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The relevance of melt convection to grain refinement in Al–Si alloys solidified under the impact of electric currents

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Abstract

This paper considers the directional solidification of Al–7 wt.% Si alloys under the influence of strong electric currents for the configuration of two parallel electrodes immersed from the free surface into the solidifying alloy. Solidification experiments were performed under the influence of both direct currents (DC) and rectangular electric current pulses (ECP). The interaction between the applied current and its own induced magnetic field causes a Lorentz force, which produces an electro-vortex flow covering the entire melt area. Numerical simulations of the magnetohydrodynamic problem were conducted to calculate the Lorentz force, Joule heating and induced melt flow. The numerical predictions were confirmed by isothermal flow measurements in eutectic Ga–20 wt.% In–12 wt.% Sn. The application of the electric current during solidification leads to the formation of refined equiaxed grain structures. There are no remarkable differences with respect to the influence of DC or ECP treatment on the mean grain size and the area of equiaxed zone in the solidified samples, provided the effective values of the current strength are identical. The results demonstrate that the grain refining effect observed in these experiments can be ascribed solely to the forced melt flow driven by the Lorentz force.

Keywords: Al–Si alloys; Solidification; Melt convection; Grain refinement

1. Introduction

Grain refinement in metal alloys is of high commercial importance, because an isotropic finer-grained structure guarantees enhanced mechanical properties in cast alloys. Various methods have been suggested to refine the solidifying structure; in particular, the addition of particulate grain refiner is standard practice in the industry. However, the inoculation of the melt by grain-refining particles may produce undesired particle agglomerates, local defects or impurities. Floating or sedimentation may cause an imbalanced distribution of inoculants, leading to an inhomogeneous microstructure. Ultrasonic melt treatment or forcing a melt flow by electromagnetic stirring have been shown as other successful ways to achieve fine microstructures in non-refined alloys [1,2]. Furthermore, diverse experimental studies propose another alternative technique to influence the microstructure formation and to achieve finer grain sizes, where high electric currents are ducted through solidifying alloys [3–14]. Vashchenko et al. [3] were the first to report the application of electric currents in cast iron during the process of solidification. They concluded that the electric current could suppress the occurrence of impurities and increase the mobility of carbon in cast iron. Misra [4] observed distinct modifications of the microstructure of Ni–Mg cast iron under the influence of an electrical potential. Nakada et al. [5] used high current pulses by discharging a capacitor bank for solidification experiments in a Sn–15 wt.% Pb alloy. A transition from columnar to globular grains was found, accompanied by a remarkable reduction in grain size. This effect was ascribed to strong

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local shear forces generated by the current pulses. High capacitor bank voltages, a short time lag from onset of solidification to pulse application and low cooling rates were identified as appropriate conditions for grain refinement. Extremely high capacitor voltages are needed to modify the grain structure in materials at higher solid fraction. The impact of pulsed electric currents has been further investigated by a number of recent studies. Zhou et al. [6] produced ultrafine-grained microstructures in low carbon steel by the electropulsing technique. Moreover, solidification experiments with electric current pulses (ECP) were conducted in pure aluminium [7–10] or Al–Si alloys [11]. Barnak et al. [12] found a reduction in the grain size in near-eutectic Pb–Sn alloys if current densities of 1000–1500 A cm^{-2} at frequencies between 1.5 and 5 pulses per second are applied. Gao et al. [13] reported an enhancement of tensile strength and elongation of ZA27 alloys as a result of a treatment with strong ECP. Jiang et al. [14] investigated the effect of electric pulses on the dissolution of the β-$Mg_{17}Al_{12}$ phase in Mg–9 wt.% Al–1 wt.% Zn alloys.

In spite of the increasing interest in applying electric currents during solidification, knowledge about the mechanisms underlying the decrease in grain size remains fragmentary, and respective explanations suggested by the previously published studies appear to be inconsistent and controversial. Various effects are under discussion, such as the fragmentation of dendrites induced by Joule heating, the reduction in the nucleation activity energy or the break out and transport of little grains from the boundary by the periodic Lorentz force. In particular, Liao et al. [7] consider the generation of a large number of crystal nuclei to be the main reason for grain refinement. They conducted solidification experiments in Al under the influence of ECP, where the current was supplied through facing electrodes located at the bottom and the top of the sample. The authors assume that magnetic pressure pulses induced by the pulsed current separate a large number nuclei or dendrite fragments from the wall and the mushy zone, respectively. The multiplication of crystal nuclei forms a grain rain in the solidifying melt and causes a significant grain refinement. This mechanism is supposed to be amplified by applying high frequencies, because the electromagnetic field lines become concentrated near the walls and the free surface as a result of the skin effect. From observations of significant perturbations at the liquid metal surface in similar experiments with parallel electrodes installed through the free surface, Li et al. [8] concluded that the periodic Lorentz force may create shock waves within the liquid. Accordingly, they found a very high efficiency of grain refinement for that configuration. An essential effect of electric pulses on the nucleation rate is also suggested by Barnak et al. [12]. The authors speculate about a reduction in the free energy difference between the solid and liquid state and an increase in the liquid–solid interfacial energy. The solidification of dendritic structures in binary Sn–Bi or Sn–Pb alloys under the influence of electric direct currents (DC) was visualized by the synchrotron radiation imaging technique [15,16]. In the case of an applied current, the authors observed the suppression of dendrite branching and a modification of the dendrite tips. With increasing current density, a change in the dendrite morphology from columnar to equiaxed growth (CET) occurs. Obviously, the current induces a melt flow, which affects the solute profile adjacent to the solidification front. Nikrityuk et al. [17] conducted a numerical study concerning the impact of a direct electric current on fluid flow, heat and mass transfer occurring during unidirectional solidification of a Sn–15 wt.% Pb alloy. The authors describe the formation of an electro-vortex flow, which produces a positive macrosegregation at the axis of the sample. For the setup of two planar electrodes at the bottom and top of a cylindrical cavity, an expression for the Lorentz force is given, and a condition is derived defining the maximum admissible potential drop that can be applied between the electrodes before the Joule heating effect starts to play a non-negligible role.

In summary, it can be said that the previous studies taken together do not provide a consistent picture of the grain refinement process under the influence of applied strong electric currents with respect to the variety of experimental parameters: DC and ECP at different magnitudes and frequency ranges, various electrode arrangements and cooling conditions. Moreover, critical experimental boundary conditions, such as the temperature and active area of the electrodes or the magnetic field induced by the current flowing through the feed lines between electrodes and power supply, are not sufficiently reported. To better understand the impact of applied electric currents, a detailed and systematic consideration of both the electromagnetic fields and the resulting Lorentz force in the sample is required.

In general, an axially aligned electric current through an incompressible, viscous and electrically conducting liquid produces an azimuthal magnetic field. The simplest configuration of a homogeneous current distribution through a cylindrical column becomes unstable when the applied current for a given fluid and geometry exceeds a critical value. Recently, this phenomenon, known as Tayler instability [18] was experimentally observed and numerically analysed [19,20]. The experimental assembly of two pencil electrodes such as considered here implies a non-homogeneous distribution of the electric current. Such a configuration shows a significant rotational component of the Lorentz force and does not feature a threshold value of applied current that has to be exceeded before a flow sets in. Convection starts early, as a weak electric current is flowing through the liquid metal.

This paper presents systematic experimental investigations of the melt flow resulting from the interaction between the strong electric current and the self-induced magnetic field and its impact on the macrostructure of Al–7 wt.% Si alloys solidified directionally in a cylindrical container from the bottom. An arrangement of a pair of