Improvement of formability and corrosion resistance of AZ31 magnesium alloy by pulsed current–assisted laser shock forming

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Abstract
This study adopted a novel pulse current–assisted laser shock AZ31B sheet micro-forming method (EP-LSF). The mechanism of improving the formability of AZ31B magnesium alloy by pulse current–assisted laser shock forming and the reason of improving the corrosion resistance were studied for the first time. Through laser shock–free bulging experiment, tensile test, optical microscope (OM), and X-ray diffraction, the change in formability was studied. After pulse current assisted–laser shock forming, the forming height of AZ31B magnesium alloy increases by 28.8%, the thinning gradient decreases by 6.7%, and the strain rate–sensitivity coefficient increases to 0.1452. The results show that the decrease of grain size and texture density is the reason why EP-LSF can further improve the formability of AZ31B magnesium alloy. The changes in corrosion resistance were studied by scanning electron microscopy and electrochemical tests. The results show that after EP-LSF, the corrosion current density of AZ31 magnesium alloy decreased, and the electrochemical impedance increased, indicating that this method further improved the corrosion resistance.

Keywords Formability · Corrosion · Pulse current · Laser shock forming

1 Introduction
In recent years, lightweight and miniaturized parts have become an unstoppable global trend in many industrial fields and have been widely used in biomedicine, electronic appliances, aerospace, and other fields. Magnesium alloys meet the requirements of lightweight materials due to their low density, high-specific strength and rigidity, excellent machining performance, and good damping and shock absorption properties [1, 2]. On the one hand, due to the dense hexagonal lattice structure of magnesium alloy, its plasticity is poor [3, 4]. On the other hand, the corrosion resistance of magnesium alloys is poor [5, 6], thereby limiting their application in micro-parts. Therefore, a high-efficiency micro-plastic forming technology that can improve the plasticity and corrosion resistance of magnesium alloys must be adopted.

Laser shock micro-forming (LSF) technology is a new technology that has developed rapidly in recent years. This technology has been widely used in research fields, such as material forming, because it does not require the production of high-precision micro-punch molds [7], reduces size effects [8], and improves the material forming performance [9]. At present, more laser shock forming studies have been conducted on copper, stainless steel, and other materials [7–9] than on lightweight materials, such as magnesium alloys, and the forming ability of materials with poor plasticity (e.g., magnesium, aluminum, and titanium alloys) and complex micro-characteristics is still insufficient.

Recent studies have found that pulse current and high strain rate treatment are conducive to the improvement of formability and corrosion resistance of metal materials. Pulse current can improve the micro-formability of metal materials by refining grains, reducing dislocation density, and reducing texture density, and high strain rate can also
improve the formability of materials to a certain extent, which shows that under the loading mode of high strain rate such as laser shock, magnesium alloy pretreated by pulse current, its forming ability may be further improved. Liu et al. [10] observed the presence of electro-plasticity in AZ31 magnesium alloy through tensile tests and found that pulse current increased the elongation and reduced the flow stress of the sample. Tan and Tan [11] found that the dynamic recrystallization temperature of AZ31B magnesium alloy in conventional forming is 250 °C. Due to the joule heat effect of pulse current treatment, the temperature of magnesium alloy can be increased. Therefore, by setting reasonable pulse current parameters, the dynamic recrystallization temperature of magnesium alloy can be reached and the original grain can be refined, so as to improve the forming ability of the material.

Feng et al. [12] found through tensile test research that high strain rate can increase the elongation of magnesium alloy. Studies have shown that grain refinement can effectively improve the forming properties of materials [13]. Hui and Wang [14] used high-density electric pulses to treat as-cast Ti–Al alloys and found that electric pulse treatment is an effective method of refining the grains of titanium alloys. Xu et al. [15] found that high strain rate can refine the processed surface grain, indicating that electric pulse and high strain rate can improve the forming ability by refining the grain. The strength of the texture also affects the forming performance of materials. That is, the lower the texture density is, the better the forming ability of the material will be [16]. Jiang et al. [17] used X-ray diffraction (XRD) and electron backscatter diffraction to study the effect of electric pulse treatment on the texture evolution of AZ91 magnesium alloy and found that electric pulse treatment advantageously weakens the strength of the basic texture of the magnesium alloy. Tiwari et al. [18] used a split Hopkinson torsion bar (SHTB) to study the deformation behavior of aluminum-zinc-magnesium-copper alloys at high strain rates and found that the overall texture of the alloy weakened as the strain rate increased. This shows that electric pulse and high strain rate can reduce the texture density to improve the forming ability.

Liu et al. [19] processed magnesium-4Sm alloy using high-current pulsed electron beam, tested the corrosion of the sample through electrochemical test, and found that the corrosion current density decreased, the electrochemical impedance increased, and the corrosion resistance improved. M. Abeens [20] found that the sample grains treated by laser shot peening were refined, the grain boundary density increased, the crack propagation was delayed, and the corrosion rate was effectively reduced. Caralapatti and Narayanswamy [21] studied the effect of laser shock repetition rate on the corrosion resistance of magnesium alloys and found that the overlap percentage has a major impact on the corrosion rate. The corrosion rate decreases as the overlap increases, indicating that electrical pulses and high strain rates can improve the corrosion resistance of materials.

The generation of cracks not only affects the forming ability of materials but also accelerates the corrosion rate of materials [22]. Relevant studies show that high strain rate can significantly improve the inertia effect of materials, and the inertia effect helps reduce the crack growth rate in the plastic deformation process [23–25]. Van Aswegen and Polese [26] found that laser shock can effectively inhibit the fatigue crack propagation of a 2024 aluminum alloy sheet. This phenomenon shows that LSF can improve the corrosion resistance of materials by suppressing the crack propagation speed. Kumar and Paul [27] found that the fatigue crack healing of steel specimens can be achieved by applying pulsed current, indicating that pulsed current can improve the corrosion resistance of materials by promoting the healing of microscopic cracks in materials.

In this paper, combining the advantages of pulse current and LSF, a method based on pulse current–assisted laser shock AZ31 magnesium alloy foil micro-forming is proposed to solve the problems with magnesium alloy properties, namely, formability and corrosion resistance. By means of optical microscopy, X-ray diffraction, scanning electron microscopy, electrochemical testing, and other advanced analysis methods, the mechanism of pulse current–assisted laser shock to further improve the formability and corrosion resistance of AZ31 magnesium alloy was revealed from three aspects of grain size, texture density and dislocation density.

### 2 Experiments

#### 2.1 Materials

This study used AZ31 magnesium alloy. The chemical composition of the AZ31 magnesium alloy is listed in Table 1.

#### 2.2 Pulse current processing

The experiment used a CTNP1621-30/4000FN pulse current generator to pre-process the sample; the dimensions of the foil

| Table 1 Chemical composition (wt%) of AZ31 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Al | Zn | Mn | Fe | Si | Cu | Ni | Mg |
|---|---|---|---|---|---|---|---|
| 2.75 | 0.64 | 0.27 | 0.0023 | 0.018 | 0.0016 | 0.00055 | Balance |
for pulsed current processing are 200 mm × 30 mm × 0.1 mm. The experimental parameters of the pulse current generator in the experiment were as follows: voltage, 10 V; frequency, 50 Hz; and root mean square current, 25 A. The peak pulse current was set to 25, 30, and 35 A by changing the duty cycle value, and the pulse current duration was 60 s, which were denoted as EPT1 group, EPT2 group, and EPT3 group, respectively. Before applying pulse current, the surface of the sample was sprayed with Ira-15 boron nitride anti-oxidation coating to prevent the surface oxidation of the sample. The two ends of the sample were connected with a copper electrode after chromium plating treatment. In pulse current pretreatment, take five samples from each group, record the peak temperature with infrared thermometer in turn, and take the average value of the peak temperature measured by each group to ensure the accuracy of the experimental results. After the pretreatment, the boron nitride anti-oxidation coating on the surface of the sample was removed with absolute ethanol, and the remaining liquid and impurities on the surface of the sample were cleaned with pure water for the subsequent experiments. The pulse current parameters and corresponding peak temperature of each group of materials are shown in Table 2.

### 2.3 Micro-bulging experiment and surface strengthening experiment under laser shock loading

To test the micro-forming properties of the cold-rolled and pulse current–treated samples under high strain rate loading, A Spitlight 2000 Nd:YAG laser was used in the experiment. The maximum energy of the pulse laser was 1.4 J. The dimensions of the foil are 10 mm × 10 mm × 0.1 mm. The diameter of the spot was 2.5 mm. The experiment was divided into three groups: cold rolling, 25- and 30-A pulse current treatment, and then each group was impacted by 40% laser energy. In the experiment of laser shock–free bulging, five samples were taken from each group, and the forming height and thinning gradient of each sample were measured in turn. The measurement results of each group are averaged to ensure the accuracy of the experimental results. A KEYENCE VHX-1000C microscope was used to observe and characterize the forming height and thinning gradient.

### Table 2 The parameters of pulsed current treatment. (The CR, EPT1, and EPT2 groups were used for laser shock–free bulging experiment, and the EPT3 group was used for corrosion resistance experiment.)

| Sample | Voltage/V | Frequency/Hz | j1/A | j2/A | Time/s | Temperature/°C |
|--------|-----------|--------------|------|------|--------|---------------|
| CR     | n/a       | n/a          | n/a  | n/a  | n/a    | 25            |
| EPT1   | 10        | 50           | 25   | 25   | 60     | 150           |
| EPT2   | 10        | 50           | 25   | 30   | 60     | 250           |
| EPT3   | 10        | 50           | 25   | 35   | 60     | 370           |

2.4 Tensile tests

To investigate the effect of pulse current on the strain rate–sensitivity coefficient of magnesium alloy, a UTM4104 micro-computer-controlled electronic universal testing machine was used in the tensile experiment. Before the experiment, the preprocessed material is cut into the sample, as shown in Fig. 2 by electric spark cutting, according to ASTM E345. The equal strain rate stretching method was used to determine the strain rate–sensitivity coefficient, and five different levels of ram speeds were set, namely, 0.5, 1, 2, 5, and 10 mm/min, for stretching.

### 2.5 Micro-structure characterization

To investigate the micro-structure of magnesium alloys after EP-LSF, various characterization techniques were used. The size of the material used for characterization is 10 mm × 10 mm × 0.1 mm.

2.5.1 Grain size and thinning

To study the effect of EP-LSF on the grain size of AZ31 magnesium alloy, the samples were polished sequentially with 400# to 3000# sandpapers and mechanically polished with a 0.5-μm diamond polishing agent. The corrosion solution was made of 1 ml of nitric acid, 20 ml of acetic acid, 60 ml of ethylene glycol, and 19 ml of water. After corrosion, the sample was placed in water-free ethanol, cleaned using an ultrasonic cleaning machine for 300 s, and dried using an air cooler. Then, a DMI8A metallurgical microscope was used to observe the transverse sectional grain of the sample.
2.5.2 Macro texture

To study the effect of EP-LSF on texture density of AZ31 magnesium alloy, the texture distribution of AZ31 magnesium alloy was observed by RIGAKU X-ray diffractometer. The scanning angle ranged from 30–90°, the scanning rate was 5°/min, and the test direction is longitudinal.

2.5.3 Phase analysis

In the XRD test, BRUKER D8 ADVANCE X-ray diffractometer was used, the scanning angle ranged from 10 to 90°, the scanning rate was 5°/min, and the test direction is longitudinal. Then, phase analysis was performed on the magnesium alloy.
2.6 Corrosion resistance

2.6.1 Scanning electron microscopy

The treated sample was corroded in 3.5% NaCl solution for 1 h; the residual liquid on the sample surface was washed with pure water and dried, and then the corrosion morphology of the sample surface was observed with a S-3400 N scanning electron microscope; the test direction is longitudinal.

2.6.2 Electrochemical measurements

A Princeton versaStat 4 electrochemical work-station was used to determine the polarization curve and for electrochemical impedance spectroscopy (EIS). The specimen was welded with copper wire, and the non-working surface was sealed with epoxy resin. A three-electrode system was adopted; the auxiliary electrode was graphite electrode; the reference electrode was saturated calomel electrode; and the electrolyte was 3.5% NaCl solution. The experiment was performed at room temperature. The constant potential scanning method was used, and the scan rate was 5 mV/s. The standing time was 300 s, the measuring potential range was $-3 \text{ to } +2.5 \text{ V}$; the scanning speed was 1 mV/s; the termination potential was 0 V; and the electrochemical impedance test frequency range was $0.5 \text{ to } 10 \text{ kHz}$, and the test direction is longitudinal.

3 Results and discussion

3.1 Surface morphology

3.1.1 Forming height

Figure 3a shows the cold-rolled sample. Figure 3b, c show the 25- and 30-A pulse current–treatment samples, respectively. The measurement results of the forming heights in Sect. 2.3 of the experiment are shown in Fig. 4.

The average forming height of the cold-rolled state is 193.7 µm.; the average forming height is 238.42 µm, when 25-A current is applied; and the forming height is increased by 23.1%. The average forming height is 249.4 µm, when 30-A current is applied, showing an increase of 28.8%. The experimental results show that the forming height of the material increases significantly as the current density increases, indicating that EP-LSF can effectively improve the micro-forming ability of magnesium alloys.

3.1.2 Thinning gradient

The experiment was divided into two groups: the cold-rolled state and the 30-A pulse current treatment, which were impacted by 40% laser energy. After laser shock forming, the thickness in the forming area decreased, and the thickness reduction varied at different positions. The closer to the top of the forming area was, the greater the thinning gradient was. Therefore, seven positions were selected on the micro-characteristic section of the forming area to observe the change in thickness of the section. The test positions of the wall thickness of the forming area of the sample are shown in Fig. 4; the measurement result is the average of five samples, and the measurement results of the wall thickness of the forming area are shown in Fig. 5. The thinning gradient is calculated by Eq. (1):

$$\text{Thinining gradient} = \frac{H_i - H_f}{L}$$
where \( t_0 \) is the initial thickness of the sample, and \( t_i \) is the thickness at the measurement position on the section of the formed micro-feature.

The wall thickness of the cold-rolled material was 100 µm. Position 4 in Fig. 4 is the maximum thinning gradient of the sample. The maximum thinning gradient of the sample treated by pulse current–assisted laser shock treatment was 10.87%; the maximum thinning gradient of laser shock–treated sample was 23.61%; the average wall thickness of the LSF-treated sample was 86.7 µm; the average thinning gradient was 13.3%; and the average wall thickness of the EP-LSF-treated sample was 93.4 µm. The average thinning gradient was 6.6%. The results show that the thinning gradient of the samples treated by pulsed current–assisted laser shock treatment decreased significantly.

### 3.2 Strain rate–sensitivity coefficient

Tensile test is an effective method of testing the plasticity of materials. To study the effect of pulse current on the plasticity of materials, the tensile test was divided into two groups, namely, the cold-rolled state and 30-A pulse current treatment, and each group was set with five different levels of ram speed for stretching. At the same ram speed, the flow stress of the pulse current–treated samples was significantly lower than that of the untreated cold-rolled samples. In this study, the stress values at the displacements at 0.5, 0.75, 1, 1.25, and 1.5 mm were taken. The measurement results are shown in Fig. 6.

The test results are shown in Fig. 7. When the strain was 0.5 mm, the \( m \) of the pulse current–treatment sample increased from 0.1140 to 0.1188, and that of the pulse current–treated sample increased from 0.1228 to 0.1348, when the strain was 0.75 mm. When the strain was 1 mm, \( m \) increased from 0.1117 to 0.1452. The results show that pulse current treatment can effectively improve the strain rate–sensitivity coefficient of the material. Previous studies have shown that the stress concentration of the material can be effectively reduced by increasing the strain rate–sensitivity coefficient, and the tendency of material necking under high strain rate loading can be reduced [28]. This phenomenon indicates that the material is more favorable for loading at a high strain rate (LSF) than that of cold rolling.

Ren et al. [29] prepared magnesium alloy using the extrusion method, studied the effect of strain rate on the strain rate–sensitivity coefficient, and found that the strain rate–sensitivity coefficient increases with the strain rate,
proving that the strain rate–sensitivity coefficient of the AZ31 magnesium alloy pretreated by laser shock–pulse current can further improve the strain rate–sensitivity coefficient to improve the formability of the material.

The laser shock–free bulging experiment and strain rate–sensitivity coefficient test results reveal that EP-LSF can effectively improve the micro-forming properties of magnesium alloys. To better reveal the EP-LSF mechanism that improves the micro-forming properties of magnesium alloys, Sect. 3.3 presents the study from three aspects, namely, grain size morphology, texture density, and microstructure evolution.

3.3 Micro-structure characteristics

3.3.1 Grain size and morphology evolution

Grain size and morphology are closely related to the properties of materials and are two of the fundamental factors affecting the mechanical properties of mechanical materials. Therefore, studying the evolution of magnesium alloy grains during pulsed current-assisted laser shock is of great significance. The experiment in Sect. 2.2 shows that when the current parameter is 30 A and the sample temperature is approximately 250 °C, the sample can reach the required temperature for dynamic recrystallization [11].

Jiang et al. [17] carried out pulse current treatment on the cold-rolled AZ magnesium alloy. Through optical microscope study, it was found that there are a large number of deformation twins in the cold-rolled material, and the initial grains are mostly large-sized elongated grains with an average grain size of about 45 μm, as shown in Fig. 8a. EBSD is used to study the change of grain size and morphology of pulse current–treated materials, as shown in Fig. 8b: With the increase of current density, dynamic recrystallization took place in the materials, forming equiaxed fine grains with uniform distribution, the average size of which is about 6 μm. These results indicate that the pulse current treatment can promote the disappearance of twins in the material and effectively refine the grain, and the grain distribution is more uniform. Huang et al. [30] studied the micro-structure changes of cold-rolled AZ31 magnesium alloy at different temperatures, as shown in Fig. 9. It was found that there were a large number of deformation twins in the magnesium
alloy, but when the temperature increased to 250 °C, the grain of the material appeared obvious refinement, and the twins disappeared completely. The grain size of the material increases, indicating that when the temperature exceeds 250 °C, although dynamic recrystallization still exists in the magnesium alloy, the grain size of the material also grows with the increase of temperature, which is not conducive to the further improvement of the forming ability of the material.

In addition, according to the research of Pan et al. [31], when the laser acts on the surface of metal materials, the grain of the material is refined, as shown in Fig. 10. In the area directly affected by the laser, the grain refinement of the material is most obvious, and the original coarse grains have been completely refined into ultra-fine equiaxed grains. The average grain size is 0.76 μm when the laser depth is 0–100 μm, and 0.94 μm when the laser depth is 300–400 μm. This proves that the laser load can also play a role in the further refinement of magnesium alloy grain.

In conclusion, the cold-rolled magnesium alloy material has large grain size and deformation twins, which makes it difficult to coordinate the deformation behavior of adjacent grains, and thus reduces the forming ability of cold-rolled magnesium alloy. After pulse current treatment, the grain size of magnesium alloy is significantly reduced and equiaxed grains are formed, which makes the deformation behavior of adjacent grains better coordinate with each other, thus improving the forming ability of the material. When laser material surface, grain appeared a further refinement; compared with larger grain size, fine grain can accidentally make uniform distribution within the material to fill the big size of grain into the area, and thus further refine grain materials were improved significantly in the process of plastic deformation of grain flow ability, so as to further improve the forming ability of the material.

### 3.3.2 Texture evolution

The orientation distribution of texture has a significant influence on the mechanical properties of materials. Thus, the texture evolution of materials after pulsed current–assisted laser shock must be studied. Figure 11 shows the XRD patterns of AZ31 magnesium alloy after cold rolling and 30-A pulse current treatment. The α-Mg matrix and the β-Mg17Al12 phase are the main phases in the cold-rolled and pulse current–treated samples. Nearly no other elements can be found in magnesium alloys. The diffraction pattern indicates that the crystal face of the cold-rolled sample (0001) had the strongest peak value, which was obtained by the strong rolling of the plate, which made the magnesium alloy produce a strong matrix texture in the rolling direction. Compared with the cold-rolled sample, the diffraction peaks of the {0001} crystal plane of the sample treated by pulse current are obviously decreased; the {10–10}, {10–11}, and {10–12} crystal plane diffraction peaks decreased in varying degrees; and the {20–21} crystal plane diffraction peaks completely disappeared. However, the diffraction peak of the {10–13} crystal plane was enhanced, indicating that the
grain orientation of magnesium alloy changed after pulse current treatment.

To further study the effect of pulsed current–assisted laser shock on the texture of magnesium alloys, Fig. 12 presents the pole diagrams with the {0001} and {10–10} crystal planes as the projection base. Figure 12a shows the cold-rolled sample; the maximum pole density of the {0001} type texture is 23, and the maximum pole density of the {10–10} type texture is 3.4. Figure 12b shows the 30-A pulse current–treatment sample. The maximum pole density of the {0001} type texture is 15, and the maximum pole density of the {10–10} type texture is 2.9. Figure 12 shows that the pulse current treatment reduced the maximum pole density of the sample (0001) type texture from 23 to 15, and the maximum pole density of the {10–10} type texture from 3.4 to 2.9.

Magnesium alloy rolled sheets have strong (0001) basal surface texture due to rolling. The extremely dense (0001) type texture is not conducive to the activity of basal <a> slips and can easily cause bending, cracks, and even fracture the material. The results in Fig. 10 show that pulse current treatment can reduce the initial texture density of the magnesium alloy (0001) and {10–10} type textures, indicating that the pulse current treatment enhances the
activity of basal $<a>$ slips by reducing the texture density. The activities improve the anisotropy [32], thereby improving the micro-forming properties of AZ31 magnesium alloy.

### 3.3.3 Micro-structure evolution

The evolution of micro-structure also plays an important role in the formability of magnesium alloy. As the magnesium alloy foil is obtained by strong rolling, many dislocations accumulate in the material, resulting in high dislocation density in the cold-rolled sample, which seriously affects the micro-formability of magnesium alloy. Many existing methods can be used to characterize the dislocation density. Gay et al. [33] studied the dislocation density of the material through the XRD data of different metals and found that when the dislocations are distributed in order, the dislocation density can be expressed by the following Eq. (3):

$$\rho = \frac{\beta}{|b|t\sqrt{2\pi\ln2}}$$  \hspace{1cm} (2)

where $\rho$ is the dislocation density, $\beta$ is the half-maximum width, $b$ is the Burgers vector, and $t$ is the single cell size.

Later, on the basis of his research, Dunn and Kogh [34] found that when dislocations are randomly distributed, the relationship between dislocation density and full width at half maximum (FWHM) is as Eq. (4):

$$\rho = \frac{\beta^2}{2(\ln2)\pi b^2} \approx \frac{\beta^2}{4.35b^2}.$$  \hspace{1cm} (3)
Previous studies have shown that many inhomogeneous high-density dislocations are generated in magnesium alloy under the action of ultra-high strain rate–laser shock wave, and the dislocation arrangement has no directionality [35]. Therefore, the relationship between the dislocation densities of EP-LSF and FWHM can be characterized by Eq. (4). According to the XRD patterns of the cold-rolled and pulse current–treated samples measured in Fig. 11, the half width of cold-rolled samples is 0.211, while that of the 30-A pulse current–treated samples is 0.104. According to Eq. (4), the dislocation density of cold-rolled magnesium alloy is significantly higher than that of the sample treated by pulse current, proving that pulse current can significantly improve the diffusion ability of the material, promote the dislocation annihilation of cold-rolled magnesium alloy, and improve the formability of magnesium alloy.

3.4 Corrosion characteristics

3.4.1 SEM

Figure 13 shows the surface morphology of the cold-rolled sample, the 80% laser energy impact sample, the 35-A pulse current–treatment sample, and the 35-A pulse treatment sample after 80% laser energy impact in 3.5% NaCl solution corrosion. Figure 13a shows that a large area of the corrosion exfoliation layer and large and dense corrosion pits appear on the surface of the cold-rolled samples. The surface of the sample has many corrosion cracks, which intersect, and the width and length of the cracks are large. The surface of the sample is seriously corroded. Figure 13c shows that the magnesium alloy treated by pulse current has no large area of corrosion exfoliation layer and reduced area and number of corrosion pits and width and length of corrosion cracks. Figure 13b, d show a large corrosion free area on the laser impact sample; the corrosion pit area decreases significantly; the corrosion cracks and corrosion holes disappeared; and the corrosion behavior of the sample surface is obviously inhibited. Compared with pulsed current–assisted laser shock-treatment sample, the laser shock–treated samples had few large area corrosion pits and numerous uniform corrosion spots. The corrosion morphology in Fig. 13d shows that the magnesium alloy subjected to pulsed current–assisted laser shock has the strongest corrosion resistance.
3.4.2 Polarization curves and EIS analysis

The polarization curves of the cold-rolled, 35-A pulse current treatment, and 35-A pulse treatment of 80% laser energy shock samples are shown in Fig. 14. The cathodic polarization curve represents the hydrogen evolution at the cathode, and the anode polarization curve represents the dissolution of magnesium in the corrosive solution [36]. The corrosion potentials of cold-rolled samples, EP-treated samples and EP-LSF-treated samples were $-1.425 \, \text{V}$, $-1.288 \, \text{V}$, and $-0.724 \, \text{V}$, respectively, and the corrosion current density was 5.226 µA/cm$^2$, 2.95 µA/cm$^2$, and 1.93 µA/cm$^2$. Figure 15 shows the electrochemical impedance spectra of the cold-rolled, 35-A pulsed current treatment, and the 80% laser energy impact samples after the 35-A pulse treatment. Figure 15 shows that the radius of the capacity impedance loop and the electrochemical impedance value of the EP-LSF sample further increase, compared with the sample treated by pulse current, indicating that the EP-LSF treated sample has the best corrosion resistance [37].

Wang et al. [38] proposed that high dislocation and twin density reduce the electrochemical potential of magnesium alloy, and stacking dislocation and high residual stress increase the local corrosion around the twins and accelerate the corrosion rate of magnesium alloy. According to the
conclusion in Sect. 3.3.3 of this paper, pulse current treatment significantly reduces the dislocation density of magnesium alloy material, reduces the active region, and thus reduces the corrosion rate of magnesium alloy. Ralston et al. [39] proposed that the grain boundary density increases due to grain refinement, and the corrosion rate decreases with the grain size. Zhang et al. [40] found that the surface passivation rate of stainless steel can be effectively improved with an ultra-fine grain size. In Sect. 3.3.1, Figs. 8 and 10 show that after pulse current treatment, the initial coarse grains of magnesium alloy are transformed into uniform and fine equiaxed grains. With the laser loading on the material surface, the grains are further refined, and the number of grain boundaries in the material increases significantly. With the increase of grain boundary number, grain boundaries will be connected to each other into a network structure, and the energy consumption of corrosion expansion along grain boundaries will be more, which further restrains the expansion of corrosion cracks. These results indicate that EP-LSF improves the corrosion resistance of magnesium alloys by further refining the grains and increasing the surface passivation rate.

Combined with the corrosion morphology and polarization curve of the sample surface, the EIS data indicate that pulse current pretreatment can improve the corrosion resistance of magnesium alloys, and pulse current--assisted laser shock strengthening can further improve the resistance of materials.

3.5 Inertial effect

Figure 16 presents the corrosion principle diagram of AZ31 magnesium alloy in 3.5% NaCl solution. Figure 16a shows the EP-LSF-treated sample. Given the good forming quality of the sample, a dense grain refinement layer formed on the surface of the material, which can effectively reduce the corrosion rate. Figure 16b shows the LSF-treated sample. Given the poor forming ability of the cold-rolled magnesium alloy, the sample is prone to cracks during plastic deformation. Part of the α-Mg matrix was exposed to the corrosive solution, accelerating the corrosion of the material. This phenomenon indicates that EP-LSF can improve the formability and corrosion resistance of the material by delaying the crack growth during plastic deformation and promoting the healing of micro-cracks.

4 Conclusions

In this study, a new material forming method, namely, EP-LSF, was used to study its effect on the micro-formability and corrosion resistance of materials. The main results are summarized as follows:

1. Pulse current treatment significantly improves the strain rate--sensitivity coefficient of the material. When the displacement is 0.5 mm, the value of m is increased to 0.1188; when the displacement is 0.75 mm, the value of m is increased to 0.1348, and when the displacement is 1 mm, the value of m is increased to 0.1452.

2. After pulse current treatment, the original long grain of the material is refined into equiaxed grain. After laser
shock, the grain in the forming area of the material is further refined, which indicates that EP-LSF treatment improves the micro-formability of the material by further refining the grain.

3. Pulse current treatment reduces the texture density of the material; the maximum pole density of (0001) type texture is reduced to 15; and the maximum pole density of {10–10} type texture is reduced to 2.9. The reduction of the texture density of the material improves the micro-forming performance of the material during laser shock forming.

4. Pulse current can improve the corrosion resistance of cold-rolled magnesium alloy by reducing the dislocation density, and pulse current–assisted laser shock can further improve the corrosion resistance of magnesium alloy by refining the grain size.

5. Pulse current–assisted laser shock can improve the formability and corrosion resistance of the materials by delaying the crack growth during plastic deformation and promoting the healing of micro-cracks.

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Declarations

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Consent to participate Not applicable.

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References

1. Kleiner M, Geiger M, Klaus A (2003) Manufacturing of lightweight components by metal forming. CIRP Ann-Manuf Techn 52:521–542
2. Li XP, Tang GY, Kuang J, Li XH, Zhu J (2014) Effect of current frequency on the mechanical properties, microstructure and texture evolution in AZ31 magnesium alloy strips during electroplastic rolling. Mater Sci Eng A 612:406–413
3. Ulacia I, Salisbury CP, Hurtado I, Worwick MJ (2011) Tensile characterization and constitutive modeling of AZ31 magnesium alloy sheet over wide range of strain rates and temperatures. J Mater Process Tech 211:830–839
4. Ma Q, El Kadi H, Oppedal AL, Baird JC, Li B, Horstemeyer MF, Vogel SC (2012) Twinning effects in a rod-textured AM30 Magnesium alloy. Int J Plasticity 29:60–76
5. Zhou WQ, Shan DY, Han EH, Ke W (2008) Structure and formation mechanism of phosphate conversion coating on die-cast AZ91D magnesium alloy. Corros Sci 50:329–337
6. Tang Y, Zhu L, Zhang P, Zhao K, Wu Z (2020) Enhanced corrosion resistance of bio-piezoelectric composite coatings on medical magnesium alloys. Corros Sci 176:108939
7. Nagarajan B, Castagne S, Wang ZK (2013) Mold-free fabrication of 3D microfeatures using laser-induced shock pressure. Appl Surf Sci 268:529–534
8. Ye YX, Xuan T, Lian ZC, Hua XJ, Fu YH (2015) Fabricating micro embossments on the metal surface through spatially modulating laser-induced shock wave. Appl Surf Sci 357:678–688
9. Zheng C, Tian Z, Zhao X, Tan Y, Zhang G, Zhao G, Ji Z (2020) Effect of pulsed laser parameters on deformation inhomogeneity in laser shock incremental forming of pure copper foil. Opt Laser Technol 127:106205
10. Liu K, Dong XH, Xie HY, Peng F (2015) Effect of pulsed current on the deformation behavior of AZ31 magnesium alloy. Mater Sci Eng A 623:97–103
11. Tan J, Tan MJ (2003) Dynamic continuous recrystallization characteristics in two stage deformation of Mg-3A-1Zn alloy sheet. Mater Sci Eng A 339:124–132
12. Feng F, Huang SY, Meng ZH, Hu JH, Lei Y, Zhou MC, Wu D, Yang ZZ (2014) Experimental study on tensile property of AZ31 magnesium alloy at different high strain rates and temperatures. Mater Design 57:10–20
13. Kumar RR, Ismail MY, Vijayarasi VS, Kumar VS (2020) Effect of grain refinement on superplastic forming of magnesium alloy AZ31 under three different conditions using rectangular die. Materials Today: Proceedings 22:364–369
14. Hui S, Wang ZZ (2011) Grain refinement by means of phase transformation and recrystallization induced by electro-pulsing. Trans Nonferrous Met Soc China 21:353–357
15. Xu X, Zhang J, Liu HG, He Y, Zhao WH (2019) Grain refinement mechanism under high strain-rate deformation in machined surface during highspeed machining Ti6Al4V. Mater Sci Eng A 752:167–179
16. Zhang H, Ren ZC, Liu J, Zhao JY, Liu ZK, Lin D, Zhang RX, Graber MJ, Thomas NK, Kerek ZD, Wang GX, Dong YL, Ye C (2019) Microstructure evolution and electroplasticity in Ti64 subjected to electropulsing-assisted laser shock peening. J Alloys Compd 802:573–582
17. Jiang YB, Tang GY, Shek CH, Liu W (2011) Microstructure and texture evolution of the cold-rolled AZ91 magnesium alloy strip under electropulsing treatment. J Alloys Compd 509:4308–4313
18. Tiwari S, Mishra S, Odeda A, Szpunar JA, Chopkar M (2017) Evolution of texture and microstructure during high strain rate torsion of aluminium zinc magnesium copper alloy. Mater Sci Eng A 683:97–102
19. Liu YR, Zhang KM, Zou JX, Liu DK, Zhang TC (2018) Effect of the high current pulsed electron beam treatment on the surface microstructure and corrosion resistance of a Mg–4Sm alloy. J Alloys Compd 741:65–75
20. Abeeens M, Muruganandhan R, Thirumavalavan K (2020) Effect of low energy laser shock peening on plastic deformation wettability and corrosion resistance of aluminium alloy 7075 T651. Optik 219:165045
21. Caralapatti VK, Narayanswamy S (2017) Effect of high repetition laser shock peening on biocompatibility and corrosion resistance of magnesium. Opt Laser Technol 88:75–84
22. Hao YW, Deng R, Zhong C, Jiang YM, Li J (2009) Effect of surface mechanical attrition treatment on corrosion behavior of 316 stainless steel. J Iron Steel Res Int 16:68–72
23. Ren L, Yu X, He Y, Wang K, Yao H (2020) Numerical investigation of lateral inertia effect in dynamic impact testing of UHPC
using a Split-Hopkinson pressure bar. Constr Build Mater 246:118483

24. Jacques N, Mercier S, Molinari A (2012) Effects of microscale inertia on dynamic ductile crack growth. J Mech Phys Solids 60:665–690

25. Qi C, Xia C, Li X, Sun Y (2019) Effect of inertia and crack propagation on dynamic strength of geologic-type materials. Int J Impact Eng 133:103367

26. Van Aswegen DC, Polese C (2021) Experimental and analytical investigation of the effects of laser shock peening processing strategy on fatigue crack growth in thin 2024 aluminium alloy panels. Int J Fatigue 142:105969

27. Kumar A, Paul SK (2020) Healing of fatigue crack in steel with the application of pulsed electric current. Materialia 14:100906

28. Li MY, Chandra A (1999) Influence of strain-rate sensitivity on necking and instability in sheet metal forming. J Mater Process Tech 96:133–138

29. Ren L, Zhou M, Lu T, Fan L, Guo Y, Zhang Y, Boehlert CJ, Quan G (2020) Eutectic phase strengthening and strain rate sensitivity behavior of AZ80 magnesium alloy. Mater Sci Eng A 770:138548

30. Huang GJ, Qing Q, Wang LY, Xing RL, Chen XP, Pan FS (2008) Microstructure and texture evolution of AZ31 magnesium alloy during rolling. Trans Nonferrous Met Soc China 18:170–174

31. Pan X, Wang X, Tian Z, He W, Shi X, Chen P, Zhou L (2021) Effect of dynamic recrystallization on texture orientation and grain refinement of Ti6Al4V titanium alloy subjected to laser shock peening. J Alloys Compd 850:156672

32. Wang LF, Li YQ, Zhang H, Zhang ZY, Yang QS, Zhang Q, Wang RX, Cheng WL, Shin KS, Vedani M (2020) Review: achieving enhanced plasticity of magnesium alloys below recrystallization temperature through various texture control methods. J Mater Res Technol 9:12604–12625

33. Gay P, Hirsch PB, Kelly A (1953) The estimation of dislocation densities in metals from X-ray data. Acta Mater 1:315–319

34. Dunn CG, Kogh EF (1957) Comparison of dislocation densities of primary and secondary recrystallization grains of Si-Fe. Acta Mater 5:548–554

35. Trdan U, Skarba M, Grum J (2014) Laser shock peening effect on the dislocation transitions and grain refinement of Al–Mg–Si alloy. Mater Charact 97:57–68

36. Shadangi Y, Chattopadhyay K, Rai SB, Singh V (2015) Effect of LASER shock peening on microstructure, mechanical properties and corrosion behavior of interstitial free steel. Surf Coat Tech 280:216–224

37. Trdan U, Grum J (2012) Evaluation of corrosion resistance of AA6082-T651 aluminium alloy after laser shock peening by means of cyclic polarisation and EIS methods. Corros Sci 59:324–333

38. Wang WH, Wu HL, Zan R, Sun Y, Blawert C, Zhang SX, Ni JH, Zheludkevich ML, Zhang XN (2020) Microstructure controls the corrosion behavior of a lean biodegradable Mg–2Zn alloy. Acta Biomater 107:349–361

39. Ralston KD, Fabijanic D, Birbilis N (2011) Effect of grain size on corrosion of high purity aluminium. Electrochim Acta 56:1729–1736

40. Zhang H, Xue P, Wu LH, Song QN, Wang D, Xiao BL, Ma ZY (2020) Effect of grain ultra-refinement on corrosion behavior of ultra-high strength high nitrogen stainless steel. Corros Sci 174:108847

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