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An Experimental Prototype of an Innovative Fluid-driven Electromagnetic Stirring Technique

Bo WANG[1], Xiao-dong WANG[1], Yuri KOLESNIKOV[2], San ZHANG[1], Yan-qing TAN[1], Xian-zhao NA[3]

(1. College of Materials Science and Opto-electronic Technology, University of Chinese Academy of Sciences, Beijing 101408, China; 2. Institute of Thermodynamics and Fluid Mechanics, Ilmenau University of Technology, Ilmenau 98684, Germany; 3. State Key Laboratory of Advanced Steel Processing and Products, Central Iron and Steel Research Institute, Beijing 100081, China)

Abstract: A new electromagnetic stirring technique that is driven by hydrodynamic forces was presented. This technique offers the following advantages. First, the stirrer can be immersed in the liquid metal, thereby significantly increasing the penetration depth of the electromagnetic forces and significantly improving the stirring efficiency; thus, this technique is particularly suitable for large-scale liquid metal. Second, under certain conditions, this technique can overcome difficulties that are encountered with traditional stirrers, such as accessing regions that are difficult to reach in working spaces with complex or narrow shapes. This stirrer also has a simpler structure than a traditional stirrer; thus, the design can be easily modified, and no external power supply is required. An experimental prototype was also presented for controlling the fluid flow rate, thereby controlling the electromagnetic force and velocity field of the driven liquid metal. The velocity distribution in a liquid GaInSn alloy under fluid-driven electromagnetic stirring was quantitatively measured using ultrasonic Doppler velocimetry (UDV). The primary results show that a remarkable velocity field has been achieved and that fluid-driven electromagnetic stirring is an effective means of stirring liquid metal. Finally, the potential applications of this technique in industry, along with key challenges, were discussed.

Key words: fluid; electromagnetic stirring; liquid metal; skin effect; Lorentz force

The first investigation into liquid metal driven by a rotating magnetic field (RMF) was reported in 1932 by Braunbek[1], who determined the swirl flow generated by an RMF and used the resulting torque to measure the conductivity of liquid metal at different temperatures. Mullin and Hulme[2] employed electromagnetic stirring to reduce segregation in the mush zone of InSbTe and InSb melts in 1958. Based on the developments achieved during the decades since then, the application of magnetic fields in metallic materials has become an interdisciplinary field, and the so-called electromagnetic processing of materials (EPM), devoted to applying various electromagnetic fields during material processing or the exploitation of new materials.

Electromagnetic stirring (EMS) with multi-phase alternating current (AC) fields aimed at efficiently driving or stirring a melt has become one of the most important branches[3] of EPM. There are two means, according to the electromagnetic media, of exerting electromagnetic force in the liquid metal. One is single- or multi-phase current-carrying coils, such as electromagnetic stirrers[4,5], which are widely used in the metallurgical industry, and the other is permanent magnets driven by a motor, such as a Halbach permanent magnet motor[6], or a spiral permanent magnetic field[7]. In the former, the frequency is an essential operating parameter, whereas

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Biography: Bo WANG, Doctor Candidate; **E-mail**: wangbo199027@126. com; **Received Date**: May 20, 2015

Corresponding Author: Xiao-dong WANG, Doctor, Professor; **E-mail**: xiaodong. wang@ucas. ac. cn

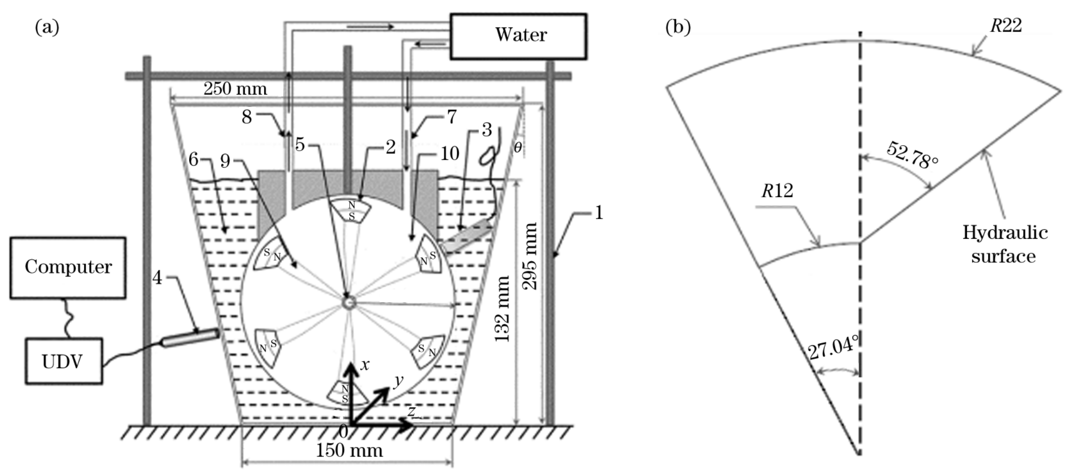
in the latter, the layout and arrangement of the permanent magnets are flexible.

In these two traditional electromagnetic stirring techniques, the electromagnetic fields are applied to outside of the liquid bulk[7-10]. The magnetic field can only penetrate to a limited distance within a liquid bulk, which is called the skin layer, and has a skin depth $\delta=\sqrt{\frac{2}{\sigma\mu\omega}}=\sqrt{\frac{1}{\pi\sigma\mu f}}$, where, σ and μ are the electric conductivity and magnetic permeability of the liquid metal, respectively; ω and f are the angular velocity and frequency of the electromagnetic stirrer, respectively and d is the typical length of the liquid metal bulk. Therefore, traditional electromagnetic stirring is subjected to the following limits: (1) If the liquid metal is sufficiently large, i. e., $d\gg\delta$, the electromagnetic force cannot achieve sufficient penetration of the entire liquid metal region ($d-2\delta$). Thus, the center part of the viscous fluid can only be driven by inertia, resulting in a limited stirring effect. (2) The electric device used to generate the electromagnetic force may consist of long cables, coils, iron cores and a magnet yoke, which make the device complex and heavy.

In this paper, an innovative prototype of fluid-driven electromagnetic stirring that may overcome the above limitations of traditional electromagnetic stirring was presented. The circular-arrangement permanent magnets provide a field, and a hydraulic driving means, instead of electrical or mechanical driving means, is adopted. The kinetic energy of fluid motion is transformed into that of the liquid metal by turbine blades and permanent magnets according to principles of gas-liquid dynamics and electromagnetism. Then, a rotating magnetic field is formed, and the electromagnetic energy is transformed into the kinetic energy of liquid metal according to magnetohydrodynamics. The stirrer can be immersed into any position of the large-scale liquid metal bulk to overcome the drawbacks of the skin effect and can be applied to complex or narrow working spaces.

1 Experimental Set-up and Stirring Process

The experimental set-up consists of permanent magnets, a water flow passage, a liquid GsInSn alloy, an enclosed cavity, a trapezoidal Plexiglass vessel, measuring apparatus and a fixed support, as shown in Fig. 1(a). The arc-shaped NdFeB permanent magnet, whose direction of magnetization is in the radial direction, was fabricated as shown in Fig. 1(b) with a width of 30 mm. The permanent magnets are fixed on six impellers with adjacent magnets having opposite magnetization directions, and they were installed onto a bearing located in the center, which was placed concentrically with an enclosed Plexiglass cylindrical cavity of ϕ108 mm×60 mm. The induction of a magnetic field on the outer cylindrical surface of the cavity reaches 180 mT in the vicinity of passing permanent magnets. The inner diameter of the water flow passage is 12 mm. The ternary eutectic alloy with the composition $Ga_{67}In_{20.5}Sn_{12.5}$, which has a melting point of 10.5 ℃ and is in a liquid state at room temperature, is contained in a transparent trapezoidal vessel with top and bottom lengths of 250 and 150 mm, respectively, a height of 295 mm, and a width of 65 mm. The relevant physical properties of the alloy are provided in Table 1[11]. The vessel used to mimic the large-scale liquid metal bulk, was



1—Supporting frame; 2—Permanent magnets; 3—Hall transducer; 4—Ultrasonic transducer; 5—Bearing; 6—Liquid GsInSn; 7—Inflow; 8—Outflow; 9—Turbine blade; 10—Plexiglass cavity.
(a) Schematic of the set-up; (b) Cross-section of the permanent magnet.

Fig. 1 Experimental set-up of the fluid-driven electromagnetic stirring system