

Effect of Low-Frequency Electromagnetic Stirring on Rare Earth Distribution in Semi-Solid Aluminum Alloys (Postprint)

Authors: Liu Zheng, Liu Xiaomei, Zhu Tao, Shen Qingchun

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Abstract

The magnetic flux density in the electromagnetic crystallizer and its variation with current frequency were simulated using Maxwell 2D software, and the distribution of rare earth elements in the A356-Y alloy melt and their influence on the solidification structure under low-frequency electromagnetic stirring were investigated. The results indicate that within the low-frequency range below the power frequency, a current frequency yielding strong magnetic flux density was identified through numerical simulation. At this current frequency, semi-solid A356-Y alloy slurry was prepared via electromagnetic stirring, wherein the equivalent circle diameter and shape factor of the primary phase reached below 65 mm and above 0.80, respectively, satisfying the requirements for semi-solid rheofforming. Driven by the electromagnetic field, the distribution of rare earth Y exhibited a tendency for edge enrichment along the ingot radius, which was influenced by the current frequency. Within the investigated range, rare earth Y tended to become more enriched at the ingot edge with increasing current frequency.

Full Text

Effects of Electromagnetic Stirring with Low Current Frequency on RE Distribution in Semi-Solid Aluminum Alloy

LIU Zheng¹), LIU Xiaomei¹), ZHU Tao¹), CHEN Qingchun²)

¹) School of Mechanical and Electrical Engineering, Jiangxi University of Science and Technology, Ganzhou 341000

²) School of Material Science and Engineering, Jiangxi University of Science and Technology, Ganzhou 341000

Correspondent: LIU Zheng, professor, Tel: (0797)8312428, E-mail: liukk66@163.com

Abstract

When solidification of aluminum alloy melt is disturbed by an electromagnetic field, its microstructure and properties are influenced by solute diffusion, distribution, and refinement in the melt. Therefore, it is necessary to study the metallurgical behavior of rare earth (RE) elements under electromagnetic stirring and to investigate their diffusion and distribution under forced convection. The magnetic induction intensity in the electromagnetic crystallizer and its variation with current frequency were simulated using Maxwell 2D software. The distribution of RE in A356-Y alloy melt and its effect on microstructure were studied under low-frequency electromagnetic stirring.

The results indicated that a current frequency producing stronger magnetic induction could be obtained within the low-frequency range below the working frequency. Using this frequency, semi-solid A356-Y alloy slurry was prepared by electromagnetic stirring, where the equal-area circle diameter and shape factor of the primary phase reached below 65 μm and above 0.80, respectively, satisfying the requirements for semi-solid rheofforming. Driven by the electromagnetic field, Yttrium (Y) distribution tended to enrich toward the edge of the ingot along the radius direction, though this was affected by current frequency. Within the studied range, as current frequency increased, Y enrichment shifted toward the ingot edge.

Keywords aluminum alloy, electromagnetic stirring, current frequency, semi-solid, rare earth

Introduction

Semi-solid processing of aluminum alloys represents a high-performance precision forming technology characterized by high efficiency and energy savings. The solidification process is controlled through external fields, grain refiners, and adjustment of solidification parameters to ensure the required service and processing properties. Among various external fields currently employed, electromagnetic field treatment is the most widely used and successful technique, offering environmental friendliness, operational simplicity, simple equipment and process control, energy savings, and applicability to both non-ferrous and ferrous metals without contamination.

While semi-solid processing can refine primary α -phase, eutectic structures, and secondary phases to some extent, additional refinement treatments are often implemented to achieve superior properties. Industrial refiners are diverse, but rare earth elements have consistently attracted attention due to their unique properties and excellent refining performance. However, most RE refining effects on aluminum alloys have been obtained under conventional production conditions or near-equilibrium states. When the solidification process is disturbed by external fields such as electromagnetic fields, diffusion, distribution, and reactions of solute elements and refiners during melt flow cause solute segregation, phase

region changes, and eutectic temperature shifts, all significantly affecting final solidification structures and properties. Current research primarily focuses on RE effects under gravity casting or natural convection, with minimal investigation under forced convection induced by external fields. Therefore, studying the metallurgical behavior of RE under electromagnetic stirring is essential to leverage their advantages in purifying, strengthening, and refining aluminum alloys.

Electromagnetic stirring can effectively improve primary phase morphology and size in semi-solid alloys. Studies have shown that when semi-solid alloys are in the solid-liquid region, short-term low-intensity stirring can produce slurry with globular primary phases. Building on previous research, this study employs frequency modulation technology to set current frequency below the working frequency to reduce energy consumption while ensuring slurry quality. Numerical calculations were performed on a self-designed electromagnetic crystallizer to clarify magnetic field distribution and investigate the effects of low-frequency electromagnetic stirring on solidification structure, particularly radial inhomogeneity and RE element distribution.

1. Magnetic Field Simulation of Electromagnetic Crystallizer

Maxwell 2D software was used to calculate and simulate the magnetic field of a self-designed electromagnetic crystallizer to obtain magnetic field distribution maps and induction intensity values, providing intuitive understanding of field distribution. This simulation focused solely on the magnetic field generator of the crystallizer.

1.1 Finite Element Model Establishment The electromagnetic crystallizer magnetic field is generated by the stator of a YZ112M-6 asynchronous motor. Therefore, the finite element model essentially represents this motor stator with the following parameters: rated power 1.5 kW, rated voltage 380 V, rated frequency 50 Hz, 6 poles, 36 stator slots, speed 920 r/min, and Y-connection.

During modeling, since the air gap is small and uniform, only radial magnetic induction intensity was considered. Magnetic induction intensity was assumed constant along the crystallizer axis with end effects neglected, making the electromagnetic field identical in any cross-section along the axis. The Maxwell 2D electromagnetic analysis module was employed for calculation, meeting simulation requirements while offering faster computation than Maxwell 3D. The simulation analyzed electromagnetic force lines and magnetic induction intensity at different input frequencies.

The geometric model of the magnetic field generator was established in the RMxpert module and then imported into Maxwell 2D for finite element analysis [Figure 1: see original paper]. Meshing was performed using maximum

edge length settings: 4.475 mm for windings and 7.1 mm for the iron core. After model generation, the project tree automatically included model, boundary conditions, excitation sources, mesh division, and simulation settings.

1.2 Simulation Results Coupling RMxpert with Maxwell 2D involved importing the established model into Ansoft Maxwell 2D for subsequent finite element analysis, automatically completing geometric drawing. Simulation parameters for electromagnetic stirring were input in RMxpert's solution settings. To save computation time, current frequencies of only 10, 20, 30, and 40 Hz were considered.

Magnetic force line and magnetic induction intensity distributions were obtained from the project tree [Figure 2: see original paper] and [Figure 3: see original paper]. In the force line diagrams, red lines represent positive peak values and blue lines negative peaks, with larger values near generator slots gradually decreasing outward. Different frequencies yielded different maximum and minimum values: at 10, 20, 30, and 40 Hz, the maximum and minimum force line values were 1.1272×10^{-3} and 5.6208×10^{-5} Wb/m; 1.7976×10^{-3} and 8.9091×10^{-5} Wb/m; 2.3428×10^{-3} and 1.181×10^{-4} Wb/m; and 1.8226×10^{-3} and 9.05×10^{-5} Wb/m, respectively. At lower frequencies, magnetic flux leakage within slots was more pronounced, decreasing as frequency increased.

Magnetic induction intensity was maximum at slot tops and minimum (near zero) at the crystallizer center. Maximum induction intensity values at 10, 20, 30, and 40 Hz were 0.72543, 1.0720, 1.5033, and 1.1478 T, respectively. Induction intensity was highest near the crystallizer edge, gradually weakening toward the center, first increasing then decreasing with current frequency. Within this study's range, maximum induction occurred at 30 Hz.

Simulation results show that magnetic force lines concentrate around the generator windings where magnetic induction is strongest, weakening elsewhere and becoming nearly zero at the center. This phenomenon relates to the skin effect, where induced currents impede magnetic field propagation, causing gradual intensity reduction from edge to center.

2. Experimental Procedure

The A356 alloy used had the following main chemical composition (mass fraction, %): Mg 0.33, Si 7.14, Fe 0.135, Al balance, as analyzed by Magix (PW2424) X-ray fluorescence spectroscopy.

Semi-solid alloy slurry was prepared using low superheat pouring and weak electromagnetic stirring. Melting was conducted in an SG2-3-10 crucible resistance furnace. A graphite crucible was preheated to 200°C, then A356 alloy was added. After melting at 700°C, slag removal and degassing were performed, followed by heating to 720-740°C. Rare earth Y was added as Al-Y master alloy at 0.5%

(mass fraction). Once fully melted, the melt was cooled to 630°C for low superheat pouring into a preheated (450°C) Fe mold of 50 mm × 100 mm with 3.5 mm wall thickness. Since stirring power is proportional to current frequency, the melt was stirred for 15 s at different frequencies (10, 20, 30, and 40 Hz), then rapidly transferred to a holding furnace for isothermal treatment (590°C for 5 min) before water quenching.

Cylindrical slices (10 mm thick) were cut from the same height of each sample, from which fan-shaped blocks through the center were taken for metallographic examination. Samples were ground and polished, then etched with 0.5% HF (volume fraction) solution for microstructure observation using an Axios-kop2 optical microscope (OM). Grain size was measured using Image-Pro-Plus software, calculating average equal-area circle diameter ($D = 2(A/\pi)^{1/2}$) and shape factor ($F = 4\pi A/P^2$), where A is grain area and P is grain perimeter. F approaching 1 indicates higher sphericity.

An XL30W/TMP scanning electron microscope (SEM) was used to study RE distribution. Backscattered electron images were taken at 200× magnification every 5 mm along the radial direction from the sample center, and the area percentage of RE compounds (bright regions) was statistically analyzed.

For comparison, control samples were prepared using identical low superheat pouring and isothermal treatment parameters without electromagnetic stirring.

3.1 Solidification Structure of Semi-Solid A356-Y Alloy

Figure 4 [Figure 4: see original paper] shows the solidification structures of semi-solid A356-Y alloy before and after electromagnetic stirring. Before stirring (Fig. 4a), some primary α -phase appeared granular but with non-uniform size, accompanied by numerous coarse dendritic primary α -phase. The grain D was 99.58 μm with F only 0.65. After electromagnetic stirring, the structure refined and spheroidized, with almost no dendritic primary α -phase remaining. 极少数初生 α 相呈蔷薇状, with most being globular or granular. As current frequency increased, primary α -phase showed a refining trend (only the optimal frequency microstructure is shown due to space limitations). Figures 4b and c show primary α -phase morphologies at the edge and core regions after stirring at 30 Hz for 15 s. In both regions, stirred samples showed superior morphology and size compared to unstirred samples. The results indicate that higher magnetic flux density and induction intensity at the ingot edge created stronger stirring, facilitating easier refinement and spheroidization of primary α -phase compared to the center region, with this effect becoming more pronounced as frequency increased. However, at 40 Hz, excessive stirring intensity was detrimental to grain refinement and spheroidization. This study employed frequency conversion technology where stirring power is proportional to current frequency. Excessive frequency increased electromagnetic field rotation speed, enlarging the slip ratio between melt and rotating field, which increased induced electro-

motive force and eddy currents. This enhanced collision and friction probability between grains, promoting grain coalescence and growth. Moreover, stirring effectiveness depends on both intensity (proportional to frequency square root and current) and penetration depth (inversely proportional to frequency square root). Therefore, higher frequency does not necessarily yield better results. Within this study's range, 30 Hz provided optimal stirring.

Figure 5 [Figure 5: see original paper] shows the variation of D and F with current frequency. Combined with microstructural observations, frequency affected primary α -phase size and shape factor differently in various ingot regions. Edge region grains were consistently finer and more spherical than core region grains, with the difference between regions increasing as frequency increased.

As frequency increased from 10 to 40 Hz, electromagnetic induction and stirring power increased. According to semi-solid electromagnetic stirring principles and numerical simulation results, maximum magnetic induction occurs near the crystallizer wall, decaying linearly to zero at the center. Stirring intensity was greater at the melt edge than at the center. Combined with the mold wall's chilling effect, the edge region experienced stronger electromagnetic forces and higher cooling rates, resulting in smaller primary α -phase than the center region, with the difference increasing with frequency. Additionally, higher frequency increased stirring power, further reducing edge region grain size. However, the center region showed a grain size decrease followed by increase due to the relationship between frequency and skin depth. At 30 and 40 Hz, the average grain size difference in the edge region was small, possibly because increased frequency caused faster attenuation, with some energy converting to Joule heat that altered cooling conditions and reduced refinement effectiveness.

During stirring, primary α -phase became passivated through mutual friction and melt scouring, rounding their edges. The post-stirring holding process promoted uniform temperature and solute distribution, reducing or eliminating constitutional undercooling and causing primary α -phase to lose preferred growth direction, resulting in isotropic growth into spherical grains. Figure 5 shows that as frequency increased, stirring intensity and internal friction in the edge region increased, improving the average shape factor, which was always larger in the edge region than in the center. At 40 Hz, the appearance of elongated and irregular dendritic grains reduced the average shape factor.

Regarding melt motion in the electromagnetic crystallizer, since primary α -phase conductivity is 2.22 times that of the melt, primary α -phase experiences greater electromagnetic force. Microscopically, the uneven force field around primary α -phase, combined with electromagnetic and centrifugal forces, drives radial outward migration of primary α -phase. Assuming spherical primary α -phase forms when melt temperature reaches the liquidus, and that spherical particle migration velocity is proportional to the square of particle diameter, larger primary α -phase migrates faster toward the mold wall. However, the cold mold wall immediately forms a chill layer upon pouring, capturing migrating primary α -phase. The captured grains at the liquid/solid interface, being

at lower temperature, are engulfed before they can coarsen, forming fine grains. Simultaneously, under electromagnetic stirring, melt temperature rapidly drops below the liquidus, precipitating primary α -phase particles that migrate outward under electromagnetic and centrifugal forces. The solid/liquid interface from the solidifying shell at the mold wall advances inward, meeting and merging with outward-migrating primary α -phase to form larger grains, while some dendrites fragment and re-enter the melt. Remaining liquid accumulates at the mold center where, without electromagnetic forces, it forms coarse grains as temperature further decreases.

3.2 Effect of Electromagnetic Stirring on RE Distribution

Figure 6 [Figure 6: see original paper] shows SEM-BE images of A356-Y alloy solidification structures stirred at different frequencies. Bright phases correspond to RE-rich compounds, primarily distributed at primary phase grain boundaries and interfaces, indicating local RE element enrichment or depletion zones.

Figure 7 [Figure 7: see original paper] illustrates RE distribution along the ingot radial direction under different stirring frequencies. At 10 and 20 Hz, RE enrichment peaks appeared 15 mm from the ingot center, with lower RE content in the core and adjacent regions but higher content near the surface. At 30 and 40 Hz, the enrichment peak shifted outward to 20 mm from the center, with lower RE content in both core and surface regions but higher content in intermediate regions. These phenomena correlate with magnetic induction distribution changes caused by different frequencies and the driving force on solid phases in the melt.

4.1 Effect of Current Frequency on Radial Inhomogeneity

Simulation results [16,17] indicate that current frequency directly determines magnetic field, flow field, and temperature field distributions. Related studies [18-20] have also found that electromagnetic stirring of semi-solid aluminum alloy slurry causes radial structural inhomogeneity. This study shows that at the same frequency, primary phase size decreases while shape factor increases along the radial direction, with radial differences becoming more pronounced as frequency increases.

As frequency increased from 10 to 40 Hz, electromagnetic induction and stirring power increased. According to semi-solid electromagnetic stirring principles [21] and numerical simulation results [22], maximum magnetic induction occurs near the crystallizer wall, decaying linearly to zero at the center [23]. Stirring intensity was greater at the melt edge than at the center. Combined with the mold wall's chilling effect, the edge region experienced stronger electromagnetic forces and higher cooling rates, resulting in smaller primary α -phase than the center

region, with the difference increasing with frequency. Additionally, higher frequency increased stirring power, further reducing edge region grain size. However, the center region showed a grain size decrease followed by increase due to the relationship between frequency and skin depth. At 30 and 40 Hz, the average grain size difference in the edge region was small, possibly because increased frequency caused faster attenuation, with some energy converting to Joule heat that altered cooling conditions and reduced refinement effectiveness.

During stirring, primary α -phase became passivated through mutual friction and melt scouring, rounding their edges. The post-stirring holding process promoted uniform temperature and solute distribution, reducing or eliminating constitutional undercooling and causing primary α -phase to lose preferred growth direction, resulting in isotropic growth into spherical grains. Figure 5 shows that as frequency increased, stirring intensity and internal friction in the edge region increased, improving the average shape factor, which was always larger in the edge region than in the center. At 40 Hz, the appearance of elongated and irregular dendritic grains reduced the average shape factor.

Regarding melt motion in the electromagnetic crystallizer, since primary α -phase conductivity is 2.22 times that of the melt [24], primary α -phase experiences greater electromagnetic force. Microscopically, the uneven force field around primary α -phase, combined with electromagnetic and centrifugal forces, drives radial outward migration of primary α -phase [25-27]. Assuming spherical primary α -phase forms when melt temperature reaches the liquidus, and that spherical particle migration velocity is proportional to the square of particle diameter [28], larger primary α -phase migrates faster toward the mold wall. However, the cold mold wall immediately forms a chill layer upon pouring, capturing migrating primary α -phase. The captured grains at the liquid/solid interface, being at lower temperature, are engulfed before they can coarsen, forming fine grains. Simultaneously, under electromagnetic stirring, melt temperature rapidly drops below the liquidus, precipitating primary α -phase particles that migrate outward under electromagnetic and centrifugal forces. The solid/liquid interface from the solidifying shell at the mold wall advances inward, meeting and merging with outward-migrating primary α -phase to form larger grains, while some dendrites fragment and re-enter the melt. Remaining liquid accumulates at the mold center where, without electromagnetic forces, it forms coarse grains as temperature further decreases.

4.2 Effect of Electromagnetic Stirring on RE Distribution in Ingot

When liquid A356-Y alloy was poured at 630°C, the Al-Y binary eutectic reaction occurred, precipitating α -Al with formation of rare earth aluminum compound Al_3Y . The physical parameters (electrical conductivity, magnetic permeability) of these two eutectic products differ significantly from the melt [29]. Therefore, under electromagnetic fields, Al_3Y experiences different electromag-

netic forces than the aluminum melt and primary α -phase, creating an unbalanced force field around Al_3Y . Additionally, Al_3Y 's theoretical density of 3.609 g/cm^3 differs substantially from melt and primary α -phase densities, causing it to accumulate near the ingot surface under centrifugal forces from electromagnetic disturbance. Under combined electromagnetic and centrifugal forces, Al_3Y diffuses radially outward; its higher density enables faster diffusion [30]. However, this diffusion is hindered by viscous forces from the semi-solid melt and by the solid/liquid interface of the solidifying shell advancing from the mold wall. The cold mold wall immediately forms a chill layer upon pouring, and as temperature continues decreasing, the solid/liquid interface advances inward, meeting and engulfing outward-migrating Al_3Y , or even pushing it toward the center [19].

Under electromagnetic and centrifugal forces, Al_3Y cannot penetrate the solidifying shell and can only accumulate at the solidification front. Larger Al_3Y particles or those experiencing greater forces diffuse faster toward the mold wall. Consequently, Figure 7 shows that RE enrichment peaks appeared in the ingot periphery (15–20 mm from center) under all frequencies, with lower content in the central region. At 10 and 20 Hz, smaller electromagnetic and centrifugal forces produced lower stirring intensity and weaker driving force for Al_3Y diffusion, resulting in enrichment peaks at 15 mm from the center. At 30 and 40 Hz, increased stirring power enhanced electromagnetic and centrifugal forces, providing greater driving force for Al_3Y diffusion and migration, ultimately enriching it at 20 mm from the center. Figure 7 also shows that RE enrichment in one region caused depletion in adjacent areas, consistent with the fixed RE addition amount. Lower RE content at 20–25 mm from the center relates to different cooling conditions—despite mold preheating to 450°C , primary cooling intensity remained relatively high, allowing the initial solidified shell to form quickly and limiting stirring effects on RE distribution. This also explains why RE segregation did not occur at the outermost ingot periphery.

Conclusions

1. Magnetic field simulation of the self-designed electromagnetic crystallizer was performed using Ansoft Maxwell 2D software, obtaining magnetic force line and induction intensity distributions. These results facilitate analysis of melt flow, microstructure evolution, and selection of appropriate electromagnetic solidification parameters.
2. Electromagnetic stirring effectively refined the primary α -phase in semi-solid A356-Y alloy. Optimal electromagnetic solidification parameters were determined: stirring at 30 Hz for 15 s followed by isothermal holding at 590°C for 5 min produced fine, spherical primary α -phase with average equal-area circle diameter of $64.95 \text{ }\mu\text{m}$ and shape factor of 0.80 in the core region, and $58.97 \text{ }\mu\text{m}$ diameter with 0.83 shape factor at the edge.

3. Current frequency significantly affects solidification structure inhomogeneity by influencing the driving force for primary α -phase diffusion and migration in the melt. Appropriate frequency selection is crucial. Using 30 Hz produced relatively uniform structure with fine, spherical grains throughout, meeting semi-solid forming requirements.
4. Current frequency significantly influences RE distribution along the ingot radius. Under electromagnetic stirring driving forces, RE tends to accumulate in the ingot periphery, with enrichment peaks shifting toward the edge as frequency increases.

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