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Coupling analysis of the electromagnetic transport of liquid aluminum alloy during casting

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ABSTRACT

Electromagnetic transport (EMT) process with plane induction electromagnetic pump (EMP) was developed for the transport of liquid aluminum alloy during casting. The temperature rise of liquid aluminum alloy when flowing into and out of the pump ditch of the EMP during the EMT process was gained by magnetic-thermal coupling analysis. The flow field and the effects of structural design and transport technological parameters on the transient and stable EMT performance of the engineering EMT prototype were obtained by magnetic-flow coupling analysis. The extra temperature rise effect accompanied with the EMT process can be neglected since the EMP induced local maximum and average temperature rises corresponding to a common sojourn time of 1.16 s are only 1.3 °C and 0.6 °C, respectively. Two recirculation zones distribute symmetrically along both sides of the central main flow in the pump ditch and the transition transport tube. Sequential air exhaust and outflow appear when the cross-sectional area shrunken ratio from the rectangular pump ditch to the circular transport tube is 0.472. The stable outlet flow rate increases with the diameter of the circular transport tube (d) due to the weakening of recirculation zones, and it increases linearly with the transport current (I), while it decreases with the initial transport height. The morphology of the stable flow field is not affected by I.

1. Introduction

The electromagnetic fields have been widely used in the materials processing fields such as electromagnetic casting (Le et al., 2007), electromagnetic vibration (Li et al., 2007), electromagnetic brake (Yu et al., 2008; Miao et al., 2012), electromagnetic stirring (Wang et al., 2010) and levitation melting (Kermanpur et al., 2011) during casting, plastic forming (Psyk et al., 2011; Cui et al., 2014) and welding (Bachmann et al., 2014). Aluminum castings are used in a wide variety of commercial applications because of their high strength to weight ratio, good corrosion resistance and relatively low raw material cost (Backer and Wang, 2007). As an effective way to transport liquid aluminum alloys directionally during casting, the electromagnetic transport (EMT) process that is driven by the electromagnetic pump (EMP) not only improves production efficiency but also isolates liquid aluminum alloys from air and reduces the oxide inclusions in castings. Since the invention of the Cosworth Process (Campbell and Wilkins, 1982) which employed the EMP to transport liquid aluminum alloys in low pressure die casting, the application of the EMT process has been extended to high pressure, squeeze and gravity casting fields. Saito et al. (1989) developed the EMT apparatus for high pressure casting with outside mounted annular induction EMP. Mercer et al. (1995) designed the EMT apparatus for high pressure casting with submerged EMP. Cheng et al. (2000) reported the EMT apparatus for low pressure and squeeze casting of aluminum alloys with outside mounted planar direct current (DC) EMP. Miura et al. (2009) proposed the EMT apparatus for die casting with outside mounted annular induction EMP, and the transport of molten metal could be stopped by inert gas. The CMI Novacast Inc. is now improving and promoting the EMT apparatus with submerged EMP for low pressure, squeeze and gravity casting.

The submerged EMP is with high efficiency but also high cost, and the outside mounted planar DC EMP has high conductive and anticorrosive demands for the electrodes that are inserted directly into the highly active liquid aluminum alloys, while the outside mounted annular induction EMP is inconvenient for cooling and

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maintenance, so the EMT apparatus with outside mounted plane induction EMP is developed in the present study to solve the above mentioned problems. In our earlier work about the plane induction EMP (Dong et al., 2013, 2014), the effects of structural and electromagnetic design parameters on the performance of the plane induction EMP were revealed. However, the former studies were only singular electromagnetic field analysis and optimal design about the EMP. The effects of the structure design parameter of the transport tube and the transport technological parameters of the transport current and the initial transport height on the transient and stable EMT performance of the whole EMT system, the spatial distribution laws of the flow field, and the extra temperature rise effect in liquid aluminum alloys when flowing into and out of the pump ditch of the EMP under the EMT process are still unknown. Le et al. (2007) investigated the flow pattern and temperature field of electromagnetic direct chill casting of magnesium alloys by coupling simulation, Zhao et al. (2011) studied the temperature and flow fields during twin-roll casting of magnesium alloy strip by thermal-flow coupling analysis, Singh et al. (2014) simulated the electromagnetic field effect on transient flow during continuous casting, Li et al. (2014) simulated the effect of submerged entry nozzle on flow and temperature fields in the electromagnetic swirling continuous casting process, and their attempts provided a way to solve problems about the flow and temperature fields during casting by coupling fields numerical simulation. The aim of the present work is to reveal the above mentioned unknown effects and laws about the EMT by magnetic-flow and magnetic-thermal coupling analysis for the optimal design and engineering application of the EMT process with plane induction EMP.

2. EMT principle and experiment

2.1. Principle of EMT process

Fig. 1 shows the schematic diagram of the EMT process of liquid aluminum alloys during casting. The liquid aluminum alloy in the holding furnace flows into the pump ditch of the EMP by gravity, and the induced current is formed in the pump ditch by the excitation of the travelling magnetic field that is generated by the EMP. The interaction of the magnetic field and the induced current generates the electromagnetic force *FMAG*, which transports the liquid aluminum alloy along the lift and outlet tubes to the molds of low pressure and gravity casting or the injection sleeves of high pressure and squeeze casting. As described in Section 1, plane induction EMP optimized by us recently (Dong et al., 2013, 2014) is adopted during the EMT process in this work, which consists of the magnet yoke, the iron core, the coil and the rectangular pump ditch. The excitation current and frequency of the coil are represented by *I* and *f*, respectively, and the excitation current of the coil is termed as current for short in the following text.

2.2. EMT experiment

According to the principle of the EMT process in Fig. 1, the experimental EMT prototype was developed to conduct the EMT experiment of liquid aluminum alloy, which was constituted of the holding furnace, the plane induction EMP, the transition tube, the lift tube, the outlet tube and the controller. The capacity of the holding furnace was 15 kg for the convenience of experiment, the plane induction EMP was reported by us earlier (Dong et al., 2013, 2014), and the detail dimensions of the pump ditch and the transport tubes were shown in Fig. 2. The mostly commonly used liquid A380 aluminum alloy in high pressure die casting was chosen for the EMT experiment, and the transport temperature of the liquid A380 alloy T_0 was controlled at 700 °C by thermocouples. EMT experiment was conducted under different transport technological conditions such as transport frequency, transport current and initial transport height. The initial transport height is the altitude difference between the surface of the liquid A380 alloy in the holding furnace and the center line of the outlet tube before EMT, which is represented by H_{10}, see Fig. 2. H_{10} was recorded by the mark left on the iron wire measuring the liquid level of A380 alloy in the holding furnace. The transport frequency, transport current and transport time were controlled by the controller, and the corresponding transport mass of the liquid A380 alloy *m* was measured by the electronic scale.

3. Numerical model

3.1. Magnetic-flow coupling model

3.1.1. Assumptions and governing equations

The following assumptions were done for the magnetic-flow coupling analysis of the EMT of the liquid A380 alloy on the experimental and engineering EMT prototypes for the simplifying of numerical calculation.

(1) The liquid A380 alloy was taken as uncompressible Newtonian fluid.
(2) The transport tubes were not deformable under the high transport temperature.
(3) Physical parameters of the liquid A380 alloy were only function of temperature.
(4) Temperature rise in the liquid A380 alloy under the EMT process was neglected.

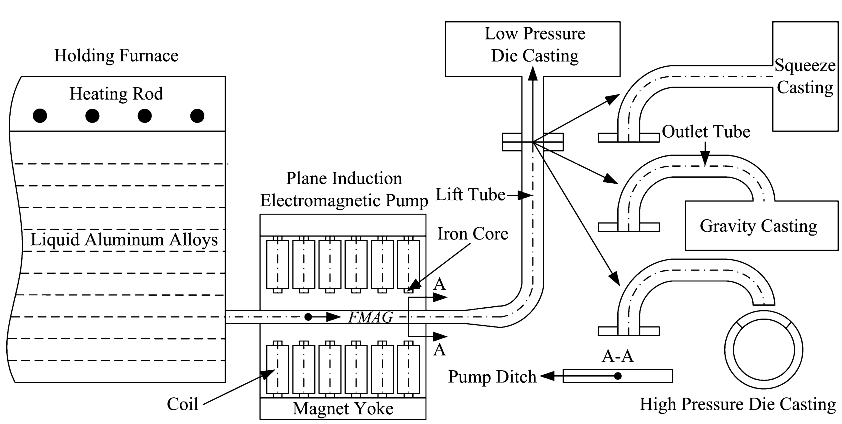

Fig. 1. Schematic diagram of the EMT process of liquid aluminum alloys during casting.