Mechanism of pulse magneto-oscillation grain refinement on pure Al

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Abstract: Pulse magneto-oscillation (PMO) was developed as a novel technique to refine the solidification structure of pure aluminium. Its grain refining mechanism was proposed. The PMO refinement mechanism is that the nucleus falls off from the mould wall and drifts into the melt under the action of PMO. The solidification structure of Al melt depends on the linear electric current density, and also the discharge and oscillation frequencies. The radial pressure of PMO sound wave is the major factor that contributes to the migration of nucleus into the melt.

Key words: pulse magneto-oscillation; grain refining; solidification; aluminium
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Mechanical properties of castings can be improved by grain refinement, or modifying dendritic grains into globular grains [1-4]. A new technique, pulse magneto-oscillation (PMO), was developed to refine the solidification structure of castings by using pulse magnetic field [5-6]. When a pulse magnetic field with narrow pulse width is applied parallel to the melt surface, a Lorentz force is generated due to the interaction of pulse magnetic field and induced electric current. The Lorentz force causes vibration of the liquid metal and leading to grain refinement. As a non-contact physical field, PMO can refine solidification structure of metals. PMO technique is different from electric current pulse (ECP) technique [7-11] in both principle and setup. PMO is a non-contact method and would not pollute the metal. PMO technique is also different from the general pulse magnetic field technique [12]. The magnetic pulse width used in PMO technique is much narrower, which prevents liquid metal spattering. In addition, the pulse magnetic field in PMO technique has almost no influence on the inner melt due to the electromagnetic shielding effect of the induced pulse electric current on the melt surface. Accordingly, the inner melt is only shocked by the pulse oscillation wave that resulted from the interaction of surface pulse current and pulse magnetic field.

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In our previous research [5-6], it was found that the nucleus on the mould wall fell off and drifted into the melt, leading to the increase in nucleation during the solidification of Al when PMO was applied. In this contribution, refinement mechanism of PMO on the solidification structure of pure Al was discussed.

1 Experimental apparatus and procedure

The experimental apparatus composed of an electrical resistance furnace, capacitor bank, triggering unit, and a digital oscilloscope for the data storage. A voltage as large as 8,000 V can be achieved by the capacitor bank with a capability of 200 μF. Any voltage between 500 to 8,000 V could be charged by a regular AC electric source. An electric current passes through the coil when the capacitor bank is triggered. The current passing through the coil was measured with a digital oscilloscope through the electric current divider. In order to protect the oscilloscope, it was insulated from the ground.

Pure Al (>99.7%) was used. Specially designed casting mould and coil were used to create plane electromagnetic wave on the surface of metal melt. Figure 1 is the sketch of experimental setup. The mould is oblong in shape and having a size of 100 mm × 30 mm × 150 mm. Pure iron plates were put on the hemispheric ends, as shown in Fig. 1, in order to reduce the influence of PMO from both ends. There are channels under the iron plate for facilitating the filling of Al melt into the hemispheric regions.

Pure Al was first melted by an electric furnace and heated to the pouring temperature of 800℃ to avoid the quenching effect of the iron plates. PMO was then applied when the melt was at 680℃ and lasted until the melt solidified completely. Experimental parameters used in this study are shown in

Table 1. After cooling down to room temperature, the casting was taken out from the mould and sectioned transversely at a location 30 mm above the bottom for metallographic examination. The etching reagent used to reveal the macrostructures was a mixture of 9 parts hydrochloric acid, 3 parts hydrofluoric acid, 3 parts nitric acid and 5 parts water.

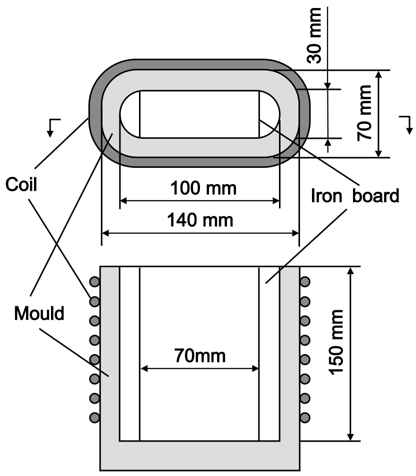

Fig. 1: The sizes of the mould and coil

Table 1: Experimental parameters

Sample	Discharge frequency (Hz)	Current peak value (kA)	Oscillation frequency (kHz)	Radius of grain (mm)
a	0.8	3.8	1.0	0.517
b	1.0	3.8	1.0	0.429
c	1.2	3.8	1.0	0.375
d	1.0	3.2	1.0	0.666
e	1.0	4.4	1.0	0.300
f	0.8	3.8	1.4	0.638

2 Results

Macrostructures of the specimens treated by PMO with different peak current values, discharge frequencies and oscillation frequencies are shown in Figs. 2(a)–2(f). Figure 2(g) shows the axial-symmetric columnar grains of untreated specimen. The structures of PMO treated samples are equiaxial grain with various sizes. The grain size was meassured by counting the number of the equiaxial grain on the lines that drawn on the sample sections. Table 1 shows the data measured by this method.

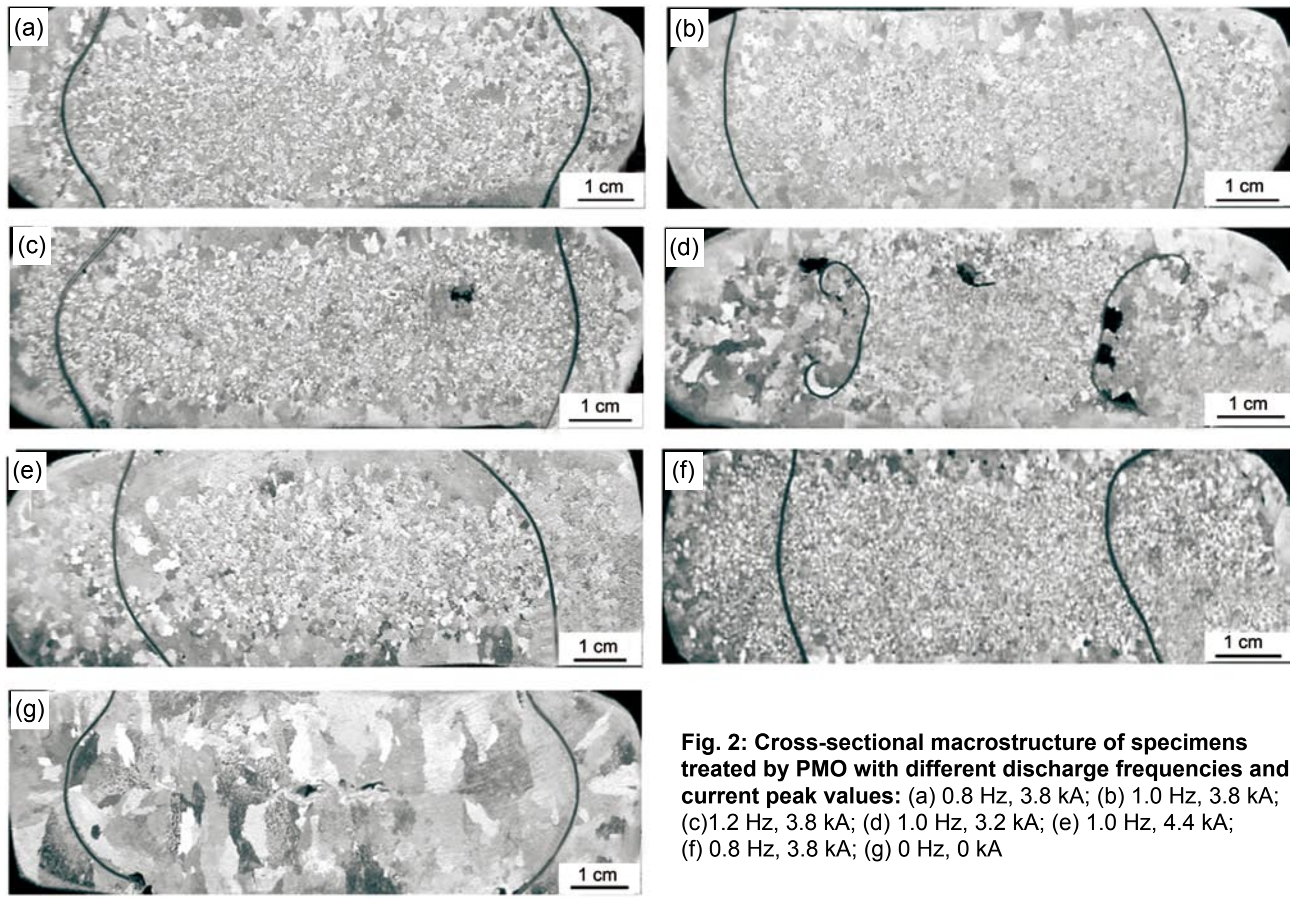

Fig. 2: Cross-sectional macrostructure of specimens treated by PMO with different discharge frequencies and current peak values: (a) 0.8 Hz, 3.8 kA; (b) 1.0 Hz, 3.8 kA; (c)1.2 Hz, 3.8 kA; (d) 1.0 Hz, 3.2 kA; (e) 1.0 Hz, 4.4 kA; (f) 0.8 Hz, 3.8 kA; (g) 0 Hz, 0 kA

3 Discussion

It is known that the nucleus formed on the melt surface were drifted into the melt during PMO treatment [5, 6]. Figure 3 shows the wave and force formed when a narrow pulse magnetic field ΔB parallelly acts on the melt surface, it will induce pulse current ΔJ on the surface of the melt. The interaction of ΔJ and ΔB will produce Lorentz force ΔF. Thus, vibration will be induced on the surface of the melt. And the pulse oscillation wave will transmit into the melt. Due to the different conductivity between the melt and the nucleus, the induced current densities across them are different also, and

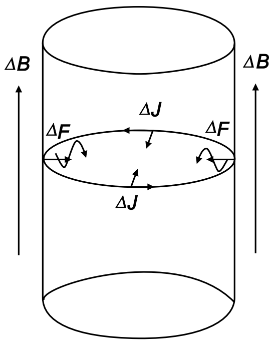

Fig. 3: Sketch of force and wave by PMO

thus, the electromagnetic forces acting on them are different. This is the reason that the nucleus moves from the surface to the center of the melt. The magnetic induction B and the induced current I in the melt decreased exponentially from surface to inside. So the electromagnetic force on the nucleus also decreased exponentially. When the electromagnetic force became too small the nucleus would slow down and begin to accumulate.

The pressure p on the surface of the metal melt that caused by the plane electromagnetic wave is:

$$p \approx \frac{1}{4}\mu J_0^2\left(1-\cos\left(2\omega t-\frac{\pi}{2}\right)\right) \tag{1}$$

where J_0 is peak value of the linear electric current density, i.e. the current density is an integral of deepness, μ is the permeability of material, t is the time and ω is the frequency of plane electromagnetic wave.

The constant part of Eq. (1) produces an invariable pressure on the metal melt; meanwhile the sound wave caused by resonance item spreads inside. When the sound wave meets the cumulated nucleus, it is reflected at the surface of the cumulated nucleus because of the different acoustics characteristics between solid and liquid. If the sound intensity is very large and sound wave reflected completely, the sound pressure of the plane sound wave on the nucleus that produced by the nonlinear sound wave is twice as the average density of sound energy. The average density of sound energy caused by the Eq. (1) is[13]:

$$\bar{\varepsilon} = \frac{p_m^2}{2\rho_0 c_0^2} = \frac{\mu^2 J_0^4}{32\rho_0 c_0^2} \tag{2}$$

where, p_m is peak value of sound pressure, ρ_0 is density of the metal melt, c_0 is velocity of sound in the melt. For the impulsive wave, the sound pressure on nucleus Δp_s is:

$$\Delta p_s = 2f_0\int_0^{f_z^{-1}} p\,dt = \frac{2f_0\bar{\varepsilon}}{f_z} = \frac{\mu^2 J_0^4 f_0}{16 f_z \rho_0 c_0^2} \tag{3}$$

where, f_0 is discharge frequency and f_z is oscillation frequency. Since the sound pressure in Eq. (3) acts on the cumulated nucleus, and the sound pressure in the melt equals to the average density of sound energy, namely, $\Delta p_l = \Delta p_s/2$, the pressure grade acting on the cumulated nucleus in the melt is:

$$\frac{\partial p}{\partial x} = \frac{\Delta p_s - \Delta p_l}{L} = \frac{\Delta p_s}{2L} = \frac{\mu^2 J_0^4 f_0}{32 f_z \rho_0 c_0^2 L} \tag{4}$$

where, L is the thickness of cumulated nucleus.

From a hydrodynamic point of view, the cumulated nucleus can be considered as porous medium. According to Newton's law of viscosity and the characteristics of liquid flow in round tube, the flow velocity of the melt in cumulated nucleus $\bar{v}_x$ can be obtained:

$$\bar{v}_x = \frac{K}{\eta f_L}\frac{\partial p}{\partial x} \tag{5}$$

Where, η is viscosity of the melt, f_L is bulk percentage of the liquid in the cumulated nucleus, and K is the infiltration coefficient, which is proportional to the square of cumulated nucleus radius (r_s^2), namely: $K = kr_s^2$. Combining Eq. (4) and Eq. (5), the melt flux per unit area flowing from the cumulated nucleus M_l is given:

$$M_l = \bar{v}_x f_L \rho_0 = \frac{K\rho_0}{\eta}\frac{\partial p}{\partial x} = \frac{\mu^2 J_0^4 f_0 k r_s^2}{32 f_z c_0^2 L\eta} \tag{6}$$

If the heat per unit area given out from mould wall is constant q and the mode of solidification is the typical volumetric solidification under the PMO effect, that is to say, the heat dissipating capacity of the mould is equal to the sum of the latent heat released from the nucleus and the heat generated from the induced current. So the overall mass of nucleus dissociated from the surface in unit time and area M is:

$$M = \frac{q-w}{L_r} = \frac{q - \dfrac{J_0^2 f_0}{2}\sqrt{\dfrac{\pi\mu}{\sigma_l f_z}}}{L_r} \tag{7}$$

where, L_r is latent heat and $w = J_0^2 f_0 (\pi\mu)^{1/2}/2(\sigma_l f_z)^{1/2}$ is Faradic heat power of PMO. If the solidification process is stable, that is to say the nucleus cannot grow up on the surface, then, the mass in Eq. (6) would be greater than or equal to the mass in Eq. (7), thus, the following equation is obtained:

$$r_s^2 \geqslant \frac{\alpha f_z}{f_0 J_0^4} - \frac{\beta\sqrt{f_z}}{J_0^2} \tag{8}$$

where, $\alpha = 32c_0^2 L\eta q/(\mu^2 k L_r)$, $\beta = 16c_0^2 L\eta\sqrt{\pi}/(\mu k L_r\sqrt{\mu\sigma_l})$

Since the casting mould has a plane surface, Eq. (8) can be used to analyze the result obtained from PMO treatment experiment. When the discharge and oscillation frequencies remain unchanged, and the intensity of PMO treatment is high enough that the nucleus cannot grow up on the melt surface, the relationship between J_0 of PMO and radius of sample nucleus is:

$$r_s^2 J_0^2 = \frac{\alpha\cdot f_z}{f_0}\frac{1}{J_0^2} - \beta\sqrt{f_z} \tag{9}$$

There is a linear relationship between $1/J_0^2$ and $r_s^2 J_0^2$. Choose the data of sample d, b and e from Table 1, the discharge and oscillation frequencies of these samples are 1 Hz and 1 kHz. Figure 4(a) is the plot of $r_s^2 J_0^2$ vs. $1/J_0^2$. It can be seen that the three data points are linear, and the linear fit of the line is $(r_s J_0)^2 = 57.091 J_0^{-2} - 1.1091$. From Eq. (9), we get $\alpha = 57.1$ $(\mathrm{kA})^4\cdot\mathrm{mm}^{-2}$, $\beta = 1.11$ $(\mathrm{kA})^2(\mathrm{ms})^{1/2}$.

Similarly, when J_0 and the oscillation frequency remain unchanged, relationship between the discharge frequency of PMO and the radius of sample nucleus is:

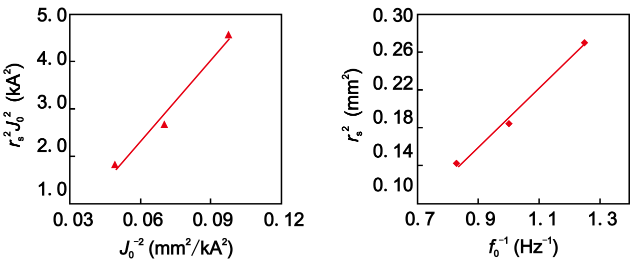

Fig. 4: Relationship between $(r_sJ_0)^2$ and J_0^{-2} under the fixed discharge and oscillation frequencies (a), and the r_s^2 and f_0^{-1} under the fixed J_0 and oscillation frequency (b)

$$r_s^2 = \frac{\alpha \cdot f_z}{J_0^4}\frac{1}{f_0} - \frac{\beta\sqrt{f_z}}{J_0^2} \qquad (10)$$

i.e. there is a linear relationship between r_s^2 and f_0^{-1}. Choose the data of samples a, b and c from Table 1, J_0 and oscillation frequency of all samples are 3.8 kA and 1 kHz. Figure 4(b) is the plot r_s^2 vs. f_0^{-1}. It can be seen that the three data points are linear, and the linear fit of the line is: r_s^2= 0.3074f_0^{-1}–0.1176. So we get α = 64.1 (kA)^4·mm^{-2}, β = 1.70 (kA)^2(ms)$^{1/2}$.

When J_0 and discharge frequency remain unchanged, relationship between the oscillation frequency of PMO and the radius of sample nucleus is:

$$\frac{r_s^2}{\sqrt{f_z}} = \frac{\alpha}{J_0^4 f_0}\sqrt{f_z} - \frac{\beta}{J_0^2} \qquad (11)$$

There is a linear relationship between $r_s^2/f_z^{1/2}$ and $f_z^{1/2}$. Choose the data of samples a and f from Table 1, J_0 and discharge frequency of the two samples are 3.8 kA and 0.8 Hz. Take $f_z^{1/2}$ as abscissa, $r_s^2/f_z^{1/2}$ as y-axis, the linear fit of the line is: $r_s^2f_z^{-1/2}$ = 0.3734$f_z^{1/2}$–0.1044, then we get: α = 62.3 (kA)^4·mm^{-2}, β = 1.51 (kA)^2(ms)$^{1/2}$.

Since the coefficients α and β are related only to the characteristic of Al and casting conditions, they should be constants. From experiment data, α equals to 57.1, 62.3 and 64.1 (kA)^4·mm^{-2}, and the corresponding β are 1.11, 1.51 and 1.70 (kA)^2(ms)$^{1/2}$, respectively. They do not change much and can be considered as constants. Therefore, it is true to say that the radial pressure of PMO sound wave drags the nucleus into the melt.

In summary, from our experimental results, it can be seen that the peak value of the linear electric current density J_0 of PMO has the greatest effect on the macrostructure of the solidified Al and it has great influence on the pressure of PMO, which is the main factor in producing the nucleus in the melt.

4 Conclusions

Application of PMO can transform large columnar grains into fine equiaxed grains during the solidification process of pure Al. The refinement mechanism is that the nucleus falls off from the mould wall and drifts into the melt during PMO treatment. The solidification structure of Al melt depends on the linear electric current density, and also the discharge and oscillation frequencies. The radial pressure of PMO sound wave is the major factor that contributes to the migration of nucleus into the melt.

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