Modeling dynamic recrystallization behavior of Al-Zn-Mg-Cu alloy during electroshock assisted tension based on cellular automata

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Abstract
Electroshock assisted forming of high-strength aluminum alloy is a new type of plasticizing manufacturing method. To study the dynamic recrystallization (DRX) behavior of Al-Zn-Mg-Cu alloy during low-frequency electroshock assisted tension, a cellular automata (CA) model coupled electro-thermal-mechanical multi-field effect was proposed on the Matlab platform. In the established CA model, the effect of additional driving force generated by the electric pulse on the dynamic recrystallization nucleation and growth has been innovatively taken into account. The grain diameters obtained by the above CA model are consistent with that obtained by the electron back scatter diffraction (EBSD) tests, which verified the accuracy of the model. The effects of current density and electrical pulse period on grain morphology, average grain diameter, DRX fraction, and grain size distribution were analyzed. Additionally, the optimal parameters of electroshock assisted tensile (current density of 30 A·mm⁻², pulse period of 5 s) were predicted by the CA method. At this time, the DRX fraction increased to 45.79% and the fracture elongation of unidirectional tensile specimen increased by 21.74%.

Nomenclatures

| Symbol | Description |
|--------|-------------|
| ρᵢ,ⱼ  | Dislocation density at location (i,j) |
| ε      | Real stress |
| K₁     | Dislocation generation |
| K₂     | Dislocation annihilation |
| ρ₀     | Initial dislocation density |
| ̄ρ     | Average dislocation density |
| a      | Correlation constant |
| μ      | Shear modules |
| b      | Burger’s vector |
| N_total| Total number of cells |
| P      | Recrystallization driving force |
| Δρ    | Dislocation density increment |
| γ      | Grain boundary energy |
1. Introduction

Al-Zn-Mg-Cu alloys have grown to be very attractive materials in the aerospace, high-speed rail, and automotive industries due to their excellent properties such as high specific strength and good impact energy absorption [1]. Many scholars have attempted to regulate the microstructure and properties of Al-Zn-Mg-Cu alloys to obtain high-performance components. Odusote et al [2] found that the addition of magnesium had a positive effect on the tensile strength of cast Al-Zn-Cu-Mg alloys due to the elimination of micro segregation by precipitation hardening. Ramesh et al [3] reduced the grain size to 8 μm and obtained an improvement hardness, yield strength and ultimate tensile strength after 3 cycles multi-direction forging of Al-Zn-Mg-Cu alloy.

Dynamic recrystallization (DRX), which can refine grains and regulate texture, has become an important means to manipulate the microstructure and enhance the overall performance of metals, including Al-Zn-Mg-Cu.
alloys [4]. Many research results show that a very limited amount of DRX can be obtained by appropriate hot forming processes in Al-Zn-Mg-Cu alloys [5]. The reason is that dynamic recovery is the main softening mechanism in Al-Zn-Mg-Cu alloys during hot forming [6] due to the pinning effect of precipitates on dislocation movement and subgrain boundary migration [7].

To date, an electropulsing treatment (EPT) process has been applied to enhance the properties of metals [8]. Lots of researchers have studied the thermal and athermal effect of pulsed current on different materials. Noell et al found that electropulsing can be used to modify the microstructures of additive manufacturing metals such as 316l stainless steel and AlSi10Mg [9]. Babutskyi et al studied the effects of electropulsing on the fatigue resistance of 2014-T6 aluminum alloy by means of scanning electron microscopy and transmission electron microscopy experiment [10]. In terms of coupled electropulsing energy simulations, Ren et al [11] used ANSYS to simulate the microcrack healing process of TC4 under the effect of the pulsed electric field. Pan et al [12] used COMSOL Multiphysics finite element analysis software to study the macroscopic temperature and stress distribution of steel under the effect of EPT. Numerous studies reveal the role of electric pulses on dynamic recrystallization. Ao et al [13] reported that the anisotropic microstructure of the Ti-6Al-4V sheet along different directions tended to be uniform due to the occurrence of DRX under electropulsing. Sánchez et al [14] believed that the electropulsing accompanying plastic deformation enhances the recrystallization in inox 308L in contrast with the other thermal treatments. Han et al [15] mentioned that the occurrence of DRX in Ni-based superalloy is mainly attributed to efficient energy transfer under EPT. Rabadia et al [16] conducted an electropulsing uniaxial tensile test on ZA22 alloy at room temperature and found that the athermal effect could increase the tensile elongation by 437%. These studies indicate that electric pulse can promote the generation of DRX and increase elongation. The above studies cannot dynamically reveal the action process of electropulsing on DRX and lack an in-depth understanding of the EPT mechanism. It is necessary to establish a microstructure evolution model to reveal the law and mechanism of DRX under electric pulse.

Recently, cellular automata (CA) have been drastically used in the simulation of DRX. Goetz et al [17] built a method based on CA that has been successfully used to simulate DRX in single-phase alloys. Ding et al [18] studied the DRX behavior of an oxygen-free high conductivity copper through the CA method. It was found that the fraction of DRX was not only related to the Zener-Hollomon parameter, but also affected by nucleation rate and initial microstructure. Lei et al [19] developed a CA model of continuous DRX in Al 2219 alloy thermal processing based on the previous work to predict the evolution of the substructure. Babu et al [20] introduced a new temperature-strain rate-dependent mobility parameter of the super austenitic stainless steel and developed a modified CA model. Since the CA method fully considers the actual deformation conditions and has the advantages of high computational efficiency and wide application range [21], it is a good method to simulate the DRX process of materials under electric pulse. However, it is challenging to couple the electro-thermal-mechanical multi-field effects into the dynamic model of grain nucleation and growth quantitatively. So far, there are few reports on the CA model of DRX in the process of electropulsing.

A two-dimensional CA model in the present work was established by coupling a pulsed electric field, additional driving forces generated by electric pulses with the grain nucleation, and growth models. Based on the established CA model, the grain morphology, DRX fraction, average grain diameter, and grain size distribution of Al-Zn-Mg-Cu alloy at different current densities and electric pulse periods were investigated. The optimal electrical parameters are predicted by the CA model, which can effectively improve the DRX behavior and material plasticity.

### 2. Materials and experimental procedure

#### 2.1. Materials

The material used in this study is a commercial Al–Zn–Mg–Cu alloy in T6 condition with a thickness of 1.5mm supplied by the Aluminum Corporation of China Limited. The chemical composition is shown in table 1. The isothermal uniaxial tensile tests in our previous work [22] have been carried out to determine the material parameters in the CA model.

| Composition | Zn | Mg | Cu | Fe | Mn | Si | Cr | Ti | Al |
|-------------|----|----|----|----|----|----|----|----|----|
| Wt%         | 5.28 | 2.66 | 1.52 | 0.35 | 0.092 | 0.07 | 0.22 | 0.029 | Bal |

Table 1. Chemical composition of the studied Al–Zn–Mg–Cu alloy.
2.2. Electroshock assisted uniaxial tensile test

The electroshock assisted uniaxial tensile test platform was set up on a CMT5205–5305 electronic universal testing machine, which was connected to a personal computer (PC) with data acquisition (DAQ). A special specimen, as shown in figure 1, was designed to facilitate clamping. The pulsed power supply used in the test was produced by a self-developed electric pulse generator. The improved tensile sample and the insulator were installed on the universal testing machine by the grips, and the extended part of the sample is connected with the copper electrode by bolts. A self-developed electric pulse generator synchronously applies ultra-low frequency electric pulse load when the universal tensile testing machine starts to apply tensile load on the specimens. The uniaxial tensile tests of different current densities and pulse periods were carried out in this work. The reliability of the established CA model will be verified based on the test results. Three groups of experiments were conducted as shown in table 2. The strain rate of each experiment is 0.1 s\(^{-1}\). The temperature distribution of the specimens during the electroshock assisted uniaxial tensile tests were measured using a thermal camera (Fotric 226) during the test. The experimental procedure is shown in figure 2(a). It should be noted that the so-called electroshock treatment (EST) has characteristics of ultra-low frequency unidirectional positive pulse and very limited energy density (figure 2(b)), to minimize the temperature rise and effectively weaken the thermal effect by the current impact.

Finally, under the same specimen shape and mechanical parameters, we carried out the non-electric uniaxial tensile test and the electroshock assisted uniaxial tensile test under the optimal parameters (current density of 30A·mm\(^{-2}\), pulse period of 5 s).

![Figure 1. Size of the sample (mm).](image1)

![Figure 2. (a) Experimental procedure of electroshock treatment test, (b) Electric pulse square wave.](image2)

| Experiment | Pulse current (A·mm\(^{-2}\)) | Pulse period (s) |
|------------|-----------------|----------------|
| Group A    | 30              | 3              |
| Group B    | 40              | 3              |
| Group C    | 40              | 5              |

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2.3. Electron back scatter diffraction (EBSD) observations
The deformed samples were sliced in a direction parallel to the tensile axis. After inlaying, specimens were
cosarily ground with 220, 500, and 1200 sandpaper, respectively, and then mechanically polished with 9 μm,
3 μm, and 1 μm diamond polisher, and finally polished with 0.05 μm SiO₂ suspension by oxide polishing
suspension. The microstructure morphology observation was carried out on a Quanta FEG 450 scanning
electron microscopy operated at 20 kV.

2.4. Transmission electron microscope (TEM) observations
The samples for TEM observation were prepared by focused ion beam milling (Helios Nanolab G3 UC, Thermo
Fisher, USA). The TEM observation was performed in a Talos F200S STEM.

3. Establishing the CA model
Figure 3 is the flowchart of CA simulation for the DRX process. A representative area of 900 × 900 μm²
composed of 900 × 900 cells was used. The CA model is divided into 4 modules based on the Matlab platform,
namely the initiation module, the nucleation module, the grain growth module, and the output module. After
inputting the initial data into the initiation module, the initial grain morphology is generated. Subsequently,
with the increase of strain variables, each cell state variable was calculated and updated synchronously. Then
judge whether the crystal grains nucleate and grow according to the formulas described in the following sections.
Finally, output from the simulation results. The initial microstructure was generated by a conventional isotropic
grain growth algorithm. The modeling process is described in the following sections.

3.1. Dislocation density evolution
During the deformation process, a massive variety of dislocations appeared. DRX occurs when the dislocation
density exceeds a critical value. Meanwhile, dislocation density is the main basis for measuring the energy storage
of grain deformation, which determines the formation of recrystallization nuclei. To reveal the dislocation
evolution behavior of Al-Zn-Mg-Cu alloy during deformation, the Kocks-Mecking model [24] is used as follows:

\[
\frac{d\rho_{ij}}{d\varepsilon} = k_1 \sqrt{\rho_{ij}} - k_2 \rho_{ij}
\]

(1)

in which, \(\rho_{ij}\) represents the dislocation density at the position \((i, j)\), \(\varepsilon\) is the real stress, and \(k_1\) and \(k_2\) respectively
stand for the dislocation generation and annihilation. The following equations can be obtained from
equation (1):

\[
\rho_{ij} = \left( \frac{K_1}{K_2} - \frac{K_1}{K_2} e^{-\frac{K_0}{\varepsilon}} + \sqrt{\rho_0 e^{-\frac{K_0}{\varepsilon}}} \right)^2
\]

(2)

here, \(\rho_0\) is the initial dislocation density when \(\varepsilon = 0\).
The dislocation density and flow stress can be calculated quantitatively using equations as [24, 25]:

\[
\bar{\rho} = \frac{1}{N_{total}} \sum_{i,j} \rho_{i,j}
\]

(3)

\[
\sigma = a \mu b \sqrt{\bar{\rho}}
\]

(4)

where \( \bar{\rho} \) is the average dislocation density; \( a, \mu \) and \( b \) are the correlation constant, shear modulus and Burger’s vector, respectively; \( N_{total} \) is the total number of cells.

3.2. Nucleation of DRX

During deformation, sub-grains developed within grain mainly are often considered as the result of continuous dynamic recrystallization, while new grains nucleated at the grain boundaries with distinctive nucleation and growth stages are often considered as the result of discontinuous dynamic recrystallization [26]. The recrystallized grains of Al-Zn-Mg-Cu alloys were formed at the grain boundaries, implying that discontinuous dynamic recrystallization was the main nucleation mechanism during the low-frequency electroshock assisted tension process.

Generally, the driving force \( P \) can be introduced in the DRX process:

\[
P = \frac{1}{2} \mu b^2 \Delta \rho - \frac{2\gamma}{r}
\]

(5)

where \( \Delta \rho \) is the dislocation density increment, \( \gamma \) stands for the grain boundary energy, and \( r \) represents the DRX grain radius.

An additional recrystallization driving force \( \Delta P \) can be generated from the thermal and athermal effects during the EST process [27]:

\[
\Delta P = P_{th} + P_{ath}
\]

(6)

where \( P_{th} \) is the micro-zone thermal stress induced by electric current, which can be expressed as:

\[
P_{th} = \frac{\delta \Delta S \text{grad} T}{\varphi}
\]

(7)

in which, \( \Delta S \) is the entropy difference between the grain boundary and the substrate (approximately equal to the melting entropy); \( \delta, \text{grad} T, \) and \( \varphi \) are the thickness of grain boundary, temperature gradient, and atomic volume, respectively.

\( P_{ath} \), an electronic wind force, can be expressed as:

\[
P_{ath} = (\rho_D/\rho_{ij})en_je
\]

(8)

where \( \rho_D/\rho_{ij} \) is the specific resistivity, \( e \) presents the electron charge, \( n_e \) and \( j \) are respectively expressed as the electron density and current density.

Under the influence of electroshock, the recrystallization driving force is:

\[
P_{EP} = P + \Delta P = P + P_{th} + P_{ath}
\]

(9)

In the process of nucleation, the total free energy decreases as the nucleus grows. There always exists a critical nucleus \( R_c \) when the size of the pre-existing nucleus is larger than that of \( R_c \), the nucleus can be nucleated and recrystallized; when it is smaller than \( R_c \), the nucleus will be annexed by large grains. In general, the critical nucleus \( R_c \) can be expressed as:

\[
R_c = 2\gamma/P_{EP}
\]

(10)

During the EST, the electric pulse promotes grain boundary migration and decreases the critical nucleation size, thus increasing the nucleation rate. The critical nucleus \( R_{EP} \) can be expressed as:

\[
R_{EP} = 2\gamma/P_{EP} = 2\gamma/(P + \Delta P)
\]

(11)

As a result, the nucleation rate \( \dot{N} \) caused by grain boundary migration is:

\[
\dot{N} = \frac{dN}{dt} = 1.5KM\tau (1/R_{EP} - 1/R_e)
\]

(12)

where \( R_e \) is the preexisting sub-grain size, \( \tau \) is the energy per unit of dislocation line, and \( K \) is a constant.

3.3. Growth of the recrystallized grain

The growth of new grains consumes the energy accumulated by dislocation density, so the dislocation density decreases compared with the previous stage. It is believed that the thermal and athermal effects caused by electrical pulse promote the migration of grain boundaries. \( V \) is the migration rate of grain boundary which is expressed as:
where grain boundary mobility $m$ is a function of temperature and the disorientation as follows [28]:

$$m = \frac{bbD_{ob}}{kT} \exp \left( -\frac{Q_b}{RT} \right)$$

where $D_{ob}$ is the boundary self-diffusion coefficient at 0 K, $k$ and $Q_b$ respectively present the Boltzmann constant and the activation energy of grain boundary; $R$ is the gas universal constant.

The change in the current pulse parameter determines the change in the driving force increment $\Delta P$. The total recrystallization driving force increases as the pulsed current applies to the specimen, while the migration rate of grain boundary increases.

### 3.4. Identification of CA model parameters

The true stress–strain relationship is a macroscopic representation of the microstructure evolution and mechanical properties during material deformation. Figure 4 shows the true stress–strain relationship of Al-Zn-Mg-Cu alloy obtained by thermal tensile experiments under the temperatures of 300 °C–450 °C and strain rates of 0.01–10 s$^{-1}$, and the detailed information can be found in our previous work [22].

During thermal tensile deformation, the increase of dislocation density causes work hardening at the beginning of plastic deformation, resulting in a sharp increase of flow stress [29]. As the deformation goes on, work hardening is offset by softening caused by dynamic recovery. When the effect of work hardening is greater than that of dynamic softening, the flow stress continues to increase at a decreasing rate. When the deformation temperature is low, the dynamic softening and work hardening reach a balance, resulting in constant flow stress [30]. Finally, the microcracks appear inside the specimen as the strain continues to increase, the stress decreases rapidly, and finally localized necking occurs until fracture.

It can be seen from Figure 4 that the flow stress is lower at lower strain rate or higher temperature. As the deformation temperature increases, the thermal activation increases resulting in a decrease in the stress required for deformation [7]. In addition, the increase of temperature can promote dislocation motion and reduce the resistance of dislocation motion, thereby reducing flow stress. The reduction of the strain rate on the one hand provides a longer time for deformation, and on the other hand leads to a decrease in the dislocation growth rate,
which reduces the entanglement of dislocations and facilitates the further movement of dislocations. Therefore, reducing the strain rate or increasing the deformation temperature is beneficial to reduce the stress required for dislocation motion, resulting in lower flow stress.

Arrhenius model has the characteristics of a simple structure and easy determination of material constants, which are quite important for the determination of parameters in the CA model. In this paper, the expressions of deformation temperature versus rheological stress are constructed by the Arrhenius model, and the hyperbolic sine equation is as follows.

\[
\dot{\varepsilon} = A \sinh(\alpha \sigma)^n \exp\left(\frac{Q_{\text{act}}}{RT}\right)
\]

where \(A\), \(\alpha\), and \(n\) are material constants; \(\sigma\) is the flow stress, \(Q_{\text{act}}\) is DRX activation energy, \(\dot{\varepsilon}\) and \(T\) respectively present the strain rate and the absolute temperature.

In addition, the Zener-Hollomon (\(Z\) parameter) represents the influence of temperature and strain rate on rheological behavior, as shown in equation (16) [31].

\[
Z = \varepsilon \exp\left(\frac{Q_{\text{act}}}{RT}\right) = A \sinh(\alpha \sigma)^n
\]

Taking the natural logarithm of equation (16), we can know that \(\alpha\) can be expressed as

\[
\left(\frac{\partial \ln \varepsilon}{\partial \ln \sigma}\right) = \left(\frac{\partial \ln \sinh(\alpha \sigma)}{\partial \frac{1}{T}}\right)^{-1}
\]

The value of \(\alpha\) can be obtained by dividing the average slopes in figures 5(a) and (b). Similarly, \(n\) can be denoted as \(\frac{\partial \ln \varepsilon}{\partial \ln \sinh(\alpha \sigma)}\), obtained from the average slope of figure 5(c). \(Q_{\text{act}}\) can be expressed as \(Rn\frac{\partial \ln \sinh(\alpha \sigma)}{\partial(1/T)}\), and the value of \(Q_{\text{act}}\) can be calculated from the product of the average slope in figure 5(d) and \(Rn\).

After the calculation according to figure 5, the value of \(\alpha\), \(n\), and \(Q_{\text{act}}\) can be obtained as \(9.189 \times 10^{-3}\) MPa, 5.549, and 137.558 kJ mol\(^{-1}\), respectively. In this paper, the value of Al-Zn-Mg-Cu during EST is assumed to be consistent with that of the thermal tensile test. Substituting the obtained value into equation (16), \(Z\) can be expressed as:

\[\text{Figure 5. (a) Relationship between } \ln \dot{\varepsilon} \text{ and } \sigma, (b) \text{ Relationship between } \ln \dot{\varepsilon} \text{ and } \ln \sigma, (c) \text{ Relationship between } \ln \dot{\varepsilon} \text{ and } \ln \sinh(\alpha \sigma), (d) \text{ Relationship between } \ln \sinh(\alpha \sigma) \text{ and } 1000/T.\]
Taking the natural logarithm of both sides of equation (16):

\[ \ln(Z) = \ln(A) + n \ln[\sinh(\alpha \sigma)] \]  

Then, the \( \ln Z \sim \ln [\sinh(\alpha \sigma)] \) relationship can be obtained as shown in figure 6. The closer the value of goodness of fit is to 1, the better the fit of the regression line to the observed value. The goodness of fit \( r = 0.993 \) in figure 6 shows that the \( Z \) parameter can be used to describe the rheological behavior of Al-Zn-Mg-Cu alloy during high-temperature tensile deformation and intercept \( \ln A = 23.459 \).

The basic material parameters used in the CA simulation are listed in table 3.

4. Results and discussion

4.1. Verification of the accuracy of the CA model

To verify the reliability of the established CA model, the initial microstructure of Al-Zn-Mg-Cu alloy was simulated and compared with the EBSD experimental results. Figure 7 illustrates the simulated and experimental initial microstructure. It can be found that both the grain morphology and grain size distribution are similar. Besides, the average grain size of the simulated results is 21.68 \( \mu m \), and that of the EBSD test is 22.02 \( \mu m \), and the relative error is 1.57\% demonstrating good reliability.

Figure 8 shows the temperature changes in the center of the specimen during the experiment. Since each pulse interval is not enough to cool the specimen temperature completely, there is an accumulation of heat, resulting in the highest internal temperature of the specimen at the last pulse.

It can be seen from figure 8 that the temperature of the deformation region of the specimen is almost uniform at the moment of electroshock. From this, it can be inferred that the electric current is uniformly distributed on the tensile specimen during the electroshock assisted tensile process. The maximum temperature of Group A is 64.1 °C and that of Group C is 85.6 °C. Group B has the highest temperature, 122.2 °C, which is still lower than the recrystallization temperature of thermal deformation (about 200 °C). Due to the long action time of the electrical pulse, the temperature of the specimen shows a sharp increase when the pulse is applied.
In the pulse interval, the temperature gradually decreases due to heat dissipation. The average temperature rise of the material under the electric pulse can be calculated according to the following equation:

$$\Delta T = (c \rho_m s^2)^{-1} \int_0^{t_d} \gamma_R I^2 dt = j^2 \gamma_R t_d (c \rho_m)^{-1}$$

where $c$ is the specific heat capacity, $c = 960 \text{ J/(kg·°C)}$; $\rho_m$ is the material density, $\rho_m = 2.81 \times 10^3 \text{ kg/m}^3$; $\gamma_R$ is the resistivity, $\gamma_R = 5.15 \times 10^{-8} \Omega \cdot \text{m}$ [33]; $j$ is the current density; $t_d$ is the pulse action time, $t_d = 1 \text{ s}$.

Based on equation (19), the calculated maximum temperatures of the three groups are 70.45 °C, 122.18 °C, and 73.31 °C, which are basically consistent with the monitored results.

Figure 9 shows the simulated and experimental results of recrystallized grains for the three groups of tests.

The colored grains are recrystallized grains and the white grains are the matrix in the simulated results as shown in Figure 9.
in figures 9(a)–(c). Under each group of electroshock parameters, the grain morphology results obtained by the simulation and experiment are very similar. The small-sized recrystallized grains are almost all distributed at the grain boundaries, which proves that the recrystallization nucleation mechanism of Al-Zn-Mg-Cu alloy mentioned above is discontinuous dynamic recrystallization. The experimental results show that the grain morphology changes greatly under different electric shock parameters, and the simulation results also capture these changes well. The average grain size and standard error of simulated \((d_s)\) and experimental \((d_e)\) results in the three sets of tests are listed in table 4. It can be found that the standard error of simulated and experimental results for all three groups is within \(\pm 4.56\%\), which means that the predictability of the established model is excellent when compared with the experimental results. Thus, the developed model is able to describe the DRX behavior of the alloy during the EST process, and the effects of current density and electroshock period on DRX fraction and grain size will be discussed in the following sections based on the simulation results.

4.1.1. Effects of the current density on DRX behavior

Grain morphologies of six different current densities were obtained using the established CA model to study the effect of current density on DRX.

Figure 10 shows the simulated microstructure at the current density from 10–60 \(\text{A} \cdot \text{mm}^{-2}\) for a constant pulse period of 5 s, in which the white zone represents the original grains and the colored zone represents the DRX.

The data obtained from figure 10 are shown in figure 11, which reveals the effect of current density on DRX fraction, average grain diameters, and grain size distribution. In the raincloud plot of figure 11(b), at a certain current density and grain diameter, each point represents 1% of the total number of grains. The colored area represents the distribution of the grain diameter. The boxplots composed of black straight lines have the function of identifying outliers. Each boxplot mainly contains 5 data nodes, from top to bottom are the upper
edge, the upper quartile \((Q_3)\), the median, the lower quartile \((Q_1)\), and the lower edge. The upper and lower ends of the rectangular box correspond to \(Q_3\) and \(Q_1\) respectively, and the line segment inside the rectangular box is the median. The upper edge value and the lower edge value are \(Q_3 + 1.5 \times (Q_3 - Q_1)\) and \(Q_1 - 1.5 \times (Q_3 - Q_1)\) respectively, they are connected with a straight line to the upper and lower ends of the box. The data outside the marginal value are all outliers. We can judge whether the grain diameters are concentrated or scattered by comparing the boxplots.

As shown in figure 11(a), the DRX fraction first increases and then decreases with the increase of current density, while the average grain diameters show the opposite trend. The significant increase in DRX is due to the two effects of EST: the accumulation effect induced by the electron wind force and the annihilation effect induced by the coupling of the thermal and electromigration effects \([34]\). Appropriate EST provides the driving force for recrystallization nucleation and growth. Therefore, we can see that the results applied EST have more small-size grain aggregation and more large-size grains than the normal one in figure 11(b). When the current density increases to 30 A·mm\(^{-2}\), on the one hand, the violent collision between the fast-moving electrons and

![Figure 10. Simulated microstructure of DRX using CA model at different current densities: (a) 10 A·mm\(^{-2}\), (b) 20 A·mm\(^{-2}\), (c) 30 A·mm\(^{-2}\), (d) 40 A·mm\(^{-2}\), (e) 50 A·mm\(^{-2}\), (f) 60 A·mm\(^{-2}\). (Pulse period: 5 s.)](image)

![Figure 11. Effect of current density on (a) DRX fraction and average grain diameters, (b) grain size distribution.](image)
the atoms inside the material generates Joule heat, which increases the mobility of atoms. On the other hand, the directional movement of free electrons increases the mobility and recovery rate of dislocations, thereby improving nucleation for recrystallization [35]. Since the large-area recrystallization covers the original large-sized grains, the grain distribution is fine and uniform. The DRX fraction rises sharply to the maximum value of 45.79%, the average grain diameter is only 14.78 μm and there are many small equiaxed grains in the microstructure, as shown in figure 10(c) and figure 11. When the current density is too high, the recrystallization nucleation rate increases according to equation (12) while the growth rate of recrystallization decreased with the increase of current density. This is mainly because EST promotes the disappearance of some intracrystalline dislocations, reduces the deformation storage energy resulting in the decrease of recrystallization growth rate [36]. At the same time, the larger joule heat can be generated under the continuous action of a larger current density. When thermal effects dominate, DRV behavior can be preserved and DRX behavior can be effectively suppressed owing to the pinning effect of precipitates on the motion of dislocation and migration of sub-grain boundaries [22]. Therefore, higher current density makes the original grains larger and recrystallization smaller, resulting in a lower DRX fraction and higher average grain diameters. It can be concluded that the electrical effect and thermal effect play the best role in adjusting the microstructure.

4.1.2. Effects of the pulse period on DRX
In order to reveal the effect of electrical pulse periods on DRX. The CA model was utilized to simulate the microstructure under different pulse periods when the current density is 30 A·mm⁻² based on the results in 4.2. The electrical pulse periods are 3 s, 4 s, 5 s, 6 s, 7 s, and 8 s, respectively. As shown in figure 12, when the pulse period is 5 s, the grain size distribution is fine and uniform, and the optimal microstructure can be obtained. The DRX fraction, average grain diameters, and grain size distribution in figure 12 were statistically calculated, as shown in figure 13. It can be seen from figure 13(a) that the DRX fraction first increases and then decreases with the increase of the pulse period, resulting in the opposite trend of average grain diameters. When the pulse period is less than 5 s, the grain size distribution is similar to that of high current density in 4.2 as shown in figure 13(b). This is because when the number of electroshocks is large, the electrical effect reduces the recrystallization growth rate. At the same time, the electric effect and accumulated thermal effect also coarsen...
The increase of the pulse period means that the number of electroshocks decreases in the deformation process, and the excess heat can dissipate in the pulse gap. We can see from figure 12(c) and figure 13 that when the pulse period is 5 s, the DRX content is the highest and the grain size is concentrated in small areas, the mechanism of electrical effect and thermal effect is the same as 4.2. When the pulse period is longer, the electrical effect and thermal effect can only make a small amount of recrystallization nucleation and growth, the DRX fraction decrease and the recrystallization size is small. These energies act more on the original grain growth, resulting in more abnormally large grains.

4.1.3. Discussion on optimal parameters

Through the simulation results described above, a current density of 30 A·mm⁻² and a pulse period of 5 s are the optimal parameters. We conducted an EBSD experiment to compare the results with the simulation results as is shown in figure 14. The average grain diameter obtained by the experiment is 15.55 μm, and the relative error with the simulation result is 5.21%, which shows that the simulation results are accurate.

Based on the optimal electroshock parameters obtained by simulation, we carried out unidirectional tensile comparative tests of different parameters. The true stress-strain curve of each group is shown in figure 15. We can see that in the process of electroshock assisted tensile tests, different from the true stress-strain curve of the non-current tensile test, the true stress-strain curve of the sample under the action of electroshock is ratchet-shaped as a whole. This phenomenon of stress reduction under electroshock is directly related to the temperature of the sample [38]. During the pulse interval, the stress increases gradually, and the material enters the yield and strengthening stage, showing obvious work hardening. Therefore, with the continuous
development of electroshock assisted tensile tests, the true stress-strain curve is composed of multiple ‘stress drop-stress recovery’ cycles.

In figure 15 we find that the flow stress of electroshock specimens is lower than that of the non-current tensile specimen, which mirrored the effect of softening produced by the electroshock. However, when the current density is 40 A mm$^{-2}$, the DRX fraction is low. Grains are not completely refined, only a small amount of DRX occurred in the severe deformation zone. There is still a large amount of stored energy caused by deformation inside the material [39]. This is the reason why Groups B and C have lower elongation and higher tensile strength than the specimen prepared by the optimal parameter.

When the strain rate is 0.1 s$^{-1}$, the elongation of normal stretching is 10.95% while the energized tensile sample of optimal parameters is 13.33%, which is increased by 21.74%. The elongation of groups A, B, and C are 10.57%, 10.07%, and 10.67% respectively, which is lower than that of normal stretching. This is due to the uneven grain morphology caused by the small recrystallization size, which reduces the elongation of the material. It can be concluded that finding the optimal parameters of electroshock assisted deformation through simulation can effectively optimize the grain morphology and improve the plasticity of materials.

Samples were taken from uniaxial tensile specimens treated with EST by the optimal parameter (30A·mm$^{-2}$, 5 s) and without EST. The TEM observations were performed along the [110]$_{Al}$ zone axis, as shown in figure 16. Meantime, the selected-area diffraction patterns (SADP) of precipitates have been obtained, and one of which (framed by red dotted rectangle) is depicted in figure 16(c). It demonstrates that the precipitates are mainly η$'$ phase. Compared with figure 16(a), the average diameter of precipitates of the specimen with optimal parameter in figure 16(b) was reduced from 16.67 nm to 6.58 nm compared to the specimen without electroshock. This may be caused mainly by the athermal effects of electroshock. Athermal effects can promote the diffusion of
atoms and the dissolution of the $\eta'$ phase, owing to the fact that electroshock can reduce the activation energy of atoms for diffusion and increase their mobility [40]. Therefore, the electroshock specimens contain fewer and smaller $\eta'$ phase. The precipitation hardening behavior of electroshock specimens contributes less to the strength. Therefore, it can be seen from figure 15 that the true stress-strain curve enters the yield stage earlier and has a lower tensile strength.

5. Conclusions

(1) A two-dimensional CA model coupling with the pulsed electric field was newly established on the Matlab platform and the additional driving force generated by the electric pulse is added to the grain nucleation and growth models. The grain morphology and average grain size are verified by EBSD tests. It is demonstrated that the established CA model can accurately predict the DRX behavior during EST assisted tensile test.

(2) With the increase of current density and pulse period, the area fraction of DRX increases and then decreases, causing the average grain diameter to first decrease and then increase under the effect of the synergy of electricity, heat, and force. Appropriate electro-thermal-mechanical effect can promote the production of DRX, while excessive energy can inhibit the DRX behavior of Al-Zn-Mg-Cu alloy.

(3) Current density of 30 A·mm$^{-2}$ and electrical pulse period of 5 s are the optimal electroshock parameters, at which the DRX fraction can reach 45.79% with an average fine-grain diameter of 14.78 $\mu$m. Besides, experimental results show that the elongation of Al-Zn-Mg-Cu alloy increases by 21.74% from 10.95% to 13.33% due to the effect of DRX under the optimal parameters.

Theoretical calculations and CA model studies on electroshock-induced dynamic recrystallization are still in the initial stage. It is suggested to build the CA models coupled with athermal effects to accurately simulate the microstructure evolution of grains and their boundaries, and also establish the relationship between microstructure and macroscopic mechanical properties.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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