Effect of electromagnetic stirring current on microstructure and corrosion resistance of Al–Sn Alloy

Shuhao Li, Hongbin Guo, Yongliang Li, Zirou Wen and Zhiyun Zhu

Faculty of Materials Metallurgy and Chemistry, Jiangxi University of Science and Technology, Ganzhou 341000, People’s Republic of China
E-mail: zhiyunzhu@126.com

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Abstract
Al–Sn bearing alloys were prepared with different electromagnetic stirring (EMS) currents. Electrochemical and immersion corrosion experiments were carried out on the samples. Optical microscope, SEM, EDS, and XPS were used to characterize the samples to study the effect of stirring current on the microstructure and corrosion properties of the alloy. The results show that the structure of the sample without EMS is all dendrites. With the increase of stirring current, the number of primary phase agglomerates is less and the grain size decreases. When the stirring parameter is 60A, 20Hz, the grain size is the most round and small, and the stirring effect is the best. In the later stage of immersion, the corrosion product film formed on the surface is more dense and uniform, which can effectively block the erosion of ions in the solution. The equivalent circuit fitting calculation shows that the $R_{\text{cotal}}$ value is the largest, which is $1.79 \times 10^6 \, \Omega \cdot \text{cm}^2$, and the corrosion resistance is the best.

1. Introduction
With the advancement of industrialization, the demand for bearing alloys has continued to increase, and the performance requirements are also improving. At the same time, it is necessary to meet the concepts of production cost reduction and green environmental protection [1]. Al-Sn-based bearing alloys can be divided into low-tin aluminum alloys (5%–10%), medium-tin aluminum alloys (10%–15%) and high-tin aluminum alloys (15%–40%) according to the Sn content. With the increase of tin content, the hardness and strength of Al-Sn alloys decrease, and the load-carrying capacity also decreases. In contrast, low-tin aluminum-based bearing alloys are cost-effective, have a wide range of applications, and have certain fatigue resistance and good seizure resistance, making them very attractive in bearing materials [2–6]. Al and Sn are immiscible with each other, and a continuous tin-rich network structure will be formed around the Al phase during the solidification process, resulting in the weakening of the strength of the Al-matrix interface. In addition, the density difference between Al and Sn is relatively large, and it is easy to produce specific gravity segregation, resulting in uneven distribution of Sn, which leads to rapid wear of the bearing in the place poor of Sn [7, 8]. Therefore, the research and development of high-performance Al-Sn bearing alloys have become a hot spot for sliding bearing researchers. It is necessary to make efforts in the production process, optimize the alloy composition, improve the quality and performance, and reduce the production cost to develop a more cost-effective Al-Sn alloy to meet the needs of the increasingly developing modern industry [9].

EMS technology uses an alternating magnetic field to interact with the metal melt, and the metal melt rotates under Lorentz force to produce a stirring effect on the melt [10]. The advantage is that the energy interaction between the alternating magnetic field and the melt is non-contact conversion, and the electromagnetic energy is directly converted into the kinetic energy of the molten metal, which is a pollution-free processing method. The melt moves as a whole under the action of the magnetic field, and the stirring range is large [11]. The parameters of EMS are easy to control, and the flow state of the melt can be controlled by changing the electromagnetic parameters, which is convenient for process optimization [12]. Li et al [13] used EMS to prepare an Al-Si alloy with a uniform and fine structure. The analysis showed that after applying EMS, the primary phase and the remaining liquid phase had uncoupled motions, which promoted crystal proliferation and refined the
solidification structure, revealing the potential of EMS technology. Zhu et al [14] compared the microstructure and corrosion resistance of 7A04 aluminum alloys prepared by as-cast and EMS, and the results showed that uniform and circular primary α-Al grains could be effectively formed under the action of EMS, and element segregation was significantly reduced, thus effectively improving the corrosion resistance of 7A04 aluminum alloy.

The microstructure of metals and alloys is one of the important parameters determining their corrosion behavior, among which factors such as chemical composition, morphology, size, and phase distribution in the alloy microstructure play a key role in corrosion resistance [15]. Osorio et al [16] proved that the refinement of the microstructure can reduce the corrosion rate of Al-Sn alloys in 3.5% NaCl solution. Barros et al [17] used electrochemical impedance spectroscopy and potentiodynamic polarization to conduct corrosion tests and equivalent circuit analysis of Al-Sn alloys with different microstructures and expounded the role of microstructure characteristics in the corrosion behavior of Al-Sn alloys.

In this paper, Al-Sn bearing alloys were prepared by different EMS currents, and electrochemical tests were carried out on the samples. Various characterization methods were used to observe and analyze the microstructure and corrosion resistance of the alloy, and to explore the effect of EMS current on the properties of the alloy. The main objective is to improve the microstructure and corrosion performance of Al-Sn alloy by EMS technology.

### 2. Material and methods

The specific process of preparing Al-Sn alloy by EMS method is as follows: put the prepared raw materials in a resistance furnace, heat to a predetermined melting temperature of 680 °C, ventilate and remove slag and keep for 8 min to ensure that the raw materials are completely melted and the temperature is uniform. At the same time, the EMS holding furnace was opened to 680 °C. The molten alloy liquid is quickly rotated into the EMS device (EM100-4T430B, Wire gauge: 2.5 mm² × 6, number of turns: 6 discs × 12 cassettes, rated current: 150 A, rated voltage: 380 V, power factor: 0.3; Conductive graphite crucible, inner diameter: 85 mm, outer diameter: 105 mm), measure the temperature of the melt with a thermometer, when the temperature drops to 630 °C, turn on the EMS, the stirring time is 1 min, after the stirring is stopped, cast to the iron Cool to room temperature in the mold. The EMS frequency was fixed at 20 Hz, and the stirring current was set at 40 A, 50 A, 60 A, and 70 A for stirring casting [18, 19]. The samples without stirring were cast after heat preservation. The ingot composition was detected by x-ray fluorescence spectrometer (PANalytical Axios), and the detection results are shown in table 1.

A sample of 10 mm × 10 mm was taken at the same position of the alloy, and the metallographic sample was obtained by inlaying, sandpaper grinding, polishing, and corrosion for microstructure observation. The electrochemical test sample needs to be smoothed with sandpaper, then soldered with copper wire on one side, put into the mold and encapsulated with epoxy resin. After the resin is cured, only the working surface of 100 mm² is exposed. Grind the sample to 2000# with sandpaper, wash and blow dry after polishing with polishing paste. The prepared electrodes were tested for electrochemical corrosion using a Princeton electrochemical workstation (PARSTAT 4000A). The test was a three-electrode system, with a saturated calomel electrode as the reference electrode, a platinum sheet as the counter electrode, and the immersion medium was 3.5% NaCl solution. Electrochemical impedance spectroscopy (EIS) tests were performed at immersion times of 0.5 h, 48 h, 168 h, 336 h, 720 h, and the frequency range of EIS was 100000 Hz to 0.01 Hz. The EIS data were fitted by ZsimpWin software, and the experimental procedures were all carried out at room temperature (25 °C). Three groups of parallel samples were statically immersed in 3.5% NaCl solution for observation and analysis of surface corrosion products. The samples were taken out after immersing for 168 h, 336 h and 720 h respectively. The morphology of the corrosion products on the surface of the samples was observed by a field emission scanning electron microscope (Carl Zeiss, SIGMA). X-ray photoelectron spectroscopy was used to determine the elements and valences of the corrosion products after immersing for 720 h.

| EMS Current | Sn | Cu | Ni | Al  |
|------------|----|----|----|-----|
| Non-EMS    | 6.23 | 1.34 | 1.41 | Bal. |
| 40A 20Hz   | 6.25 | 1.25 | 1.34 | Bal. |
| 50A 20Hz   | 6.33 | 1.31 | 1.43 | Bal. |
| 60A 20Hz   | 6.26 | 1.41 | 1.23 | Bal. |
| 70A 20Hz   | 6.42 | 1.35 | 1.38 | Bal. |
3. Results and discussion

3.1. The effect of EMS current on the microstructure

Figure 1 shows the microstructure of Al-Sn alloy prepared by different EMS currents. It can be seen from the figure that the microstructure of Al-Sn alloy without EMS is dendrite. When the stirring current is 40A, although there are signs of separation inside the particles, most of them are still connected and did not become isolated and complete particles. The grain shape is not round either, it is short rod-shaped or rose-shaped. When the stirring current is 50A, a small part of the crystal grains are isolated, but some of the crystal grains are still agglomerated together, and there are few primary phases freed, and some are in a rose-shape. When the stirring current is increased to 60A and 70A, the dendrites are completely broken, most of the crystal grains are independent, and the shape of the primary phase changes significantly, becoming small and round, and the whole tends to be spherical or ellipsoidal, and the stirring effect is extremely significant. There is no obvious difference in the microscopic grain structure when the stirring current is 60A and 70A, indicating that the EMS intensity when the stirring current is 60A reaches the peak of the crushing effect on the dendrites during the solidification process, and further increases the stirring current cannot enhance its crushing effect.

When the stirring current is small (40A, 50A), the electromagnetic force is not enough to break the dendrites, and there are more grains to agglomerate together. The electromagnetic force also increases with the increase of the stirring current, which accelerates the rotation speed and range of the Al-Sn melt. The metal melt directly

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Figure 1. Optical microstructures of samples prepared with different EMS currents. (a) Non-EMS; (b) 40A 20 Hz; (c) 50A 20 Hz; (d) 60A 20 Hz; (e) 70A 20 Hz.
contacts the wall and bottom of the crucible, and rapidly cools down to form a solidified thin shell, which enhances the crushing effect on the primary phase. When the stirring current reaches 60A, the broken dendrites are rubbed and rotated under the action of electromagnetic force, forming crystal grains with small size and regular morphology. During the experiment, the graphite crucible acts as a charged conductor to shield the magnetic field excited by the alternating current. When the stirring intensity is too high, due to the skin effect, the alternating current will be concentrated near the edge of the conductor, that is, in the rotating melt near the edge of the graphite crucible, resulting in uneven distribution of the magnetic induction intensity of the rotating magnetic field and serious attenuation of the magnetic field at the rotating center. The ‘penetration’ of the melt in the center of the graphite crucible is poor, and the stirring effect is weakened. Therefore, the continuous increase of the stirring current cannot continue to optimize the structure.

3.2. Influence of EMS current on corrosion resistance

3.2.1. Electrochemical impedance analysis

Figure 2 shows the Nyquist curves measured for different immersion times. The larger the impedance arc radius, the smaller the degree of ion exchange, and the better the corrosion resistance of the alloy. There are two impedance arcs in the Nyquist curve at the initial stage of immersion. The impedance arc in the high frequency region may be related to the formation of the surface corrosion product film. Oxygen in the solution can promote the formation of corrosion products, but the dissolution rate at the beginning of the immersion is much faster than the formation rate, and the protective effect is weak. The low-frequency impedance arc may be caused by the anodic dissolution of the alloy matrix directly in contact with the NaCl solution after the oxide film on the surface of the Al alloy is corroded and perforated, and the resulting corrosion products are accumulated in the corrosion holes. It shows that it has been severely corroded, and there is a mass transfer process, and the corrosion mechanism is controlled by the charge transfer process and the mass transfer. With the increase of immersion time, the radius of impedance arc increases, and the Warburg impedance disappears. At this time, the corrosion product film is gradually complete, the dissolution of the metal matrix is inhibited, and the surface reaction of the alloy is controlled by the charge transfer process. The Nyquist curve radius of all samples immersed for 48 h is larger, and a protective corrosion product film is formed after the reaction at 48 h. However, this product film is not stable, peeling off during the immersing process, the protective effect disappears, and the impedance arc radius began to decrease again. With the progress of immersion, the impedance arc radius of the samples with EMS gradually increased. When the stirring current was 60A and 70A, the impedance radius of the immersion for 336 h tended to increase. It indicates that a dense and complete corrosion product film is formed in the later stage of immersion, which acts as passivation on the surface of the alloy. It can physically block the corrosive anions in the corrosive medium, reduce the reaction of the matrix, weaken the material exchange effect, and effectively protect the metal matrix. Compared with the sample without EMS, the corrosion rate of the alloy is reduced and the corrosion resistance is improved.

Figure 3 shows the bode diagrams of Al-Sn alloys immersed in 3.5%NaCl solution for different times. It can be seen from the phase angle diagram that the phase angle width of the sample without EMS is always narrow during the immersion process. With the increase of stirring current, the phase angle curve with double peaks decreases. When the stirring current is 50A, 60A, and 70A, the phase angle diagram only has double peaks when immersing for 0.5 h, and the peak position is wider when immersing for 720 h. It shows that the whole immersing system is stable at this time, and the reaction reaches dynamic equilibrium. The impedance modulus value corresponding to the Bode curve of the test alloy gradually increases with the prolongation of immersion time, and the maximum value is in the low frequency region. The magnitude of the impedance modulus value is proportional to the corrosion resistance of the alloy. The larger the impedance modulus, the stronger the corrosion resistance. After applying EMS, the samples showed higher impedance modulus values at the later stage of immersion.

The fitted equivalent circuit is shown in figure 4. Figure 4(a) is used to fit the immersion 0.5h impedance, L corresponds to the pitting parameters, R, is the electrolyte resistance, the original passivation film is represented by CPE, and R, in parallel, and the corrosion product film at the initial stage of immersion is represented by CPE, and R, in parallel. The impedance of immersion for 48–720 h is fitted with the circuit shown in figure 4(b). CPE, and R, are constant phase angle elements and resistances related to the loose and porous outer corrosion product film, and CPE, and R, are constant phase Angle elements and resistances related to dense inner corrosion product film. CPE, is double layer capacitor, C is parallel with R, and connected in series with R, to represent the capacitor circuit related to the precipitation of the corrosion product. The experimental data and fitting results are represented by colored dots and black solid lines in figure 2, respectively. The electrochemical parameters of impedance fitting for immersing for 0.5 h and 48 h–720 h are shown in appendix tables A1 and A2.

According to the interaction of different components in the circuit, R(total) is used to represent the total resistance of the corrosion product film to quantify the corrosion resistance of the sample. R(total) is calculated
according to equation (1), and the result is shown in figure 5.

\[ R_{\text{total}} = R_1 + R_2 + R_3 + R_4 \]  

(1)

The \( R_{\text{total}} \) values of all samples were similar before immersing time of 168 h. With the increase of immersion time, the thickness and structure of the film layer changed, and the \( R_{\text{total}} \) value of the sample increased, and the effect was more obvious when the stirring current was 60 A and 70 A. It indicates that in the later stage of immersion, corrosion product films are formed on the samples. When the stirring current is large, corrosion products with thicker and denser thicknesses are generated on the sample surface. Therefore, the resistance arc radius of the alloy is larger and has a higher \( R_{\text{total}} \) value. The corrosion product film of the sample without EMS was peeled off during the immersing process, and the \( R_{\text{total}} \) value was still small when immersing for 720 h. At this time, the stirring parameter is 60 A, 20 Hz, the \( R_{\text{total}} \) value of the sample is the largest, which is \( 1.79 \times 10^6 \) \( \Omega \cdot \text{cm}^2 \).
Figure 3. Bode curves of samples prepared with different EMS currents immersed in different times. (a) Non-EMS; (b) 40A 20 Hz; (c) 50A 20 Hz; (d) 60A 20 Hz; (e) 70A 20 Hz.
3.2.2. Morphology of corrosion products

The corrosion resistance of the material is closely related to the protection of the corrosion product film formed during use, and the protection of the passivation film is determined by its composition, structure, thickness and adhesion to the substrate [20]. Therefore, deepening the understanding of the corrosion behavior of Al-Sn alloys. Figures 6–8 shows the surface corrosion product film morphology of samples prepared by different EMS currents immersed in 3.5% NaCl solution for 168 h, 336 h and 720 h. The samples prepared without EMS and the stirring current of 40A were immersed for 168 h and the corrosion product film was loose and flocculent, a small amount of messy and not dense enough growth on the surface of the sample. However, it can also be seen in figure 6(b) that the surface corrosion products increase significantly after applying EMS. With the increase of stirring current, the corrosion product film grows along the grain boundary and covers the surface of the sample in a ring shape. The distribution of Sn in the Al-Sn alloy is at the grain boundary, indicating that the formation of the corrosion product film is closely related to the distribution of Sn.

Figure 7 shows the morphology of corrosion products of different samples immersed in 3.5% NaCl solution for 336 h. At this stage, a continuous corrosion product film was formed on the surface of the samples by applying EMS. However, obvious cracks and holes can still be found on the surface of the corrosion product film, and these defects become the channels for the corrosion ions in the solution to contact the matrix and have further corrosion reactions with the matrix. In the sample without EMS, this phenomenon is extremely serious, and no corrosion product film is formed in the local area, resulting in the matrix being exposed to the immersion solution, severely corroded, and cracked.

Figure 8 shows the morphologies of corrosion products of different samples immersed in 3.5% NaCl solution for 720 h. (a1)–(e1) and (a2)–(e2) are the surface topography at 1000× and 5000× magnification, respectively. At this time, there is a big difference in the morphology of the corrosion product film between the sample without EMS and the sample with EMS. There are many holes in the corrosion product film on the surface of the sample without EMS, which is discontinuous and dense. In the process of immersing, the barrier to corrosion ions is not strong enough and does not play a good protective role. It can be seen from the high magnification diagram that the corrosion products are irregular in shape and angular granular, and the sizes of different particles differ greatly. After applying EMS, there are more corrosion product films composed of fine particles on the surface. Meanwhile, the surface holes are reduced, the density is increased, and the adhesion is more tightly. The increase in compactness reduces the channels through which the corrosive medium penetrates to the surface of the Al matrix, which plays a role in slowing down the corrosion. It can be seen from the energy spectrum of the selected area that the fine particles generated on the surface after applying EMS have more Sn content.

In order to understand the types of corrosion products formed, XPS narrow spectrum scanning was performed on different elements in the corrosion product films of the samples with stirring parameters of 60A and 20 Hz. Figure 9 shows the evolution of the high-resolution spectra of Al 2p, Sn 3d and O 1s and their corresponding deconvolution results. The Al 2p high-resolution spectrum found two sub-peaks after deconvolution, which are aluminum oxide Al2O3 and metal aluminum Al, respectively [21]. It can be seen from the Sn 3d high-resolution spectrum that after deconvolution, three sub-peaks appear in both the Sn 3ds/2 and Sn 3d5/2 orbitals, which are the state of Sn2+ in the tin oxide lattice, and the tin oxide crystal The state of Sn2+ in the lattice, and the metallic Sn. There are three types of Sn in the corrosion product film, namely metal Sn, SnO and SnO2 [22]. The asymmetric peaks in the high-resolution spectrum of O 1s indicate that the contained oxygen should be in three states: oxide, hydroxide and adsorbed water. O2− in the lattice of aluminum or tin oxide, OH− in the lattice of aluminum or tin hydroxide, and hydroxyl group in the adsorbed H2O molecule in the oxide film, respectively [23].

According to XPS detection of elements and EDS analysis, combined with the analysis of electrochemical test results, it can be found that the Sn element plays an important role in the corrosion resistance of Al-Sn alloy.
Table A1. Impedance fitting parameters after immersed for 0.5 h.

| Time (h) | Parameters | L (H cm$^2$) | $R_s$ (Ω cm$^2$) | $Y_0$ (Ω$^{-1}$ cm$^2$s$^n$) | n | $\chi^2$ | $R_s$ (Ω cm$^2$) | $Y_0$ (Ω$^{-1}$ cm$^2$s$^n$) | n | $\chi^2$ |
|----------|------------|--------------|-----------------|--------------------------|---|--------|-----------------|--------------------------|---|--------|
| 0.5h     | Non-EMS    | $4.90 \times 10^{-7}$ | 5.18 | $3.38 \times 10^{-3}$ | 0.93 | 332.9 | $6.91 \times 10^{-4}$ | 0.61 | 504.4 | $2.26 \times 10^{-3}$ |
|          | 40A 20 Hz  | $2.19 \times 10^{-10}$ | 3.36 | $3.66 \times 10^{-3}$ | 0.65 | 546.7 | $2.98 \times 10^{-4}$ | 0.99 | 103.2 | $8.93 \times 10^{-3}$ |
|          | 50A 20 Hz  | $1.26 \times 10^{-12}$ | 5.09 | $1.77 \times 10^{-3}$ | 0.69 | 2680 | $1.91 \times 10^{-4}$ | 0.91 | 480 | $7.51 \times 10^{-4}$ |
|          | 60A 20 Hz  | $3.14 \times 10^{-8}$ | 2.89 | $2.99 \times 10^{-3}$ | 0.67 | 616.3 | $3.09 \times 10^{-4}$ | 0.99 | 136.8 | $1.31 \times 10^{-4}$ |
|          | 70A 20 Hz  | $1.83 \times 10^{-7}$ | 3.95 | $3.82 \times 10^{-3}$ | 0.67 | 378.5 | $2.69 \times 10^{-4}$ | 0.97 | 101.5 | $7.46 \times 10^{-3}$ |
Table A2. Impedance fitting parameters after immersed for 48h, 168 h, 336 h, 720 h.

| Time (h) | Parameters  | R_s (Ω·cm²) | Y_d(Ω⁻¹·cm²·s) | n  | R_i (Ω·cm) | Y_d(Ω⁻¹·cm²·s) | n  | R_b (Ω·cm) | C(F·cm²) | R_b (Ω·cm²) | χ²  |
|----------|-------------|-------------|----------------|-----|------------|----------------|-----|------------|---------|-------------|-----|
| 48       | Non-EMS     | 2.22        | 2.73 × 10⁻⁴    | 0.41| 5.43       | 9.53 × 10⁻⁴    | 0.91| 901        | 8.15 × 10⁻⁴ | 0.89        | 2.55 | 6.17 × 10⁻⁹ | 6.82 | 9.50 × 10⁻³  |
| 40A 20 Hz|             | 2.10        | 4.22 × 10⁻⁴    | 1.00| 1.74 × 10⁻³| 0.83 × 10⁻⁴    | 0.82| 452        | 1.33 × 10⁻⁴ | 0.22        | 7.84 × 10⁻³ | 48.20 | 3.42 × 10⁻⁴  |
| 50A 20 Hz|             | 3.53        | 1.35 × 10⁻³    | 1.00| 1016       | 4.67 × 10⁻³    | 1.00| 977        | 1.83 × 10⁻⁴ | 0.96        | 0.47 | 1.59 × 10⁻⁶ | 642.1| 1.18 × 10⁻³  |
| 60A 20 Hz|             | 1.78        | 9.22 × 10⁻⁴    | 1.00| 1.47       | 1.42 × 10⁻³    | 0.91| 319        | 3.34 × 10⁻³ | 0.24        | 63.18| 4.76 × 10⁻³ | 660.0| 7.75 × 10⁻⁴  |
| 70A 20 Hz|             | 3.42        | 6.48 × 10⁻⁴    | 1.00| 2.64       | 6.84 × 10⁻⁴    | 0.92| 1370       | 2.36 × 10⁻³ | 0.29        | 1307| 2.82 × 10⁻⁷ | 645.2| 4.64 × 10⁻⁴  |
| 168      | Non-EMS     | 4.29        | 4.07 × 10⁻³    | 0.94| 6.72       | 1.79 × 10⁻⁴    | 0.69| 2.73       | 3.09 × 10⁻³ | 0.88        | 621.4| 1.89 × 10⁻² | 207.0| 4.54 × 10⁻⁴  |
| 40A 20 Hz|             | 3.14        | 3.66 × 10⁻³    | 0.80| 135.7      | 1.36 × 10⁻²    | 1.00| 58.35      | 5.43 × 10⁻⁹ | 0.20        | 2.29 | 4.40 × 10⁻⁴ | 0.94 | 1.55 × 10⁻³  |
| 50A 20 Hz|             | 4.18        | 3.95 × 10⁻³    | 0.49| 0.34       | 5.37 × 10⁻⁴    | 0.98| 369.8      | 0.68       | 0.96        | 88.95| 9.23 × 10⁻² | 0.28 | 3.10 × 10⁻⁴  |
| 60A 20 Hz|             | 2.73        | 2.26 × 10⁻³    | 0.79| 2.76       | 1.54 × 10⁻⁴    | 0.90| 139.3      | 1.35 × 10⁻² | 0.67        | 1.02 | 6.22 × 10⁻³ | 90.6 | 1.27 × 10⁻³  |
| 70A 20 Hz|             | 4.18        | 1.79 × 10⁻³    | 0.81| 1.93       | 1.94 × 10⁻⁸    | 0.86| 202.0      | 1.12 × 10⁻² | 0.83        | 2.31 | 9.64 × 10⁻⁸ | 201.4| 2.52 × 10⁻⁴  |
| 336      | Non-EMS     | 1.81        | 1.99 × 10⁻⁵    | 0.88| 7.51       | 1.75 × 10⁻⁷    | 1.00| 2.43 × 10⁵  | 6.39 × 10⁻⁴ | 0.63        | 73.08| 3.66 × 10⁻⁴ | 243.8| 3.40 × 10⁻⁴  |
| 40A 20 Hz|             | 2.95        | 5.23 × 10⁻¹    | 0.87| 22.52      | 7.16 × 10⁻⁵    | 0.87| 6.85       | 6.10 × 10⁻² | 1.00        | 56.71| 2.27 × 10⁻⁴ | 254.9| 8.52 × 10⁻⁵  |
| 50A 20 Hz|             | 4.59        | 9.30 × 10⁻⁴    | 0.89| 0.69       | 1.87 × 10⁻⁸    | 0.91| 206.3      | 1.45 × 10⁻³ | 0.87        | 713.4| 5.97 × 10⁻² | 9.96 | 1.80 × 10⁻⁴  |
| 60A 20 Hz|             | 4.06        | 1.28 × 10⁻⁴    | 0.81| 702.8      | 1.61 × 10⁻⁴    | 1.00| 1.25 × 10⁵  | 8.8 × 10⁻⁴ | 0.56        | 4.43 × 10⁵ | 689.9 | 6.49 × 10⁻⁹ | 422.0| 6.64 × 10⁻⁴  |
| 70A 20 Hz|             | 8.62        | 4.25 × 10⁻⁵    | 0.76| 19.35      | 2.32 × 10⁻⁷    | 0.79| 1.69 × 10⁵  | 6.89 × 10⁻⁴ | 0.29        | 64.68| 2.57 × 10⁻⁵ | 560.3| 2.40 × 10⁻⁵  |
| 720      | Non-EMS     | 8.02        | 3.57 × 10⁻⁴    | 1.00| 4.80       | 3.51 × 10⁻⁷    | 0.77| 3.94 × 10⁵  | 5.52 × 10⁻⁴ | 0.66        | 2.43 × 10⁵ | 2.63 × 10⁻⁵ | 2.1 × 10⁻² | 6.60 × 10⁻⁷  |
| 40A 20 Hz|             | 4.02        | 1.02 × 10⁻⁴    | 0.80| 1401       | 2.36 × 10⁻⁷    | 0.75| 4.02 × 10⁵  | 6.17 × 10⁻⁴ | 0.91        | 3391| 2.30 × 10⁻³ | 2548.0| 1.98 × 10⁻⁸  |
| 50A 20 Hz|             | 5.36        | 7.00 × 10⁻⁵    | 0.83| 132.8      | 1.36 × 10⁻⁸    | 0.99| 6.82 × 10⁵  | 3.55 × 10⁻⁴ | 0.52        | 3.96 × 10⁵ | 8.13 × 10⁻³ | 1065.0| 2.47 × 10⁻³  |
| 60A 20 Hz|             | 5.57        | 5.05 × 10⁻⁵    | 0.84| 13.1       | 4.23 × 10⁻⁵    | 0.85| 1.79 × 10⁵  | 4.05 × 10⁻⁴ | 0.43        | 284.7| 1.21 × 10⁻³ | 3345.0| 2.10 × 10⁻³  |
| 70A 20 Hz|             | 4.72        | 7.24 × 10⁻⁵    | 0.84| 11.39      | 4.59 × 10⁻⁵    | 0.82| 1.23 × 10⁵  | 3.05 × 10⁻⁴ | 0.41        | 612.4| 1.09 × 10⁻⁴ | 4566.0| 2.44 × 10⁻³  |
**Figure 5.** Variation curve of $R_{total}$ with time during immersing of samples. Prepared with different EMS currents.

**Figure 6.** Micromorphology of corrosion product film after immersion for 168 h. (a) Non-EMS; (b) 40A 20 Hz; (c) 50A 20 Hz; (d) 60A 20 Hz; (e) 70A 20 Hz.
Since the oxide film belongs to the category of metal surface conversion film, and the base metal will directly participate in the formation of the oxide film, the structure and composition of the surface oxide film are restricted by the state of the base metal [24]. Due to the large density difference between Al and Sn during the casting process, specific gravity segregation occurred in the sample without EMS, and the segregation degree of the Sn element was relatively high. The aggregation of Sn is not conducive to the formation of dense corrosion product film [25]. The uniformity of the oxide film formed on the surface is damaged and the structure is relatively loose, which does not have a good corrosion protection effect. After applying EMS, the segregation of Sn is improved, the segregation degree of Sn is low, and the oxide film formed on the surface is uniform and dense, which has a good protective effect and improves the corrosion resistance of the alloy. The formation of a dense SnO2 oxide film in the corrosion product film on the surface of the alloy can further improve the corrosion resistance of the alloy [26].

4. Conclusions

(1) The structure of the sample without EMS is all dendrites. With the application of electromagnetic stirring, the grains gradually become smaller and rounder. When the stirring current reaches 60A, the grains tend to be nearly spherical as a whole, and the refining effect is remarkable. With the continuous increase of the stirring current, there was no significant difference in the grains.
Figure 8. Micromorphology of corrosion product film after immersion for 720 h. (a) Non-EMS; (b) 40A 20 Hz; (c) 50A 20 Hz; (d) 60A 20 Hz; (e) 70A 20 Hz.

Figure 9. High-resolution spectra of Al 2p, Sn 3d and O 1s.
(2) There are two impedance arcs in the Nyquist curve of all samples at the initial stage of immersion. With the increase of immersion time, the impedance spectrum gradually changes into a single impedance arc feature. The impedance arc radius of the samples with EMS increased gradually with the immersing time and showed good corrosion resistance in the later period of immersing.

(3) When the immersion time is 720 h, a dense oxide film is formed on the surface of the Al-Sn alloy prepared under the stirring parameter of 60A 20 Hz, which can physically block the corrosive anions in the corrosive medium and improve the corrosion resistance.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration of competing interest

The authors declare no financial or commercial conflict of interest.

Appendix

ORCID iDs

Shuhao Li @ https://orcid.org/0000-0002-1512-0174
Zhiyun Zhu @ https://orcid.org/0000-0001-9534-9229

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Zhiyun Zhu @ https://orcid.org/0000-0001-9534-9229
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