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Effect of permanent magnet stirring on solidification of Sn-Pb alloy

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ABSTRACT

An experimental investigation has been conducted with respect to the influence of permanent magnet stirring (PMS) under different rotation speeds ($\omega = 60$, 120 and 150 r/min) and center magnetic flux densities ($B =$ 757 and 1080 Gs) on the solidification of Sn-20 wt%Pb alloy. The magnetic field was generated by a pair of arc-shaped NdFeB permanent magnets with a gap that could be adjusted to obtain the required magnetic flux density. The effects of different values of ω and B were investigated by analyzing the driven flow intensity, surface and internal quality, macrostructure, microstructure and tensile properties. It was observed that with increasing ω and B there was significant improvement in the flow intensity of the liquid, surface pinholes, grain refinement and tensile properties. The results obtained have important implications for industrial metal casting processes.

1. Introduction

The effects of physical fields including electromagnetic field, electric current pulse and ultrasonic field on the solidification of metals have been studied and discussed [1–3]. In recent decades, with the use of electromagnetic stirring during solidification, the magnetic field has been mainly generated by three-phase alternating current. A large number of studies [4–7] have been performed on the influence of a low frequency electromagnetic field on the grain refinement of alloys and pure metals. However, the electromagnetic field based on the use of rotating permanent magnets has been rarely reported. In 1992, Vives [8,9] developed a moving permanent magnet device, which allows the production of intense 3-D multiphase flows in solidifying semisolid alloy slurries and proposed that this process, which is characterized by a very low electric power consumption, could be applied to continuous casting of billets and slabs. In 2005, Wang et al. [10] presented a method to induce rotating and travelling magnetic fields inside metallic alloys by a pair of arc NdFeB permanent magnets. In 2014, Luo et al. [11,12] investigated the effect of magnetic stirring which was produced by a pair of permanent magnets on the microstructure and mechanical properties of magnesium alloy and aluminum alloy. Recently, a permanent magnet stirring apparatus driven by a hydraulic system has been developed and used industrially during continuous casting of high-carbon steel [13].

The Sn-Pb alloys with low-melting characteristics and good electrical conductivity have been widely used as solders for electronic materials, plumbing and assembly of sheet metal parts. They have also been used to investigate the influence of electromagnetic stirring on solidification structure and other properties [14,15] and to predict the effects of electrical magnets on the solidification behavior of high temperature metals and alloys. The beneficial effects of rotary magnetic stirring on the macrostructure and microstructure of Sn-Pb alloys are directly related to changes in the metal flow. Both theoretical studies and experimental research have been conducted on the mechanisms associated with columnar to equiaxed transition (CET) and grain refinement by electromagnetically driven melt convection [16,17]. The transport of hot liquid towards the solidification front most likely induces fragmentation of columnar dendrites due to thermal remelting. If the solidifying Pb-Sn ingot is exposed to a rotating magnetic field increase of dendritic fragments ahead of the solidification front will promote the CET [17]. Hunt [18] suggested that melt stirring contributed to grain refinement through two effects: (1) metal flow into the mushy zone is enhanced which in turn promotes remelting of dendrite arms; and (2) the thermal gradient in the liquid is lowered, thus extending the undercooled region and favoring the columnar to equiaxed transition. However, the effects of permanent magnet stirring (PMS) with different values of ω and B on the driven flow intensity and hence on grain refinement and subsequent tensile properties of alloys have received relatively little attention [10,19]. The goal of this work is to assess the influence of PMS under different conditions of ω and B on the solidification of Sn-20 wt%Pb alloy and in particular on flow intensity, macro-defects, macrostructure, microstructure and tensile properties.

2. Experimental procedure

A schematic diagram of the PMS apparatus is shown in Fig. 1. The variable magnetic field is produced by rotating permanent magnets

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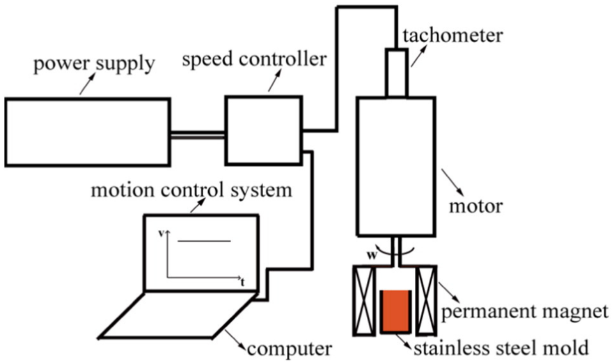

Fig. 1. Schematic diagram of the PMS process.

driven with an angular velocity *w*, by an adjustable speed motor connected to a power supply system that is coupled to a controller which permits precise speed variations ranging from 0 to 200 r/min. The sintered NdFeB permanent magnetic material with a $(BH)_{max}$ of 400 kJ/m^3, and a working temperature up to 453 K (180 °C), was selected to generate the magnetic field because of its excellent magnetic characteristics. Experiments were performed with Sn-20 wt%Pb alloy prepared from 99.99% Pb and 99.9% Sn. Melting was carried out in a resistance furnace with a stainless steel crucible. Approximately 600 g of alloy was melted, superheated by 100 °C for 30 min, the crucible then taken from the furnace and placed in a preheated stainless steel mold with a temperature of 200 °C. The alloy is initially molten and being stirred in the whole solidification process with nature cooling at an ambient temperature of 25 °C. The Sn-Pb cylindrical ingot had a diameter of 45 mm and a height of 50 mm.

As is illustrated in Fig. 2, the magnetic field was generated by a pair of arc-shape NdFeB magnets and the gap adjusted in order to achieve the required value for the center magnetic flux density. The magnetic field was measured using a gauss meter. The variation in the horizontal direction was assumed to be a quadratic function of the distance which was large at the edge and small at the center. Two magnetic field strengths were used with center magnetic flux densities of 757 Gs and 1080 Gs, respectively. Moreover, rotation speeds in the range 0–150 r/min were selected and these are sufficiently small so that any influences arising from the skin effect can be neglected.

Metallographic specimens were ground using SiC-paper and subsequently polished with 1.5 μm diamond abrasive. The Sn-Pb cylindrical ingots and metallographic specimens were etched using acid solution

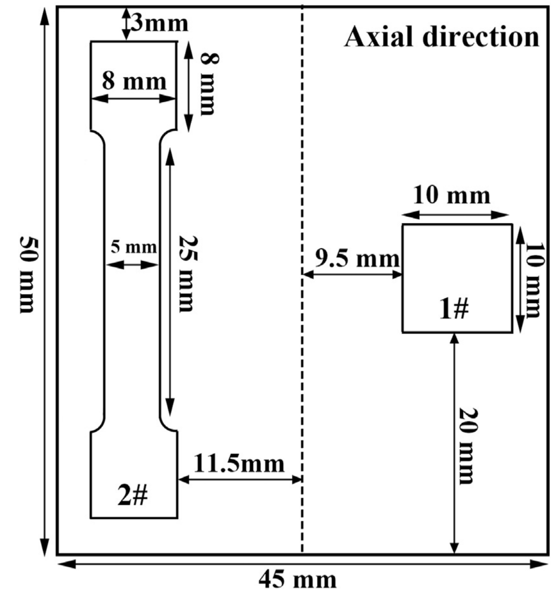

Fig. 3. Schematic diagram of samples: microstructure samples (1#) and tensile properties samples (2#).

(2 ml HCL; 10 g $FeCl_3$ and 100 ml H_2O) [20]. The microstructures of etched specimens were examined using a metallographic microscope (Zeiss Axio Imager M2 m). As is demonstrated in Fig. 3, microstructure samples (1#) and tensile properties samples (2#) were taken from the ingots in axial direction for various experiments. The tensile specimen diameter and narrow section length were 5 mm and 25 mm respectively and the overall diameter and total length were 8 mm and 44 mm respectively. The tensile tests were performed using a WDW-200D universal test machine with a strain rate of about 1×10^{-3} s^{-1}. Two tensile tests were carried out for each condition. The surface morphology of tensile fracture specimens was investigated using a scanning electron microscope (SEM) FEI (MLA 250).

3. Results and discussion

Solidification experiments were conducted with variations in the rotation speed *w* and center magnetic flux density *B*. The effects *w* and *B* on the solidification of the Sn-20 wt%Pb alloy were investigated by

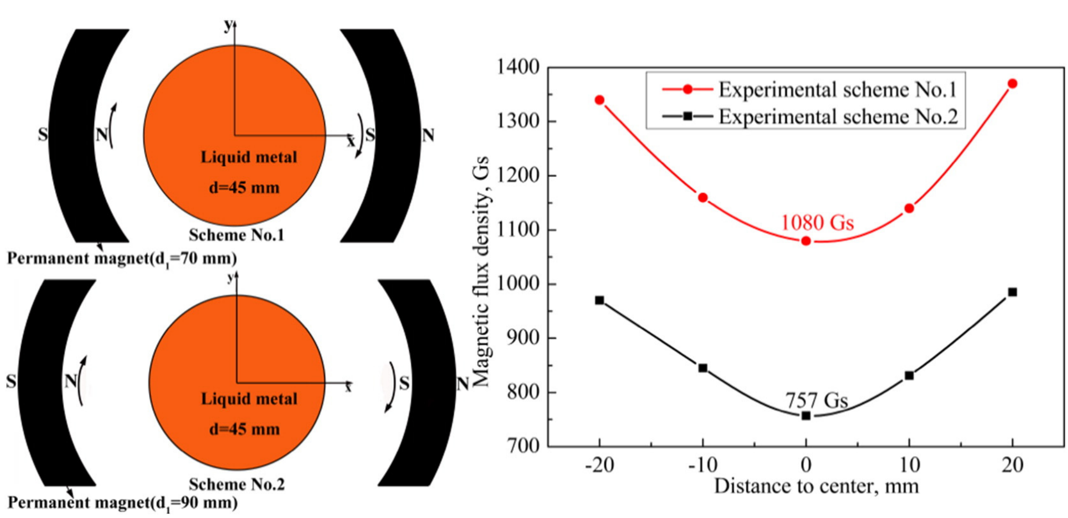

Fig. 2. Schematic (left) and measured (right) magnetic field generated by a pair of arc-shape NdFeB magnets with different horizontal distances: scheme No.1 with a distance of 70 mm and scheme No.2 with a distance of 90 mm.