Control of solidification microstructure using programmable electro-magnetic pulses

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Abstract. A programmable electro-magnetic pulse (PEMP) apparatus has been designed and made, and used to study the effect of different pulse amplitude and frequencies on the solidification microstructure. The measured magnetic fluxes agree well with the simulated fluxes using finite element method. The solidification microstructure of a Sn-18\%wtPb was studied using different pulse amplitudes and frequencies. It was found that higher pulse amplitude and frequency lead to more grain refinement.

1. Introduction
The mechanical properties of cast alloys, such as strength and ductility, are mainly determined by the grain structure and defect formed during solidification processes. How to achieve an optimal morphology, size and distribution of the grains and those of the defects (porosity and/or inclusions) to maximise the alloy’s mechanical properties are the main driving force for metal alloy research for many years. Conventional methods of adding external grain refiners to refine the solidification structure of metal alloys have been used in industry for many decades [1, 2]. Those methods have inherent problems. Firstly different alloys need grain refiners of different chemistry, such as Al-Ti-B for Al-based alloys, Zr for Mg-based alloys, etc. [2, 3]. Secondly, different operation practices are needed for different alloys systems, and each of the operation inevitably add extra cost to the manufacturing of the alloys and most likely an adverse impact to the environment. To reduce the environment impact and develop a sustainable and green manufacturing strategy, in the past twenty years or so, many researches have been carried out to develop novel grain refining technologies. Among them, electrical or magnetic field based techniques have attracted a great deal of attention in research communities and industry. The electrical pulse current and electromagnetic stirring [4-7], for example, have shown to be effective techniques for grain refinement. The practical challenge is how to apply those current or field uniformly in a large volume of melt, and therefore to refine a large volume of melt without consuming a huge amount of energy with dangerously high electrical current or voltage [7, 8].

Currently, extensive worldwide researches have been conducted in this field in university laboratories in the UK, USA, Europe, Japan and China [9-13]. However, most of the research has been done by applying the electromagnetic pulses into stationary crucibles and there are very limited reports on applying the electro-magnetic pulse into a continuous casting operation. In this research, we designed a programmable electromagnetic pulse (PEMP) device, and a small scale continuous casting apparatus to mimic the operation in DC casting. The effects of electro-magnetic pulse of different voltages on the resulting solidification microstructure were studied in details.
2. The design of the PEMP device

We designed a novel device to generate programmable electro-magnetic pulses (PEMP). The amplitude, frequency and duration can be programmed to suit different alloys and processing conditions. The principle and design of the apparatus is briefly described below.

The PEMP device consists of two main units: the energy charging unit and pulse generating unit. In the charging unit, a capacity bank is charged using a long-duration but low-power energy. The voltage charged into and the energy stored within the capacitor can be calculated by:

\[ V = V_c(1 - e^{-\frac{t}{RC}}) \]  
\[ E = 0.5CV^2 \]

where \( V_c \) is the voltage applied to the circuit, \( t \) is time and \( E \) is the energy stored in the capacitor bank.

In the pulse generating unit, the energy stored in the capacitor bank is discharged in a controlled short period of time to send high power pulse to the working unit (the induction coil in this case) as showed in figure 1(a). The novelty of this device is that a Thyristor pulse trigger is designed to control the release of the pulse in term of time and duration and repetition. In this way, programmable high energy pulses with tuneable amplitudes, frequencies and duration can be generated to suit different alloys systems for process optimisation purpose. Examples of the charging process of the capacitor bank, and the pulse generated to the coil are shown in figure 1a and b. Through the induction coil (45 turns and 120 mm height), pulsed Lorentz forces are generated into the alloy during solidification process as schematically shown in figure 1(b) [14-16], and the Lorentz force vector points towards the centre of the coil.

![Diagram](image)

**Figure 1.** (a) Schematics to show the energy charging and pulse generating units of the PEMP device, (b) the Lorentz force created by the coil, (c) the peak magnetic flux as a function of the input voltages.
3. Experiment procedure

We also designed a small-scale casting apparatus. It consists of a furnace with close-loop temperature control unit, a sample stage to hold glass tubes (as a crucible) with metal, and a linear actuator that can release a controlled sample withdrawing out of the furnace with very high accuracy of travel (the travel step resolution is 0.49 µm). The apparatus can be used to mimic the semi-continuous DC casting operation.

3.1 Casting of alloy bars

Low melting point binary alloy (Sn-18%wt.Pb) was made by melting together pure Sn (purity of 99.75%) and pure Pb (purity of 99.97%) with the designed weight ratio in a Carbolite furnace. The alloys were cast into 130 mm long borosilicate glass tubes with the inner diameters of 9 mm by using a custom-made small counter-gravity casting apparatus. The controlled negative pressure draws the liquid metal uphill and fill into the glass tubes in a quiescent manner, avoiding the turbulence of the liquid metal during the filling process and therefore any entrainment of air bubbles, porosity or oxide films during casting.

3.2 Solidification experiment under pulse magnetic field

Borosilicate glass tubes were again used (130 mm long with 9 mm inner diameter) as the casting moulds. The alloy ingots were placed into the glass tubes, and at the bottom end, the glass tubes were sealed by Duratec ceramic rods, which were placed and linked to a linear actuator with a programmable travel speed of 100 µm/s. Five K-type thermocouples were positioned inside the glass tubes at 1, 3, 5, 7 and 9 cm from the bottom of the sample to measure the temperatures at those locations during the experiment and recorded using the TC-08 Thermocouple Data Logger, and PicoLog for Windows (PLW) recorder software.

The glass tubes with alloy bars inside were heated in the furnace and held above the alloy melting point at ~230 °C for 30 minutes to homogenise the melt temperature. Then the glass tubes were withdrawn out of the furnace at a constant speed of 100 µm/s.

Two groups of samples were cast, one with PEMP, one without. The experimental parameters used are listed in table 1, and the PEMP was applied continuously after the glass tubes were withdrawn out of the furnace until the melt completely solidified.

| Discharged Pulse Frequency (Hz) | Discharge voltage (V_d) |
|-------------------------------|-------------------------|
| 1                             | 40                      |
|                               | 80                      |
|                               | 120                     |
| 10                            | 40                      |
|                               | 80                      |
|                               | 120                     |

After solidification, the as-cast alloy samples were taken out of the glass tubes, and were sectioned longitudinally into two halves. The sectioned surfaces were ground using SiC grinding papers of 600, 1200, 2500 grid size, and then polishing using diamond suspension of 6 and 1 µm size using Motopol 12 grinder and polisher operated at 150 rpm. Each grinding and polishing steps takes 20–30 minutes.
4. Modelling
In order to quantify the magnetic flux density induced by the voltage pulse discharged into the coil, we used COMSOL Multiphysics to calculate the induced magnetic flux density. Figure 2 shows the 2D symmetric geometry used in the simulation and the mesh (triangular mesh of 94,262 elements). The induction coil is defined as the Single-Turn Coil domain. The Biot–Savart law (equation 3 and 4) [17] was used to calculate the magnetic flux density:

\[ 0 = \nabla \cdot B \]  
\[ B = \frac{\mu_0 I}{4\pi} \int \frac{dl}{r^2} \]

where \( B \) is the magnitude of the magnetic field (the magnetic flux density), and is measured by Tesla (Wb/m²), \( \mu_0 \) is permeability of free space, \( r \) is the distance between the location of \( dl \) and the location at which the magnetic field is being calculated.

![Figure 2](image)

(a) the 2D symmetrical geometry for the simulation, and (b) the mesh structure.

5. Results and discussions

5.1 The effect of PEMP on the grain growth and dendrite morphology
Figure 3a shows the microstructure of the alloys cast without PEMP. The grains grew unidirectionally against the direction of withdrawing and formed very long columnar dendrites. Figure 3b-g show the microstructure formed under the influence of PEMP with the corresponding parameters applied listed in table 1. Apparently, when the PEMP was applied, the long columnar dendrites typically shown in figure 3a were disrupted, forming a series of dendrite clusters along the growth direction. We used ImageJ to segment the dendrite clusters of those showed in figure 3b-g where different discharging voltages and pulse frequencies applied. It was found that the average dendrite clusters become smaller and smaller as the discharge voltages and frequencies increase.
Figure 3. The solidified microstructure of the 9 mm diameter samples: (a) without PEMP, (b) PEMP with 40 V and 1 Hz, (c) 80 V and 1 Hz, (d) 120 V and 1 Hz, (e) 40 V and 10 Hz, (f) 80 V and 10 Hz, (g) 120 V and 10 Hz.

Figure 4. (a) The point where the magnetic flux density was measured, (b) the comparison of measured and simulated pulses of magnetic flux density, (c) the magnetic flux density as a function of the discharged voltage and frequency.
5.2 FEM simulation
Figure 4a shows the point where the maximum magnetic flux density is measured using Gaussmeter. Figure 4b shows the comparison between the measured magnetic flux density and those simulated using FEM method. In general, the measured and simulated shapes of the pulses for all different discharging voltages are very similar. While the peak values of the simulated pulses are 10~15% higher than those of the measured ones, indicating that, in the modelling, the energy loss in the discharging circuit and the coil is not considered, and therefore the simulated values are slightly higher than the measured values. It is interesting to find that the peak values of the magnetic pulses increase linearly with the increase of discharging voltages as shown in figure 4c, and the higher the discharging frequency, the higher the peak value of the magnetic pulse.

6. Conclusion
The peak of the magnetic flux density pulse has a linear relationship with the discharging voltages, and the higher the discharging voltage/frequency, the higher the peak value of the pulse. The magnetic pulse applied to the liquid metal during solidification can effectively disrupt the growth of the dendrite, and change a long columnar dendrite to many dendrite clusters. The higher the pulse density, the smaller the dendrite cluster created.

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