Original Article

Investigation of microstructure and texture during continuous bending of rolled AZ31 sheet by experiment and FEM

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Abstract

Various continuous bending experiment with three loading rates (100, 300 and 500 mm/min) at room temperature was adopted to investigate the diversity of microstructure, springback and texture of sheet after straightening. Due to grain size at the central layer of the bent plate decreased with the augment of bending rate, and the grain size was finest and most homogeneous at the bending rate of 500 mm/min. After each bending process, due to the springback and the shift of the neutral layer, the load of each time was gradually degressive. The deviations of springback between bending passes declined by degrees under 300 and 500 mm/min rates. However, the springback difference reached a minimum on the ninth pass under 100 mm/min bending rate. In addition, the intensity of \{0002\} basal texture, which is close-packed plane got to a minimum on the 100 mm/min bending rate. Meanwhile, the intensity of \{10 \: 11\} and \{10 \: 12\} textures, which shifted from TD-split to concentrating on the side of the RD, declined with incrementing the bending rate. The FE software was used and the experimental process was simulated accurately.

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1. Introduction

Magnesium (Mg) alloy plates have been widely used in aerospace, transportation and 3C (computer, communication and consumer electronic) industries because of their high specific strength, high specific stiffness, lightweight, excellent damping capacity, admirable thermal conductivity and so on. The 3–6 mm thickness plates can be employed to aero-engine casting, reducer housing and box cover in the aerospace field [1]. The plates with a thickness of 6–100 mm are mainly used for instrument bulkheads of missiles and rockets and satellites and lunar craft bases. In the field of transportation, 1–3 mm thick magnesium plates are used to manufacture instrument panel, door plate, engine cover board, roof plate, seat skeleton and backrest. In 3C and other electronic industries, 0.4–1.5 mm thickness sheets are applied in acoustics...
Mg alloy plates and sheets will appear some shape defects in the rolling process, such as wave, bow, residual stress and so on. Jia et al. [3–5] indicated that the edge cooling faster than the center during single-pass flat rolling of AZ31B Mg alloy, so the pre-width reduction could alleviate edge cracks and fracture. Zhi et al. [6] investigated multi-cross rolling could improve Mg alloy edge cracks. Therefore, the process of finishing rolling and leveling is conducted before curling to make the flatness and straightness of Mg alloy plates meet the requirements of the industry. Plate leveling is an elastic-plastic bending process carried out by alternating loading and unloading. The plate will undergo a certain pressure from the leveling roll when it entering the leveling machine. The plate is subjected to continuous bending owing to the opposite pressure from upper rolls and lower rolls. The plate turns flattening from bending after it out of the leveling machine. Wang et al. [7] indicated that the longitudinal profile of the unbent plate could be divided into three layers, upper and lower surface layers and the central layer. The deformation mechanism of the central layer was basal slip when the tension strain was lower than 5%. However, the deformation mechanism of the surface layer was a basal slip with twin during compress and basal slip with reverse twin during tension.

Recent studies on leveling theories and technologies are as follows, Wang et al. [8] established an analytical model (1–1) for the thermal straightening process of moderate thickness plate by curvature integral method and deduced the basic model of curvature integral method in detail, thus connecting the reduction amount with the bending curvature of plate. According to the basic theory of elastoplasticity, Guan et al. [9] built a numerical solution for the continuous solution of multiple back bending processes considering the deformation history. Zhang et al. [10] used ABAQUS to model the formation and tensile straightening process of thin plate strip wave shape and studied the rule of sheet strip forming shape defect under the action of original stress. Gong et al. [11] studied that the stress change by a three-dimensional dynamic finite element model and obtained that stress propagated from the head to the tail in the leveling process similar to the stress wave. Chen et al. [12] developed a mechanics model (1–2, 1–3) based on the curvature integration method and utilized a global nonlinear unconstrained optimization method to solve the model. Doege et al. [13] developed an analytic forming model which analyses the leveling process with sufficient precision in a shorter time.

\[
\frac{1}{\kappa_x} = \frac{d^2 y}{dx^2} = \frac{M_x}{ET}
\]  
(1-1)

\[
M_x = \text{bending moment of workpiece section},
\]  
\[
\kappa_x = \text{sectional curvature radius},
\]  
\[
l = \text{cross section moment of inertia},
\]  
\[
E = \text{modulus of elasticity}.
\]  
(1-2)

![Image](image_url)

2. Materials and methods

AZ31 magnesium alloy was rolled into the plate with a thickness of 3.66 mm through 15 passes rough rolling with 20%–30% reduction of each pass and 2–3 passes finish rolling with 15%–20% reduction. Samples for continuous bending (CB) measuring 150 mm in the rolling direction (RD), 60 mm in the transverse direction (TD) and 3.66 mm in the normal direction (ND) were cut from the plate using wire electrical discharge machining. The edges of the sample ground to 2500 silicon carbide (SiC) paper to remove the scratches. Detailed information about the samples was shown in Fig. 1a. Specimens (as shown in Fig. 1a at the dotted line) for microstructural examination and macrotexture measurement were sliced from the samples after bending experiment. The specimens for microstructure were ground using SiC papers followed by polishing with 1.0 μm diamond paste. The etchant was used to reveal the microstructure which was analyzed by OM. The macrotexture was measured by X-ray diffraction.

The samples were subjected to CB on the three-point bending die by the universal tensile testing machine. The diameters of upper roll and back-up rolls are 30 mm. The distance between the two back-up rolls is 90 mm. Seventeen-roll leveling process was simulated by CB physical experiments (as shown in Fig. 1b, the numbers 1, 2, 3 et al. represent bending pass). Therefore, fifteen-bend processing and its load with the pressure velocities of 100 mm/min, 300 mm/min and 500 mm/min were conducted. The reduction was defined as 10 mm. Meanwhile, the warpage before and after bending was measured by vernier caliper.

The finite element (FE) analysis of bending and succedent leveling process were carried out and the stress and strain data before and after the springback were extracted to compare with the experiment data.
3. Results and discussion

3.1. Microstructure

The microstructure of unbending plate and CB plate on the pressure velocities of 100 mm/min, 300 mm/min and 500 mm/min are shown in Fig. 2. In order to intuitively analyze the effect of CB on grain size and grain size distribution at different rates, a statistical lognormal density probability function is used (as shown in Eq. (3-1)) [15], where $d_m$ is the average grain size.

$$P = \frac{1}{\sqrt{2\pi}wd} e^{-\frac{\ln^2(d/d_m)}{2w^2}}$$  \hspace{1cm} (3-1)

Considering the non-uniformity of grain size, the specimens are divided into 3 areas, upper surface ($S_{upper}$), center and a lower surface ($S_{lower}$). The least square method is used to fit grain sizes distribution according to Eq. (3-1). Then the average grain size of vary process is determined with $d_m$ in the regression equation. This method can enormously improve solving accuracy of $d_m$ compared with traditional estimation method. As shown in Fig. 3, the distinction of grain size of the upper surface and a lower surface on the different bending rate is slight. The average grain size maintains at 14–16 μm. However, the average grain size of center decreases from 22.55 μm to 15.68 μm. To research the uniformity and distribution of the grain size for each bending process, linear fitting and standard deviation (SD) are actualized, as shown in Eq. (3-2)

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(d_i - d_m)^2}{n}}$$  \hspace{1cm} (3-2)

where $d_i$—grain size, $d_m$—average value. The regression line of central grain size of each process has a negative slope (~0.20848) and large fluctuation of SD, which means that the central grain size of CB rate from 0 to 500 mm/min diminishing. The absolute values of the slope of the upper surface and lower surface are all pretty small, which signifies that the grain size of both surfaces is almost invariant, fine and uniform. With the combination of microstructure graphs and SD values, the grain size on 500 mm/min condition is finest and most homogeneous.

During the bending process of magnesium alloy plate, plastic deformation is generated on the upper and lower surface, while elastic deformation is happened on the central layer, as shown in Fig. 4a. The grains of the upper and lower surface are subjected to repeated tensile and compressive plastic deformation, which turn uniform and fine [16]. Nevertheless, grains in the elastic zone of the central layer are not undergone plastic deformation. The grain size is closely related to strain rate and diminishes with the increase of strain rate [17].
3.2. Bending load and springback

Zou et al. [18] studied the strain rate effect of elastic modulus and indicated that the increase of strain rate would argument the modulus of elasticity. And the change of elastic modulus will affect the springback.

After each bending pass of the plate, due to the springback and the shift of the neutral layer, the load of each time is also changing with the distance. The load-distance recorded at various bending rates are shown in Fig. 5. The solid lines represent odd-numbered pass bending, while the dot lines are an even-numbered pass bending. From Fig. 5, it can be concluded that the first bending pass required a large load, and the odd one needs a higher load than the even-numbered one because of the plate bouncing after odd bending and the load decreases in subsequent even bending. As the rate increases, the phenomenon becomes more apparent, which is related to the decrease of twins [19,20]. As the bending rate of the plate increases, so does the load that bends to the same position and the load difference between odd and even times becomes obvious. Fig. 6 is the strain hardening rate (dɛ/dσ)-bending strength (σ) curves at various bending rates. It can amplify the hardening effect of plates under different bending passes. As seen in Fig. 6a–c that the strain hardening rate curve of even-number bending becomes more and more gentle with the increase of bending rate after reaching the maximum value, such as the second bending curves declining from 15 × 10³ MPa to 7 × 10³ MPa. At 100, 300 and 500 mm/min, the maximum strain hardening rate for each bending pass except the first pass is 5 MPa to 11 MPa, 17 MPa to 40 MPa and 13 MPa to 22 MPa, respectively. This is related to the deformation resistance of the plate and the migration of the neutral layer [21]. Wang et al. [7] indicated that the asymmetry of tension and compression descended with the decrease of strain rate. Therefore, the offset of the neutral layer drops with a decrease of strain rate.

The sketch graph of bending and springback is shown in Fig. 4b, which the dashed outline representing the initial state, the green meaning the bending state and the red referring to springback state. The load stroke of each bending is 10 mm, and the quantity of spring deflection is δs. There are the following formulas according to the elastic-plastic theory of materials combined with Fig. 4a and b.

\[
\frac{\varepsilon_C}{\sigma} = \frac{(H - h)}{\rho} \quad (3-3)
\]

\[
\sigma_C = E \cdot \varepsilon_C \quad (3-4)
\]

\[
\delta_s = \frac{M^2}{12EI} \quad (3-5)
\]

\[
M = \frac{\sigma_C}{E} \left\{ \frac{b(H - h)^2}{6} \left( \frac{\varepsilon_C\rho}{H - h} \right)^2 + \frac{E}{E^2} \left[ \frac{H - h}{\varepsilon_C\rho} + \frac{1}{2} \left( \frac{H - h}{\varepsilon_C\rho} \right)^2 - \frac{3}{2} \right] \right\} 
\]

(3-6)

where \( \varepsilon_T, \varepsilon_C, \sigma_T, \sigma_C, \rho, h, l, E, \sigma, H \) are tensile strain, compressive strain, tensile stress, compressive stress, tensile stress, compressive stress, elastic modulus, tensile modulus, yield stress, yield strain, material thickness, material length, springback rate, hardening modulus, hardening strain.
stress in elastic zone, compressive stress in elastic zone, bending radius of the neutral layer, distance from neutral layer to outer surface, rolling spacing, modulus of elasticity, thickness of sheet and elastic-plastic bending moment respectively.

When the bending deformation degree of the material reaches the yield limit, the stress and strain of the material no longer conform to Hook’s law, and a certain kind of curve form will be shown at this time. The stress can be written as the following formula in the plastic zone beyond the elastic zone.

\[ \sigma = \sigma_{ec} + E (\varepsilon - \varepsilon_{ec}) \]  

(3-7)

The internal moment and external moment of a plate are equal in the process of leveling, so the formula of the internal
Fig. 4 – Sketch graph of (a) the distribution of stress-strain on bending and (b) bending and springback.

Fig. 5 – Load-distance curves at different bending rates. (a) 100 mm/min, (b) 300 mm/min, (c) 500 mm/min.

Fig. 6 – Strain hardening rate-bending strength curves at various bending rates. (a) 100 mm/min, (b) 300 mm/min, (c) 500 mm/min.
moment of elastic-plastic bending is the formula of bending moment of the plate.

\[
M = 2 \int_{0}^{Z_{b}} \sigma Z dF + 2 \int_{Z_{b}}^{H} (\sigma_{ec} + \Delta \sigma) Z dF
\]

(3-8)

From formula \( \frac{\varepsilon}{\varepsilon_{f}} = \frac{Z_{c}}{Z_{b}} \) and \( \Delta \sigma = \left( \frac{Z}{Z_{b}} - 1 \right) \frac{E}{\varepsilon_{f}} \sigma_{ec} \),

\[
M = Z \sigma_{ec} \left[ \int_{0}^{Z_{b}} \frac{Z_{c}^{2}}{Z_{b}} dF + \frac{E}{\varepsilon_{f}} \int_{Z_{b}}^{H} \left( \frac{Z}{Z_{b}} - 1 \right) Z dF \right]
\]

(3-9)

Can be obtained.

\[ dF = bdZ \]

(3-10)

\[
M = 2 \sigma_{ec} b \left[ \int_{0}^{Z_{b}} \frac{Z_{c}^{2}}{Z_{b}} dZ + \frac{E}{\varepsilon_{f}} \int_{Z_{b}}^{H} \frac{Z}{Z_{b}} - 1 \right] Z dZ \]

(3-11)

\[
M = \left( \frac{\eta k^{2}}{2} + \frac{1}{h} \right) \cdot \frac{b(H - h)^{2}}{6} \sigma_{ec}
\]

(3-12)

Where \( \eta = \frac{E}{\varepsilon_{f}} \) is strengthening factor, \( k = \frac{Z_{c}}{Z_{b}} \) is elastic layer thickness factor.

Loads of each bending pass at a distance of 4 mm (before the gap) and 6 mm (after the gap) in Fig. 5 and springback quantities are especially shown in Fig. 7. The trend of load variation at 4 mm and 6 mm under 100 mm/min is similar, except that the load fluctuation increases earlier when the stroke is 4 mm (see Fig. 7b black dot line). However, the variation trend of the load at 300 and 500 mm/min is very distinct. The load fluctuation at 6 mm was gradually smooth, but the load at 4 mm changed slowly after the 11th pass on 300 mm/min (see Fig. 7b red dot line) and after the 8th pass on 500 mm/min (see Fig. 7b green dot line). The load difference at the 300 and 500 mm/min rate shows a downward trend throughout the bending process. With the augment of bending pass, the load fluctuations tend to be gentle under the conditions of 300 and 500 mm/min. However, the fluctuation, load difference, turns sharp after the ninth pass at the 100 mm/min condition at a distance of 6 mm (see Fig. 7a at a dashed line). These correspond to the springback quantities in Fig. 7c. The regression lines of even-numbered and odd-numbered springback quantities at 100 mm/min intersect at the ninth bending pass. Nevertheless, the regression lines at 300 and 500 mm/min gradually tend to intersect. Reduction of working hardening rate can reduce mechanical power and further cut down the energy loss. This can be used as a reference for the establishment of proper leveling roller arrangement and leveling rate [22].

The mechanical properties of materials will change dramatically under high strain rate deformation, and the microstructure will change correspondingly [23]. There are two main deformation modes in magnesium, which are dislocation slip and twinning. The plastic deformation mode depends on the relative location between the loading direction and the crystallography direction. The activation condition of the dislocation slip is that only when the resolved shear stress exceeds the critical value for the magnesium crystal. The \( \{10 \ 12\} \) tension twinning in magnesium can only be activated by a tensile stress parallel to the c-axis or compression stress perpendicular to the c-axis when the c/a ratio is less than 1.73 [24]. Magnesium has a c/a ratio of 1.628 and is almost ideally hexagonal close packed. Similar to tension twinning, the \( \{10 \ 11\} \) contraction twinning can only be activated by a compression stress parallel to the c-axis. During the continuous bending process the randomly orientated grain gradually rotated and reoriented to form a strong texture, in which the prismatic and pyramidal plane are essentially split to rolling direction. It can be seen from Fig. 8a that the material soften when stretched at a rate of 300 mm/min, of which the strain hardening exponents decrease with increasing rate.

3.3. Texture

Ma et al. [25] demonstrated that texture composition could alter elastic modulus, which was anisotropic and maximum at the close-packed plane. Mg and its alloys belong to the hexagonal close-packed structure with an atomic close-packed plane of \( \{0002\} \). The textures of bending at different rates are detected by XRD, as shown in Fig. 9. The maximum texture intensity \( (I_{max}) \) of \( \{0002\} \) basal texture slightly increases after bending, but with the increase of bending rate, the \( I_{max} \) gradually diminishes. After bending, the basal plane texture distribution spreading along RD is attenuated. During the first bending deformation of the plate, the outer side and inner side of the plate are subjected to tensile stress and compressive stress respectively. And alternative twin bands are observed on the inner side [26,17]. In the subsequent anti-bending and continuous bending process, detwinning and twinning occur alternately at the surface of the sheet. As a result, there are few twins on the surface and the \( \{0002\} \) texture is slightly stronger. It is obvious that \( \{10 \ 11\} \) prismatic plane and \( \{10 \ 02\} \) pyramidal plane textures have transformed greatly, rotating from TD toward RD (see Fig. 9e-f). Sun et al. [27] indicated that texture formation in Mg products was associated with the reiterative tensile stress and compressive stress in the CB process.

The basal plane is perpendicular to the c axis, and the deformation resistance of the material is small and easy to deform. While the prismatic plane is parallel to the c axis, and the material is subjected to high deformation resistance and is difficult to deform. The initial rolled sheet is dominated by the \( \{0002\} \) <11–20> basal plane texture, owing to the continuous reciprocating bending process, the \( \{0002\} \) pole density center is deflected towards the center of normal direction. With the development of bending experiment, the \( \{10 \ 11\} \) prismatic texture and \( \{10 \ 12\} \) pyramidal texture change from the original TD-split bimodal texture to the R texture, and the texture strength increases by 13%. As can be seen from Fig. 8 in the manuscript, the pole density profile becomes denser after bending. There are three reasons for a sudden rotation of the grain orientation: firstly, a large number of grains with \( \{11–20\} \) <10–10> orientation occur tensile twins while other grains are still in the stage of elastic deformation. Although the amount of twin deformation is slight, the elastic deformed grains cannot return to their original position after unloading,
thus resulting in a change of orientation. Secondly, the symmetry of hexagonal crystal structure is poor, the deformation between grains is heterogeneous, and some grains with no twins and only plastic deformation caused by slip can also play the effect of "sticking position". Thirdly, the twins themselves are associated by orientation transformation. At room temperature, the increase of strain rate accelerates the formation of non-base texture to a certain extent, which increases the strength of prismatic and pyramidal texture. As we all know, the strong basal texture will affect the subsequent deformation of the Mg alloy, and the increase of non-basal texture can improve the plasticity of the Mg alloy. With the increase of bending rate, the elongation of the material increases, indicating that the plasticity becomes better, which is consistent with the results shown in Fig. 9 in the manuscript.

The stress sketch diagram is shown in Fig. 10a, which the red arrows and the sign of ♦ represent odd-numbered compressive stress and the green arrows and the sign of ♠ show even-numbered tensile stress. The c-axis is almost parallel to the ND direction and the arrow on basal plane embodies rotation direction of majority grains. After multiple bending and leveling, the texture is regulated with the increase of prismatic texture ($l_{\text{max}} = 1.607, 1.625, 1.633$) and pyramidal texture ($l_{\text{max}} = 1.935, 2.013, 2.084$) [28].

The sheets are exposure to an asymmetric deformation during continuous strainghtening, as illustrated in Fig. 10b. Furthermore, the {10 1 1} and {10 1 2} textures have been a shift from TD-split (bimodal distribution) to concentrating on the side of the RD. However, the identity of the basal plane texture is dominant. Under the condition of fine grain, the non-basal slip is more easily activated and even grain boundary turns slip owing to the grain boundary hardening. Thus, the uniformity of plastic deformation is improved significantly and the possibility of twinning is reduced. When significant dynamic recrystallization occurs in the microstructure (Fig. 2), the original coarse equiaxed grains with different orientations begin to grow at the same time, but the {0002} basal grains have lower distortion energy, and the grains grow faster in the direction of {0002} plane. The growth of other-oriented grains is inhibited, and the grain in the direction of {0002} crystal plane is increased continuously, which leads to the increase of texture strength on the basal plane.

3.4. Finite element analysis

The bending experiment is simulated under the same conditions (500 mm/min) and the results after bending are shown in the following figure.

The max principal true stress-strain in-plain before and after springback in the bending process is shown in Fig. 11. The stress in Fig. 11b is between 172 MPa and 193 MPa, which consistent with the bending stress in Fig. 6. Taking the elset 1 and 4 in Fig. 11a as an example, the strain of the tensile region becomes smaller after springback, while the change of the compression region is opposite. The variation of the stress in Fig. 11b before and after springback is the same as the stain, except that the magnitude of the stress variety is larger. The simulation results verify the variation of stress and
strain in bending experiment. That is due to the asymmetry of tension and compression of magnesium alloy and the shift of the neutral layer.

Fig. 12 is the max principal true stress-strain in-plain before and after springback in 17 rollers leveling process. Two elset 1 and 2 in front of the roller are selected to analyze the stress and strain before and after springback in the leveling process. Large tensile stress exists in the plate after leveling and reduces by 93.48% (from 57.71 MPa to 3.76 MPa) after springback. However, the change in compressive stress is slight. This is related to the tensile stress of the plate in the leveling process. In contrast, the diversification of strain is to a small extent, less than 0.5% (from 0.1656 to 0.1648).

Fig. 13 is stress-time curves of the elset 3 in Fig. 11 in reduction and straightening process. The unit 2414 reaches the maximum value in the reduction process, whose stress presents a fluctuant distribution in the subsequent leveling. The stress value of unit 1280 is always in the middle and its variation is not severe. This is because unit 1280 is in an elastic deformation zone, while unit 2414 is in a plastic deformation zone.
Fig. 11 – (a) Max principal true strain in-plain and (b) true stress in-plain before and after springback in the bending process.

Fig. 12 – (a) Max principal true stress in-plain and (b) true strain in-plain before and after springback in the leveling process.

The finite element software can accurately simulate the actual straightening process and obtain the data which are not easy to achieve in the experimental process.

4. Conclusions

In this study, continuous bending experiment with various loading rate (100, 300 and 500 mm/min) at room temperature was conducted to research the variety of microstructure, springback and texture of sheet after straightening. The increase of strain rate will make the increment of elastic modulus and springback and refine the grain size. And the elastic modulus is affected by the texture. The concrete results are as follows:

(1) The grain size of the central layer decreased with the increase of bending rate, and the grain size was finest and most homogeneous at the bending rate of 500 mm/min.

(2) After each bending process, due to the springback and the shift of the neutral layer, the load of each time was gradually degressive. The load-distance curves of odd-time and even-time deformed gap was at the distance of about 5 mm, which caused by neutral layer shift and
springback. The deviations of springback between bending passes declined by degrees under 300 and 500 mm/min rates. However, the springback difference reached a minimum on the ninth pass under 100 mm/min bending rate. (3) The texture intensity of (0002) basal texture strengthened slightly with increasing bending rate, but the growth was decreasing. Nevertheless, the texture intensity of (10 11) and (10 12) textures declined with augmenting the bending rate, and the (10 11) and (10 12) textures shifted from dispersing on each side of TD to concentrating on the side of the RD.

Conflicts of interest

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

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REFERENCES

[19] Bhattacharyya A, El-Danaf E, Kalidindi SR, Doherty RD. Evolution of grain-scale microstructure during large strain

Fig. 13 – Stress-time curves of the elset3 in Fig. 10 in reduction and straightening process.


