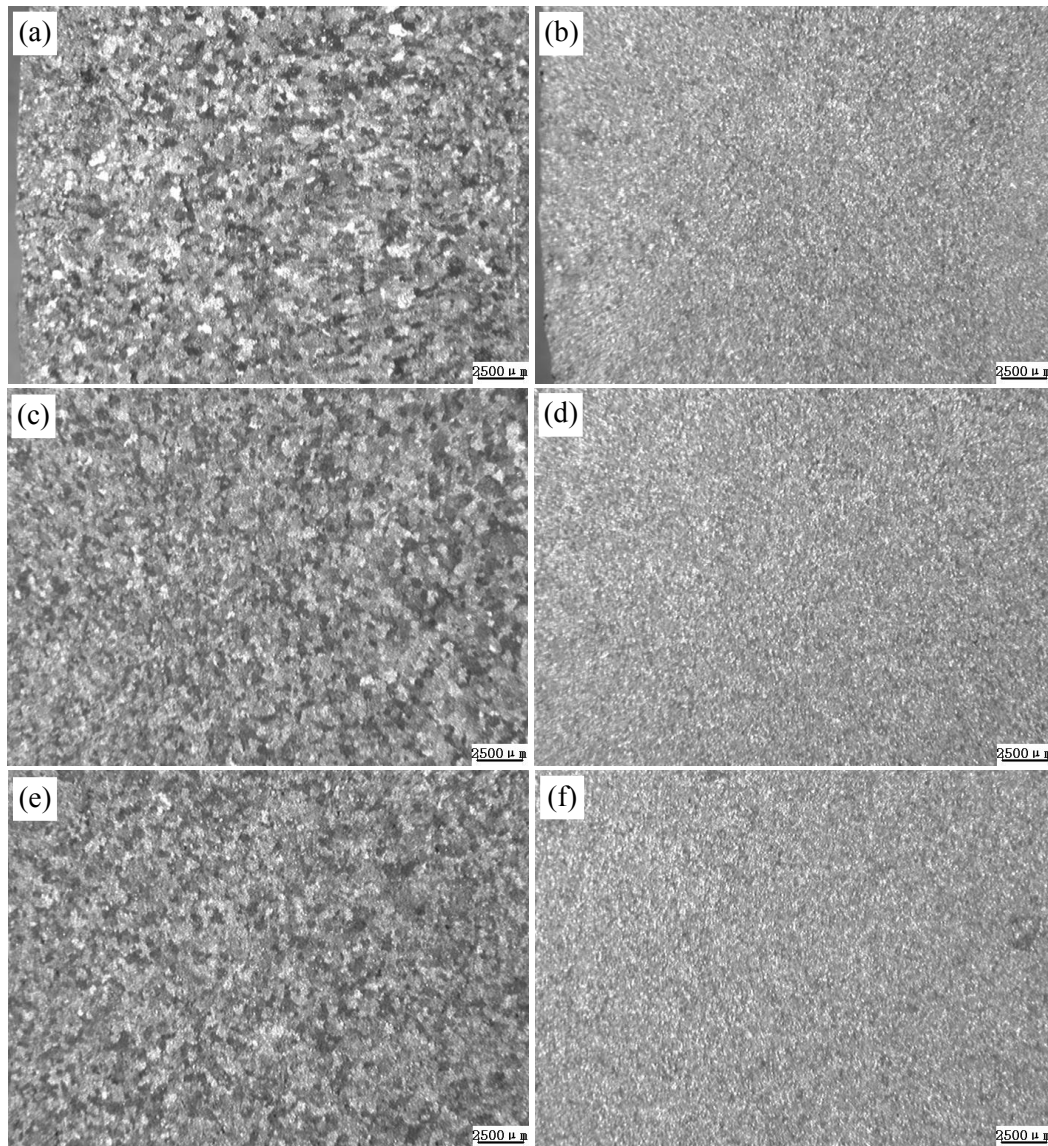
During casting process, thermocouples (type K) were used to measure and record the temperatures, the positions of which were schematically shown in figure 1. The thermocouples T2 and T1 were fixed on a stainless steel rod which was connected to the bottom block. Thermocouples therefore can move with the billet to record the temperature variation from the liquid surface to the billet.

Samples for metallographic examinations were ground, polished and etched using a standard metallographic technique. Microstructures of these samples were analyzed under optical microscope (Leica DMR).

### 3. Results and discussions

#### 3.1 Macrostructure

The ingots were prepared by the conventional DC casting process and LFEVC (DC current 100A, AC current 150A, 25Hz) process, respectively. The macrostructure of the ingot are shown in figure 2.

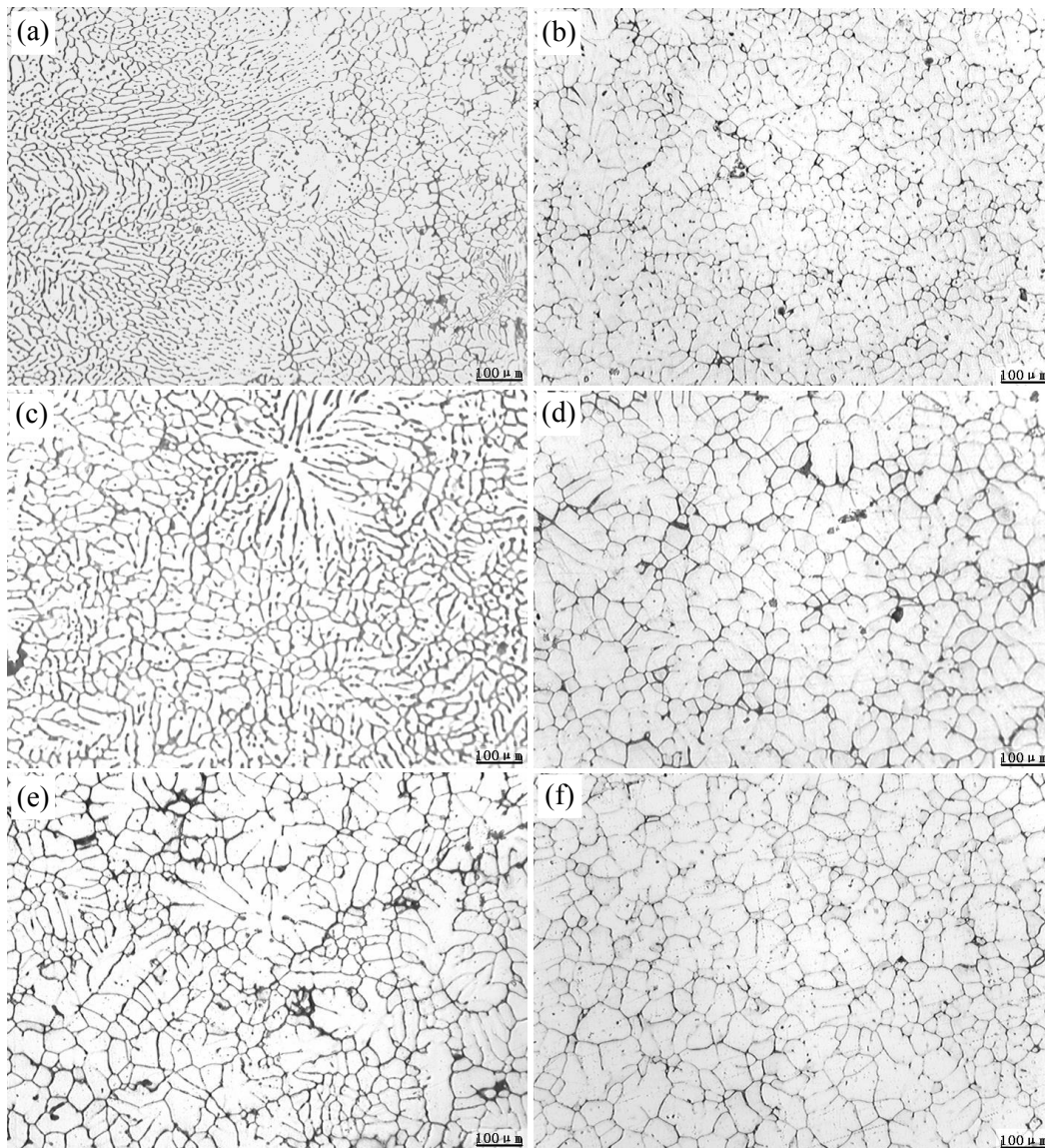


**Figure 2.** Macrostructure of the ingots prepared by DC and LFEVC (a), (b) border; (c), (d) 1/2 radius; (e), (f) centre; (a),(c),(e) DC; (b),(d),(f) LFEVC.

In general, the ingot prepared by the conventional DC casting process shows coarse macrostructure from the ingot surface to the centre of the ingot. As shown in figure 2a, there is a thin layer (about 2 mm) of fine macrostructure. Then the macrostructure shows a transition zone from fine macrostructure to coarse equiaxed structure then to coarse columnar structure and then to coarse equiaxed structure again. The ingot in both the 1/2 radius, figure 2c, and in the centre, figure 2e, shows a coarse equiaxed structure. The macrostructure of the LFEVC ingots is much finer than that of DC ingots. The macrostructure of the ingot from the surface, figure 2b, to the centre, figure 2f, shows fine and uniform equiaxed structure.

### 3.2 Microstructure

The microstructure of the LFEVC ingot is much finer than the coarse microstructure of DC ingot. Figure 3 a, c, e show dendritic microstructures of DC cast ingot, with the increase of the dendrite arm space from the surface to the centre. With the application of electromagnetic vibration, figure 3 b, d, f show fine and uniform equiaxed microstructure.



**Figure 3.** Microstructure of the ingots prepared by DC and LFEVC (a), (b) border; (c), (d) 1/2 radius; (e), (f) centre; (a),(c),(e) DC; (b),(d),(f) LFEVC.

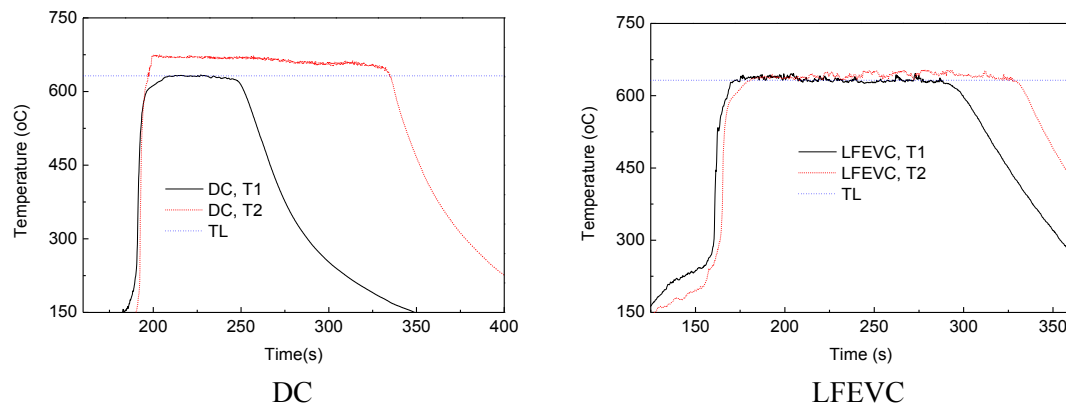
### 3.3 Temperature curves

The application of electromagnetic vibration results in a significant grain refining effect on the Al-Zn-Mg-Cu alloy. In order to understand and analyze the mechanism of grain refinement, the temperature curves were measured during casting process. As schematically shown in figure 1, thermocouple 1 (T1) and thermocouple 2 (T2) were fixed on the stainless rods connected to the bottom block. Therefore, T1 and T2 can be used to record the thermal history from liquid to the solid and analyze the thermal gradient of the melt and/or ingot.

As shown in figure 4, during conventional DC casting process, the temperature near to the ingot surface is close to the liquidus of the alloy while in the centre it is much higher than the liquidus, indicating a radial thermal gradient. During LFEVC casting process, the measured temperature both in the centre and near to the surface are close to the liquidus. The temperature field during LFEVC casting process is more uniform than that of conventional DC casting process, making a significant contribution to the grain refinement.

During LFEVC casting process, an alternating magnetic field,  $B(t)$ , and a stationary magnetic field,  $B_0$ , are generated in the melt by imposing an alternating current (frequency  $f$ ) into AC induction coil and a direct current into the DC coil as shown in figure 1. The alternating magnetic field,  $B(t)$ , gives rise to an induced current,  $J$ , in melt and/or ingot. The interaction of stationary magnetic field,  $B_0$ , and induced current  $J$  engenders a vibrating force:  $F_1 = J \times B_0$  with a frequency of  $f$ , which is schematically shown in figure 1 by dual direction arrows. Therefore an electromagnetic vibration is generated in the melt and/or ingot, resulting in an alternation of high pressure and low pressure in a local region. The electromagnetic vibration could increase the nucleation on oxide particles, intermetallics or the wall of the mould.

The interaction of the alternating magnetic field,  $B(t)$ , and its induced current,  $J$ , can also generate a Lorentz force,  $F_2 = J \times B(t)$ . The Lorentz force,  $F_2$ , is composed a potential force and a rotational force. The potential electromagnetic force is balanced by the stationary pressure of the melt, resulting in a decrease in the contacting pressure on the mold (soft contact). The rotational force can induce a forced convection in the melt, which is also schematically shown in figure 1 by circles and arrows under the liquid surface. The forced convection can improve the uniformity of temperature field in the melt as shown in figure 4 and promote the separation and movement of nuclei resulting in the fine and uniform microstructure, as shown in figure 2 and figure 3.

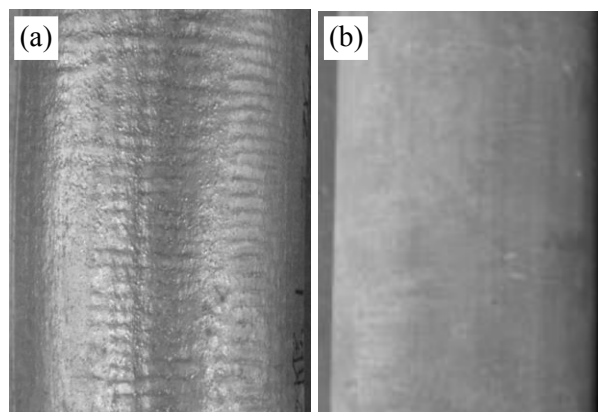


**Figure 4.** Measured temperature curves during conventional (left) DC casting and (right) LFEVC process.

### 3.4 Ingot surface

The ingot surface was observed to further understand the LFEVC casting process. As shown in figure 5a the conventional DC cast ingot shows a shining surface with cold shuts; while the ingot prepared by the LFEVC process shows smoother gray surface without shining. The gray colour of the surface could be due to the electromagnetic vibration and some graphite was adhered to the surface of the ingot.





**Figure 5.** Surface of ingots prepared by DC and LFEVC (a) DC ingot; (b) LFEVC ingot.

#### 4. Summary

An electromagnetic vibration was achieved by the combined application of an alternating magnetic field and a stationary magnetic field during direct chill (DC) casting process. The ingots of an Al-Zn-Mg-Cu alloy with 200 mm in diameter were prepared under the influence of electromagnetic vibration. The results showed that electromagnetic vibration has a significant grain refining effect on the Al-Zn-Mg-Cu alloy. Under the influence of electromagnetic vibration during DC casting process, the uniformity of microstructure is evidently improved.

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