Original Article

Evolution of microstructure and properties during homogenization of the novel Al–Li alloy fabricated by electromagnetic oscillation twin-roll casting

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**Abstract**

As a new non-traditional method of alloy preparation, the electromagnetic twin-roll casting (ETRC) technology overcomes the defects of traditional technologies in the preparation of traditional aluminum alloy, especially Al–Li alloy, such as gas hole in the traditional mold casting and macro segregation in the twin-roll casting (TRC) process, which greatly improves the comprehensive properties of the alloy strip. In present work, the evolution of microstructure and properties of Al–Li alloy fabricated by copper mold casting, and TRC and ETRC processes during homogenization have been investigated in detail. Under the action of electromagnetic field, the secondary dendrite arm spacing (SDAS) of the alloy reduces significantly and the solidification structure of the alloy refines dramatically. Moreover, the volume fraction of non-equilibrium eutectic phases and intermetallics which continuously distributes in the interdendritic region and grain boundaries decreases remarkably, and the dendritic network as well as the microsegregation of the alloying elements eliminates effectively. Therefore, compared with the traditional technologies, the homogenization time of the alloy fabricated by ETRC is greatly shortened, which provides a new idea for the short process and efficient preparation of Al–Li alloy.

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1. Introduction

Al–Li alloy has a combination of low density, high strength and stiffness and excellent fracture toughness compared with those of traditional 2XXX and 7XXX series aluminum alloy, and is widely used in new generation aircraft, aerospace and military industries [1-6].

Nowadays, the light-weight multicomponent alloy has attracted much attention, especially Al–Cu–Li alloy [7]. The superior comprehensive properties of Al–Cu–Li alloy are attributed to the appropriate composition ratio of Cu/Li and the other alloying elements, which promotes the formation of the main strengthening phases such as \(\mathrm{T_1} (\mathrm{Al}_2\mathrm{CuLi})\), \(\theta' (\mathrm{Al}_2\mathrm{Cu})\), \(S' (\mathrm{Al}_2\mathrm{CuMg})\) and \(\theta (\mathrm{Al}_3\mathrm{Li})\) [8,9].
Al–Cu–Li alloys prepared by traditional casting process will have shrinkage porosities and gas holes defects due to the gas absorption of lithium element. However, TRC process combines continuous casting and rolling deformation into one process. The melt subjected to a certain rolling force during cooling and solidifying, which compensates for the solidification shrinkage of liquid metal in the roll casting region, hence solving the problems of porosity and other defects in Al–Cu–Li alloy [10]. In addition, the surface quality of the strip produced by TRC is good. The excellent surface quality can prevent crack initiation, delay small crack growth, improve corrosion resistance and even improve wear performance [11]. By friction stir welding (FSW), the TRC strips can be welded together to obtain thick Al–Li alloy plates, and this technology has been widely used to improve the physical and mechanical properties of high-end metallic components [12,13]. Because aluminum is very alloy able with other metals, TRC technology has become an important preparation technology for metal composite plates, such as aluminum titanium alloy composite plate, and the alloy offers excellent mechanical properties [14].

However, whether in traditional casting or TRC process, the non-equilibrium solidification of alloys will inevitably lead to the non-uniform distribution of solute elements, which results in micro-segregation and weaken the workability of the cast structure and seriously deteriorates the mechanical properties of the alloys [15–17]. Therefore, the inhomogeneity of chemical composition and structure in alloys must be eliminated or reduced by homogenization treatment [18,19]. In addition, the mechanical properties of the Al–Cu–Li alloy in final service state are particularly sensitive to the microstructure of as-cast alloys, heat treatment process and subsequent processing, thus the homogenization treatment is a primary and important step for the manufacturing of Al–Cu–Li alloy [20].

The preparation process or solidification manner will affect the type and characteristics of the second phase, thus affecting the homogenization process of the alloy [21]. The cooling rate of the TRC process is one order of magnitude higher than that of traditional casting process, and the high solidification rate makes the distribution of solute elements between grains and within grains more uneven, which makes the micro-segregation of alloys more serious. However, the long-term homogenization treatment adopted to eliminate the serious micro-segregation will reduce the unique advantages of TRC process as a short production period, green environmental protection, energy-saving and high efficiency process [22]. As an effective external physical field, the effect of electric and magnetic fields on refinement of solidification structure and homogeneous solute field of ferromagnetic and non-ferromagnetic materials has been confirmed [23], which provides a new idea for the efficient preparation of Al–Cu–Li alloy.

Until now, few reports have been reported on the preparation of high-strength aluminum alloy by introducing electromagnetic field into the TRC process, and the reports on the effects of homogenization treatment on the microstructure and properties of Al–Cu–Li alloy are limited. Therefore, we innovatively introduces electromagnetic oscillation field in the TRC process, in an aim to improve the microstructure and reduce the micro-segregation of the alloy, so as to shorten the homogenization process and save energy consumption.

In the present study, we adopted TRC technology to solve the defects such as gas hole in Al–Cu–Li alloy prepared by traditional casting process, and a new ETRC technology was developed to solve the problem of serious micro-segregation caused by rapid cooling rate in traditional TRC process. The corresponding microstructures and properties evolution mechanisms of the Al–Cu–Li alloy prepared by conventional casting, TRC and ETRC before and after homogenization are revealed in detail, and the optimum homogenization heat treatment system for the alloys prepared under different fabrication conditions is also explored carefully. These results provide indispensable information for optimizing process and improving the overall performance of the Al–Cu–Li alloy cast-rolled strip.

### 2. Experimental

The Al–Cu–Li alloy ingots are fabricated by traditional casting technology in a water-cooled copper mold of 29 mm, 17 mm and 25 mm in length, width and height respectively. While the cast-rolled strips and electromagnetic cast-rolled strips are fabricated by TRC process in a horizontal twin-roll casting mill. The schematic and physical drawings of the TRC process are shown in Fig. 1(a) and (b), respectively. The chemical compositions of the experimental alloy strips and ingots are shown in Table 1.

The Al–Cu–Li alloy ingots, cast-rolled strips and electromagnetic cast-rolled strips are homogenized at 495 °C, 505 °C, 515 °C, 525 °C and 535 °C for 24 h respectively, so a better homogenization temperature can be determined. At this optimum temperature, the alloys were kept for 6 h, 12 h, 24 h, 36 h and 48 h respectively. By comparing the homogenization effect of each group of the samples, the best homogenization parameters of the experimental alloys are obtained. The equipment used for homogenization treatment is a hot-air furnace independently developed by the laboratory with a temperature error less than ±5 °C. After homogenization, all specimens are cooled to room temperature outside the furnace.

The metallographic structure before and after homogenization of the alloys produced by three different preparation processes is observed with a Leica DMI 5000M optical microscope (OM). The SDAS of alloys fabricated under different conditions are counted by Image-Pro Plus image analysis software. SDT–Q.600 differential scanning calorimeter is employed to the differential scanning calorimetry (DSC) analysis. The distribution of alloying elements at grain boundaries and in grains before and after homogenization treatment of the experimental alloys are quantitatively analyze by X’Pert 8–3530 F type electron probe micro analysis (EPMA). The D/max–2500 PC type (Cu Kα) X-ray diffraction (XRD) is employed to identify the phase composition of the alloys. D60K digital metal conductiv-

### Table 1 – Chemical composition of the Al–Cu–Li alloy (wt.%).

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Li</th>
<th>Zn</th>
<th>Mg</th>
<th>Zr</th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Al</th>
</tr>
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<tbody>
<tr>
<td>wt.%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.657</td>
<td>1.885</td>
<td>0.765</td>
<td>0.259</td>
<td>0.085</td>
<td>0.270</td>
<td>0.147</td>
<td>0.041</td>
<td>Bal.</td>
</tr>
</tbody>
</table>
ity tester and KB3000BURZ-SA macroscopic Vickers hardness tester are carried out to test the conductivity and hardness of the experimental materials before and after homogenization, respectively.

### 3. Results and discussion

#### 3.1. Metallographic structure of the alloys

Fig. 2 shows a comparison of microstructures and morphologies of the alloys obtained under different preparation conditions. As can be seen from Fig. 2, the Al–Cu–Li alloy prepared by traditional mold casting process shows the typical as-cast eutectic structure and has many defects such as shrinkage holes. This is due to the high content of Li in this alloy, which is easy to absorb air during the ordinary casting process, thus resulting in the formation of gas holes and microcracks in the ingot as shown in Fig. 2(a). The as-cast structure of the alloy is composed of coarse dendritic network and a large amount of non-equilibrium eutectic phases which distribute in the grain boundaries and interdendritic region, as shown in Fig. 2(b).

The TRC process combines continuous casting with rolling deformation, and the melt is subjected to a certain rolling force during cooling and solidification, which compensates the solidification shrinkage of molten metal in the roll-casting zone, thus obtaining compact strip without shrinkage holes. But there are obvious macro-segregation bands with the width close to 1 mm in the middle of the TRC slab, as shown in Fig. 2(c). The central macro-segregation bands of TRC strip will have a negative impact on slab quality and subsequent processing performance [19]. When the central segregation is serious, the central delamination fracture phenomenon will occur in the cast-rolled strips, which will seriously deteriorate the properties of the alloy strips. However, after applying electromagnetic oscillation field \((f=20\text{Hz}, \sigma=20\%, I=300\text{A}, B=35.7\text{mT})\) in the TRC process, the central macro-segregation bands of the strip is significantly eliminated, hence the quality of the slab is significantly improved, as shown in Fig. 2(f).

Fig. 3 displays the statistical results of the SDAS of the alloys under different preparation conditions. It can be seen from Fig. 3 that the SDAS of the Al–Li alloy fabricated by conventional water-cooled copper mold casting, TRC and ETRC processes are 32.48 μm, 9.04 μm and 6.03 μm, respectively. Compared with the traditional casting method, the TRC process can significantly reduce the SDAS of the alloy. After introducing the electromagnetic oscillation field into the TRC process, the SDAS of the alloy is further reduced. The SDAS of the ETRC strip is 5 times smaller than that of ingot, and the effect of refining solidification structure of alloy is further enhanced compared with TRC process.

#### 3.2. Microsegregation of the alloys

To explore the micro-segregation of the alloys fabricated under different conditions, electron probe microprobe (EPMA) and its associated spectrometer wavelength dispersive spectrometer (WDS) are adopted to detect the ingot, cast-rolled and electromagnetic cast-rolled strips, and the results of spectral line scanning are shown in Fig. 4(a1) & (a2), Fig. 4(b1) & (b2) and Fig. 4(c1) & (c2) respectively. The microscopic morphology of the alloys on the left and the yellow line shows the position of line scanning, and on the right is the schematic diagram of the content change of Cu, Zn and Mg at the characteristic position corresponding to the line scanning.

It can be seen from Fig. 4 that the contents of Cu, Zn and Mg in ingot, cast-rolled strip and electromagnetic cast-rolled strip are periodically distributed between intragranular and grain boundaries, and the content of alloying elements at grain boundaries is obviously higher than that in grains. The experimental results show that there is obvious micro-segregation in Al–Cu–Li alloy fabricated under three different process conditions. The periodic distribution of the content of Cu element is particularly obvious, which indicates that the segregation of Cu element is the most serious among all alloy-
ing elements. Besides, the fluctuation of alloying elements content in the alloy prepared by TRC process is higher than that by traditional casting method. But after applying electromagnetic field in the TRC, the fluctuation of elements content such as Cu, Zn and Mg is relatively gentle, and the microsegregation of the alloy is dramatically reduced, as shown in Fig. 4(C2).

Fig. 5 presents the SEM photos of the as-cast alloy and the distribution of the main alloying elements such as Cu, Mg, Zn, Mn, Zr and impurity elements such as Fe, Si at grain boundaries and in grains. It can be seen from Fig. 5 that there is obvious element segregation at grain boundary in the alloy, and the degree of the segregation of each element is different. Among them, Cu element segregation is the most serious, Zn element the second, and there is a little Fe element segregation at grain boundary. No segregation of other alloying elements such as Mg and Mn is observed, which indicates that the distribution of other alloying elements is more uniform. The experimental result further confirms the existence of grain boundary segregation and mainly the segregation of Cu element, which is consistent with the results of EPMA detection in Fig. 4. The EDS spectra analysis in Table 2 shows that the main non-equilibrium eutectic phases at grain boundaries are Al₃Cu phase and the AlₓCu phase with a small amount of Zn, Mg, Mn and Fe dissolved.

The formation mechanism of segregation at grain boundaries is related to the distribution of solutes and inhomogeneous diffusion during melt solidification process. Because of the negative temperature gradient and the high undercooling in the liquid at the front of the solid-liquid interface, some parts of the solid-liquid interface protrude into the liquid phase and further penetrate into the liquid phase with higher undercooling, and dendrites continue to elongate and grow to form dendrite network during solidification [24]. Grooves are easily formed at the interface between grain boundaries and liquid phases during the grain growth, which provides favorable circumstances for the segregation of Cu, Zn and Fe solute atoms at grain boundaries. At the same time, solute atoms may squeeze into the solid-liquid interface in the crystallization process, so that the solute atoms enrichment at the grain boundaries and leading to the micro-segregation. The sketch

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Mg</th>
<th>Al</th>
<th>Mn</th>
<th>Cu</th>
<th>Zn</th>
<th>Zr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.47</td>
<td>76.62</td>
<td>0.12</td>
<td>21.79</td>
<td>0.80</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>B</td>
<td>2.34</td>
<td>76.84</td>
<td>0.16</td>
<td>17.91</td>
<td>1.18</td>
<td>-</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Fig. 2 – Macro and Microstructure of the Al-Cu-Li alloy: (a) & (b) ingot; (c) & (d) TRC strip; (e) & (f) ETRC strip (TD: transverse direction; ND: normal direction).
map of the micro-segregation formation mechanism is shown in Fig. 6.

However, the cooling rate of the metal melt can reach $10^2 \sim 10^3 \text{ } ^{\circ} \text{C/s}$ under the action of crystalizing rolls in TRC process. At such a high cooling rate, the solute elements cannot diffuse uniformly [25], and the actual crystallization process of the alloy during TRC is more deviated from the equilibrium position. Therefore, the degree of microsegregation in cast-rolled strips is more serious as shown in Fig. 4(b2). After introducing the electromagnetic oscillation field into the TRC, the electromagnetic oscillation can reduce the solute gradient and slow down the temperature gradient at the front of solid-liquid interface, and promotes melt convection and solute transport. In addition, the Lorentz force generated by the electromagnetic oscillation field will act on the roll casting region, thus enhancing the diffusion ability of solute atoms [26], and the number of the solute atoms accumulated in the grooves will be greatly reduced. Therefore, the micro-segregation in electromagnetic cast-rolled strip is significantly reduced as shown in Fig. 4(C2).

High cooling rate and non-equilibrium solidification process in water-cooled copper mold casting, especially in TRC process lead to the formation of non-equilibrium eutectic phases and intermetallic compounds [27], and serious dendrite segregation as well as dendrite network existing in solidified structure. A considerable number of coarse non-equilibrium eutectic phases and intermetallic compounds distribute continuously along interdendritic regions and grain boundaries, which not only seriously deteriorates the strength and toughness of alloys, but also brings many adverse effects on the processing properties and applications of materials. Therefore, the intermetallic compounds and non-equilibrium eutectic structures enriched on grain and dendrite boundaries must be dissolved in the matrix by homogenization annealing to eliminate dendritic network and micro-segregation, so as to make alloying elements uniformly distributed and improve the structure and properties of the alloy [28].

### 3.3. Content of non-equilibrium eutectic phase in the alloys

The DSC curves of the ingot, TRC strip and ETRC strip are listed in the Fig. 7. Around $532 \text{ } ^{\circ} \text{C}$ there is an obvious endothermic peak A, B and C in ingot, cast-rolled strip and electromagnetic cast-rolled strip, respectively. The endothermic peak results from the dissolution of non-equilibrium eutectic phase in the alloy, and the area of non-equilibrium eutectic melting peaks is positively correlated with the content of non-equilibrium eutectic phase in alloy matrix. The order of the area of three non-equilibrium eutectic melting peaks is $A>B>C$, and the enthalpy values calculated by integrating the area of the three endothermic peaks A, B and C are 7.368 J/g, 6.599 J/g and 2.556 J/g respectively as shown in Fig. 8, which indicates that the TRC process, especially ETRC process, can significantly reduce the content of non-equilibrium eutectic phase in the alloy. The peak temperature of the endothermic peak is about $532 \text{ } ^{\circ} \text{C}$, so it can be determined that the homogenization temperature should be below $532 \text{ } ^{\circ} \text{C}$, otherwise there will be over-burning. In order to determine a reasonable homoge-
3.4. Microstructure evolution of the alloys during homogenization

The metallographic micrographs of the Al–Cu–Li alloy ingots, cast-rolled strips and electromagnetic cast-rolled strips homogenized at different temperatures for 24 h are presented in Fig. 9. As can be seen from Fig. 9, compared with the original solidification structure of the alloy, certain results have been achieved in homogenization after homogenization treatment at different temperatures. When the temperature is 495 °C, the dendrites in the ingot are still obvious as shown in Fig. 9(a). A small amount of non-equilibrium eutectic structure remains at the grain boundaries of the cast-rolled and electromagnetic cast-rolled strips, and they are distributed discontinuously along the grain boundaries as shown in Fig. 9(f) and (k). When the homogenization temperature increases from 495 °C to 505 °C, the non-equilibrium eutectic phase dissolved in the matrix increases gradually with the increase of homogenization temperature, and the dendrites are refined obviously, and the dendritic network becomes thinner as shown in Fig. 9(b). The grain boundaries of cast-rolled and electromagnetic cast-rolled strips become smaller and flatter as shown in Fig. 9(g) and (l). When the temperature reaches 525 °C, slight over-burning structures begin to appear in the alloys prepared under three different process conditions because of the melting compounds can be observed at grain boundaries. When the temperature further rises to 535 °C, the over-burning phenomenon becomes serious, and a large number of obvious over-burning characteristic structures such as triangular grain boundaries and re-melting balls appear in the structure as shown in Fig. 9(e), (j) and (o).

The homogenization process is realized by the diffusion of solute atoms under high temperature conditions. The relationship between the diffusion rate of solute atoms and temperature can be expressed by the following formula:

\[ D = D_0 \exp \left( -\frac{Q}{RT} \right) \]  

(1)

where \( D \) is the diffusion coefficient of the alloying elements in matrix, \( D_0 \) is diffusion coefficient constant, \( Q \) is the diffusion activation energy, \( R \) is the thermodynamic constant, and \( T \) is the temperature.
Based on Eq. (1), with the increase of homogenization temperature, the diffusion rate of solute atoms increases significantly, and the homogenization process accelerates greatly. When the homogenization temperature is 495 °C, the temperature is low and the diffusion rate of solute atoms is low, which makes it difficult to achieve the homogenization effect. The eutectic phase with low melting point in the alloy begins to dissolve gradually when the temperature reaches a certain value, and the micro segregation is significantly reduced. Over-burning phenomenon will
occur by further increasing the temperature, which will affect the homogenization effect and comprehensive properties of the alloy.

The metallographic structures of Al–Cu–Li alloy fabricated under different preparation conditions after holding at 505 °C for 6h–36h are at the view of Fig. 10. When homogenization time is 6h, there still exist a considerable number of obvious dendrites in ingot, and a small amount of non-equilibrium eutectic phase are continuously distributed along the grain boundary in the cast-rolled strip and electromagnetic cast-rolled strip as shown in Fig. 10(a), (f) and (k) respectively. This is due to the short holding time and insufficient diffusion of solute elements. As the holding time prolonged to 12h, the grain boundaries of cast-rolled and electromagnetic cast-rolled strips become clearer and straighter, and the homogenization treatment achieves good results. Especially for electromagnetic cast-rolled strip, the grain size is still relatively small at this time as shown in Fig. 10(i).

Continue to extend the holding time, the effect of homogenization is not improved, but the phenomenon of grain growth appears as shown in Fig. 10(i) and (n). With the prolongation of homogenization treatment time, more non-equilibrium eutectic phases and intermetallic compounds dissolve in the matrix, segregation decreases gradually, and each alloying element tends to distribute more evenly. When the ingot is homogenized for 12h, the dendrite network is still developed and the dendrite segregation is serious. The dendrite network does not become thinner until the ingot is homogenized for 24h or even 36h, and the homogenization effect is obvious as shown in Fig. 10(d) and (e). It is noteworthy that the homogenization effect of 12h heat preservation of the cast-rolled strip is equivalent to that of 24h or even 36h heat preservation of the ingot. Under the same holding time, the homogenization effect of electromagnetic cast-rolled strip is the most distinguishing.

The X-ray diffraction patterns of the experimental materials before and after homogenization are depicted in Fig. 11. The diffraction peaks of $\theta$ (Al$_2$Cu), $T_1$ (Al$_2$CuLi) and $S$ (Al$_7$CuMg) phase are observed in the original solidification structure of ingot, cast-rolled strip and electromagnetic cast-rolled strip besides $\alpha$(Al). However, there are no diffraction peaks of other substances being observed except for the $\alpha$(Al) after the alloy is homogenized at 505 °C/12h and 505 °C/24h. The experimental result shows that the homogenization treatment can re-dissolve the $\theta$, $T_1$ and $S$ phases in $\alpha$(Al) matrix.

The DSC curves of the ingot, cast-rolled strip and electromagnetic cast-rolled strip after homogenization at 505 °C/12h and ingot homogenized at 505 °C/24h, as shown in Fig. 12. The heat absorption peak area of the alloy during thermal analysis process after homogenization treatment decreases significantly compared with that before homogenization treatment, whether it is ingot, TRC strip or ETRC strip. The result indicates that the non-equilibrium eutectic phases produced during non-equilibrium solidification process of the alloy are eliminated well under the selected homogenization system. In addition, the content of non-equilibrium eutectic phases in ingot homogenized at 505 °C/24h is still higher than that in cast-rolled strip homogenized at 505 °C/12h, and the enthalpy
of them is 0.960 J/g and 0.643 J/g respectively, as shown in Fig. 13. Under the same homogenization condition, the area of dissolution peak of non-equilibrium eutectic phases in electromagnetic cast-rolled strip is the smallest and the enthalpy of eutectic phase is 0.290 J/g, which indicates that the content of residual eutectic phase in the electromagnetic cast-rolled strip is the least and the effect of homogenization is the best (Fig. 13).

The element distribution maps of EPMA line scanning of alloy after homogenization are shown in Fig. 14. Compared with the results in Fig. 4, the periodic fluctuation of the content of Cu, Zn and Mg at grain boundaries and in grains is significantly reduced after homogenization treatment. The experimental results show that the dendrite segregation is remarkably reduced and the alloying elements are more uniformly distributed by homogenization treatment. After homogenization at 505 °C/12 h, the content fluctuation of elements in the ingot is still quite intense. The content fluctuation of elements in the ingot homogenized at 505 °C/24 h is similar to that of cast-rolled strip homogenized at 505 °C/12 h. Under all conditions, the fluctuation of elements in the electromagnetic cast-rolled strip is the most gentlest, which indicates

Fig. 13 – The enthalpy of the Al-Cu-Li alloy produced by different process conditions after homogenization.

that the distribution of each alloying element is the most uniform. The experimental results are consistent with the metallographic results in Fig. 10 and the detection results of DSC as shown in Fig. 12.

3.5. Homogenization kinetic analysis

According to the study of Samaras et al. [29,30], the kinetic equation of homogenization process can be expressed by the following equation:

\[
\frac{1}{T} = \frac{R}{Q} \ln \left( \frac{4 \pi^2 D_0 t}{4.6 L^2} \right)
\]

(2)

where \( T \) is the homogenization temperature; \( Q \) is the activation energy of diffusion; \( R \) is the thermodynamic constant; \( L \) is the secondary dendrite arm spacing; \( D_0 \) is diffusion coefficient constant; \( t \) is the holding time. The order of diffusion rate is \( \text{Zn} > \text{Mg} > \text{Cu} \) during homogenization process [31,32], and the segregation in the alloy is mainly the segregation of Cu element as shown in Figs. 4 and 5, hence the homogenization process is mainly controlled by the diffusion of Cu. The \( D_0(\text{Cu}) = 0.084 \text{ cm}^2/\text{s} \) and the \( Q(\text{Cu}) = 136.8 \text{ kJ/mol} \), and by substituting the parameters into the Eq. (2), the homogenization kinetic curves of three experimental materials with different SDAS mentioned in Fig. 3 can be obtained, as shown in Fig. 15.

As can be seen from Fig. 15, the holding time required for homogenization reduces greatly with the decrease of the SDAS, and the kinetic curves agree well with the homogenization test results as shown in Figs. 9, 10 and 14.

3.6. Residual phases analysis of the ingot and TRC strip after homogenization

Fig. 16 shows the SEM images and EDS type spectra of the residual phases of ingot homogenized at 505 °C/24 h and electromagnetic cast-rolled strip homogenized at 505 °C/12 h, respectively. The experimental results of the corresponding EDS type spectra listed in Table 3 shows that the irregular massive or acicular residual phases after homogenization of ingot and electromagnetic cast-rolled strip are AlCuFe and AlCuFeMn phases. The formation of these residual phases is due to the fact that the melting point of Mn and Fe is higher than that of Cu, and their solubility in \( \alpha(\text{Al}) \) matrix is much lower than that of Cu in aluminum. During solidification process, Mn and Fe atoms precipitate preferentially from the aluminum melt and become the nucleation core of Mn-rich and Fe-rich second phase particles. As the solidification proceeds, the melting temperature decreases continuously, and Cu atoms gradually deposit on these cores, and eventually form AlCuFe and AlCuFeMn phases. These Mn-rich and Fe-rich phases usually have high melting points, which can only be removed at higher temperatures, and it is difficult to eliminate them completely by homogenization treatment.

3.7. Hardness change of the alloys during homogenization

Fig. 17 illustrates the hardness curve of the Al-Cu-Li alloy prepared under different technological conditions after homogenization for 24 h at different temperatures. As can be seen from Fig. 17, homogenization treatment increases the hardness of the alloy when the homogenization temperature is less than 515 °C. The hardness of ingot, cast-rolled strip and electromagnetic cast-rolled strip undergo homogenization at 515 °C/24 h is 106.0, 109.7 and 114 respectively, and the hardness of three experimental materials after homogenization treatment at 505 °C for the same time is 109.9, 111 and 112.6 respectively, so it can be concluded that the two homogenization temperatures have little effect on the hardness of the alloys. While the hardness of the alloy decreases sharply when the homogenization temperature exceeds 515 °C. Homogeneous annealing can dissolve the non-equilibrium eutectic phase and the metal compounds with low melting point, thus increasing the supersaturated solid solubility of the experimental materials, and the supersaturated solid solution will precipitate rapidly and form same strengthening phases such as \( T_1 \) and \( S \) phases during the subsequent air cooling process, so increases the hardness of the alloy. On the premise of not over-burning, the higher the homogenization temperature is, the more fully the non-equilibrium eutectic phase dissolves, the faster the diffusion rate of solute atoms is, and the more uniform the distribution of solid solution elements is. Therefore, the second phase particles will precipitate more evenly and dispersively during the cooling process, which will

<table>
<thead>
<tr>
<th>Spectrogram</th>
<th>Atomic percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>0.80</td>
</tr>
<tr>
<td>Al</td>
<td>0.66</td>
</tr>
<tr>
<td>Mn</td>
<td>0.31</td>
</tr>
<tr>
<td>Cu</td>
<td>0.31</td>
</tr>
<tr>
<td>Zn</td>
<td>0.32</td>
</tr>
<tr>
<td>Zr</td>
<td>0.28</td>
</tr>
<tr>
<td>Fe</td>
<td>0.20</td>
</tr>
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</table>
gradually improve the hardness of the alloys. Once the homogenization temperature exceeds 525 °C, the overburnt structure of the experimental materials begins to appear as shown in Fig. 9. The over-burning of grain boundaries will weaken the grain boundaries, thus reducing the hardness of the alloy rapidly [33]. Continue to heat up to 535 °C, the over-burning phenomenon intensifies and the hardness of the experimental materials decreases rapidly, and the hardness of ingot, cast-rolled strip and electromagnetic cast-rolled strip decreases to 71.4, 98.2 and 86.6, respectively.

3.8. Conductivity change of the alloys during homogenization

The effects of holding time on the conductivity of the alloy when the homogenization temperature is 505 °C are presented in Fig. 18. It can be seen from Fig. 18 that the conductivity of the alloy fabricated under different conditions increases gradually with the prolongation of homogenization time, and then tends to be stable. In addition, after the same homogenization treatment time, the conductivity of the alloy prepared

Fig. 14 – Microstructure and element distribution of the alloys after homogenization: (a1) & (a2) ingot - 505 °C/12 h; (b1) & (b2) ingot - 505 °C/24 h; (c1) & (c2) TRC strip - 505 °C/12 h; (d1) & (d2) ETRC strip - 505 °C/12 h.
by ETRC process is always higher than that of the other two preparation processes. The conductivity of the ETRC strip, TRC strip and ingot after 505 °C/12 h homogenization treatment is 16.56 %IACS, 16.22 %IACS and 15.92 %IACS, respectively. It is noteworthy that the conductivity of the ingot after homogenization for 24 h is 16.60 %IACS, which is equivalent to that of the ETRC strip after homogenization for 12 h.

The longer the holding time is, the more complete the dissolution of eutectic phase with low melting point is, and the more sufficient the diffusion of alloying elements is. Hence, the segregation degree of the alloying elements in grains decreases gradually, the lattice distortion degree of matrix lattice will be weakened, and the density of electron scattering source in matrix lattice will be reduced. As a result, the conductivity of the alloy increases [34]. The interfacial heat transfer coefficient in TRC process is 5000–20,000 W/(m² K), while in the secondary cooling stage of conventional semi-continuous casting or traditional mold casting process, the interfacial heat transfer coefficient is 60–130 W/(m² K) [35,36].

In general, the diameter or thickness of ingots prepared by traditional casting is larger than the thickness of the strips produced by TRC production technology. Hence the cooling rate of the TRC process is much higher than that of traditional mold casting technology. At such a rapid cooling rate during TRC process, a great quantity of alloying elements will be dissolved in the aluminum matrix. Therefore, the supersaturated solid solubility of alloying elements in cast-rolled strip is higher than that of ingot. During the cooling stage

Fig. 15 – Kinetic curves of the Al–Cu–Li alloy during homogenization.

Fig. 17 – Hardness curve of the alloys after homogenization for 24 h at different temperatures.

Fig. 18 – Conductivity curve of the alloys with different homogenization time at 505 °C.

Fig. 16 – SEM microstructure and EDS type spectra of the Al–Cu–Li alloy after homogenization: (a) ingot - 505 °C/24 h; (b) TRC strip - 505 °C/12 h.
after the homogenization treatment, more second phase particles will precipitate, thus increasing the conductivity of the alloy. The introduction of electromagnetic field in the TRC process effectively enhances the mixing ability of solute atoms and further improves the supersaturated solid solubility of the alloy [9]. After homogenization, a large number of supersaturated solid solutes decompose and precipitate in the matrix, which reduces the supersaturated solid solubility of the alloy. Therefore, the conductivity of the electromagnetic cast-rolled strip is the highest after homogenization under the same conditions.

4. Conclusion

1. The ETRC process can overcome the defects such as gas holes in the traditional mold casting and macro segregation in the TRC process, which greatly improves the comprehensive properties of the Al-Li alloy strip.

2. The TRC process especially ETRC process can significantly reduce the SDAS and refine the solidification structure of the Al-Li alloy. The SDAS of the Al-Li alloy fabricated by conventional water-cooled copper mold casting, TRC and ETRC processes are 32.48 μm, 9.04 μm and 6.03 μm, respectively.

3. The conductivity of ETRC strip, TRC strip and ingot after 505 °C/12 h homogenization treatment are 16.56 %IACS, 16.22 %IACS and 15.92 %IACS respectively, while the value of the ingot after homogenization for 505 °C/24 h is 16.60 %IACS.

4. The hardness of ETRC strip, TRC strip and ingot after homogenization at 505 °C for 24 h is 114, 109.7 and 106.0, respectively. Once the homogenization temperature exceeds 525 °C, the over-burning of grain boundaries will weaken the grain boundaries and decrease the hardness of the Al-Li alloy.

5. ETRC process can not only reduce the content of non-equilibrium eutectic phase in the Al-Li alloy, but also reduce the degree of micro segregation of the alloying elements such as Cu, Zn and Mg in the alloy, which significantly reduces the homogenization time. The suitable homogenization system of the ingot is 505 °C/24 h, and that of the ETRC strip is 505 °C/12 h, and the experimental results are in good agreement with the homogenization kinetic curves.

Conflicts of interest

The authors declare no conflicts of interest.

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