Original Article

Effect of tension on edge crack of on-line heating rolled AZ31B magnesium alloy sheet

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1. Introduction

Magnesium has attracted tremendous attention due to its excellent lightweight potential in aerospace, automobile, rail transportation, 3C, and construction formwork applications, as the density of magnesium is 1.78 g/cm³, which is 2/3 of aluminum and 1/4 of iron [1,2]. Besides, magnesium is extremely rich in resources, which has been estimated to be exploitable for more than a thousand years. The abundant resources provide a good solution to the limited resources of other structural metals.

Edge crack is a common defect in the rolled magnesium alloy sheet which increase the rolling cost. In this study, the effect of tension on the edge crack of AZ31B sheet rolled with on-line heating rolling was investigated. The sheets were rolled under different tension at the rolling temperature of 523 K with thickness reduced from 1 mm to 0.6 mm in 1 single pass. The microstructures, texture, and mechanical properties, fracture surfaces of the sheets were characterized. The results show that the number of edge crack and crack depth increase with the increase of the tension. EBSD results show the crack tip area are mainly composed of fine recrystallized grains.

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alloys with the lowest c/a of 1.619. Manabe et al. investigated the effect of rolling speed on the formation of edge crack and found that AZ31B can be rolled without edge cracks at a high rolling speed of 1000 m/s [8]. The suppression of edge crack formation at high rolling speed is due to dynamic crystallization induced by fast accumulated heat during the rolling process. High rolling temperature generally results in less edge crack for magnesium alloys. In Zhi et al.’s study, remarkable edge crack were observed in AZ31 sheets rolled at 523 K (250 °C) while they are hardly seen in the sheets rolled under 623 K (350 °C) and 673 K (400 °C) [9]. Liu et al. also found that the edge crack of Mg-1Al-1Sn-1Mn alloy sheet is eliminated as the rolling temperature increases from 423 K (150 °C) to 523 K (250 °C) [10]. Reduction is another very important factor to formation of edge crack. Zhang et al. found that the edge crack appears in AZ31 alloy sheet when the accumulated reduction increased to 51.6 % [6]. It is also reported that low pass reduction results in less edge crack in magnesium alloy sheet [11]. In addition, texture is reported to play an important role on the formation of edge crack, as better rollability along the extrusion direction than along transverse direction is observed due to the different texture distribution [12,13].

Several solutions to the elimination of edge crack were proposed in the past decades. Huang et al. proposed that [14] an initial sheet with prefabricated edge convex metric can reduce the edge crack. No crack is generated in specimen with prefabricated convex metric of 4 mm after five passes in which the accumulated reduction reached 77 %. Other researchers focus on optimize the rolling parameters and improve the rolling facilities to avoid edge crack. In the traditional rolling process, magnesium alloy sheets are generally rolled at elevated temperature for several passes with annealing between each pass. Elevated temperature helps to improve the formability of magnesium alloy with activating non-basal slip during deformation. However, such traditional rolling for producing magnesium alloy sheet is time and energy consuming which leads to high price of the rolled sheets. To improve comprehensive properties and reduce the formation of defects like edge crack in conventional rolling, several new rolling processes were developed, such as equal channel angular rolling (ECAR) [15], cross rolling (CR) [16], asymmetric rolling (AR) [17,18], vertical rolling [19] and so on [20,21]. For instance, Zhi et al. reported that change the rolling direction in each pass helps to eliminate the edge crack of AZ31B alloy sheet [9]. Most recently, researchers have developed on-line heat rolling technology (ON-LHR) [10,22], which highly improves the surface quality of commercial AZ31B alloy sheets. Such improvement is due to ON-LHR enables the simultaneously heating of both sheet and rolls, which reduce the temperature difference between the edge and the middle of the sheet. In addition, tension is applied to the magnesium alloy sheet during the ON-LHR process which leads to the reduction/elimination of edge wave of the sheet.

However, the influence of tension on edge crack of magnesium alloy sheet in the ON-LHR process is not clear. Combining with the established thermal-mechanical-damage coupled finite elements model [6], we speculate that the change in tension will affect the rolling force and the flow velocity of the sheet in the RD direction along the width direction. Thus change the stress state of the rolled sheet will ultimately affect the formation of edge crack. AZ31B is the most commonly used wrought magnesium alloys to produce the sheets for applications like laptop shell. In this study, commercial AZ31B alloy was rolled under 523 K with a single pass reduction of 40 % using ON-LHR to investigate the relationship between tension and edge crack.

2. Experimental procedures

The original samples used in this study are extruded commercial AZ31B alloy sheet with the size of 600 mm × 120 mm × 1 mm, and the chemical composition tested by inductively coupled plasma optical emission spectrometry (ICP-OES, Optima 8000) is given in Table 1.

The rolling experiment was conducted on ON-LHR with a four-roll rolling mill with the support rolls and work rolls of 320 mm and 120 mm in diameter, respectively. Detailed description of the rolling machine can be found in Ref. [22]. Specifically, the tension device from the rolling machine can provide tension range from 0.05KN to 13KN. The rolling speed was set at 0.05 m/s, temperature of the sheet was kept at 523 K. Due to the temperature limit of the heating oil in the roll, the temperature of the roll was set to 473 K. The original sheets were rolled under different tension of 1, 3, 5KN under one single pass with the total reduction of 40 %.

The dog-bone shaped specimens were cut from the rolled sheets along rolling direction (RD), with a standard size of 35 mm in length, 10 mm in width and 0.6 mm in thickness. The tensile experiment was carried out by CMT-5105 microprocessor controlled electronic universal testing machine at room temperature. For each condition at least three specimens were tested.

The macrotexture measurement was carried out on Rigaku D/max 2500/PC X-Ray diffraction (XRD) instrument. The samples were cut at the edge of rolled sheets and pole figures were obtained.

To observe the microstructure of cracks, rectangular samples with size of 10 mm × 8 mm were cut from cracked area. The samples were ground with SiC abrasive paper, polished and chemically etched in a solution of 8g picric acid, 5 ml acetic acid, 10 ml distilled water, and 100 ml ethanol for around 5s. The microstructures were observed by optical microscope (OM, Leica DM5000M), electron backscattered diffraction (EBSD) and scanning electron microscope (SEM). The fracture surfaces of the edge crack were characterized with SEM. Both EBSD and SEM were carried out by JEOL JSM-7800F field emission scanning electron microscope.

3. Results

3.1. Microstructures of the rolled sheet

Fig. 1 shows the microstructures at both side and middle of the rolled sheet under different tension. It can be seen that when the tension is 1KN, the grains at the edge and the middle are relatively small and uniform. And they are mainly consisted of equiaxed grains, only a small portion of grains are
Table 1 – Chemical composition of the AZ31B alloy sheet (mass, %).

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Zn</th>
<th>Si</th>
<th>Ca</th>
<th>Mn</th>
<th>Fe</th>
<th>Cu</th>
<th>Ni</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>3.1</td>
<td>0.9</td>
<td>0.08</td>
<td>0.04</td>
<td>0.43</td>
<td>0.003</td>
<td>0.01</td>
<td>0.001</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Fig. 1 – The optical microstructures of edge and middle area of rolled sheets: (a) 1 KN edge; (b) 1 KN middle; (c) 3 KN edge; (d) 3 KN middle; (e) 5 KN edge; (f) 5 KN middle.

Elongated. When the tension increases to 3KN, many coarse grains existed in both the edge and the middle. Twins are clearly visible in the coarse grains in the microstructures of both the edge and middle sheets rolled at 3KN. When the tension increases to 5KN, the microstructures at the edge and the middle is similar to those of samples rolled under 3KN. It is therefore observed that the microstructures of samples rolled under 3KN and 5KN are less uniform than that of rolled under 1KN.

3.2. Mechanical properties

The typical stress-strain curves of the sheets are shown in Fig. 2, the detailed mechanical properties are listed in Table 2. It can be seen that the sheets rolled under 3KN without heat treatment exhibit the highest strength and lowest ductility among all. The yield strength, ultimate tensile strength and the fracture elongation is $262 \pm 2$ MPa, $317 \pm 4$ MPa and $11 \pm 2$ %, respectively.

3.3. Macrotexture

In order to check the effect of rolling tension on the macrotexture of AZ31B sheets, the macrotexture was performed with XRD. The pole figures of the three sheets are shown in Fig. 3. It can be seen that all the three sheets show typical rolling macrotexture with the maximum macrotexture slightly decreases from 10.452 at 1 KN to 9.863 at 5 KN.
Table 2 – Mechanical properties of AZ31B sheets rolled under different tension.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Yield strength (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Fracture elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 KN</td>
<td>244 ± 3</td>
<td>314 ± 4</td>
<td>14 ± 3</td>
</tr>
<tr>
<td>3 KN</td>
<td>262 ± 2</td>
<td>317 ± 4</td>
<td>11 ± 2</td>
</tr>
<tr>
<td>5 KN</td>
<td>254 ± 2</td>
<td>309 ± 3</td>
<td>16 ± 1</td>
</tr>
</tbody>
</table>

As a result, it is noted that the applied tension during rolling process has little effect on the macrotexture of AZ31B sheets.

3.4. Macro morphology of edge cracks

Under the given condition in this study, edge cracks were observed in all the sheets. Fig. 4 shows the macroscopic morphology of AZ31B sheets rolled under different tension with the single pass reduction of 40%. As can be seen from Fig. 4(a), when the tension is 1 KN, there are only a few edge cracks (indicated by red arrows) on the sheet, which is difficult to see with the naked eye. With the tension increases to 3 KN, obvious cracks appear on the sheet. It is also noted that there are little difference in the crack depth. When the tension increases to 5 KN, as shown in Fig. 4(c), extremely large cracks together with small cracks are observed. In addition, the crack propagation path changes direction in the largest two cracks, which is similar to the oblique crack IV observed in steel [23].

Usually, the rolling feasibility can be judged by the number and maximum depth of cracks. Maximum depth of crack is an important characteristic for rolled sheets, especially in industrial. Generally, the edge of the sheets with crack will be cut prior to the next rolling pass or be sold, and the maximum depth of cracks determines how much sheets should be cut. Lower number and maximum depth of edge cracks generally indicate better rolling feasibility. The number of edge cracks and the maximum depth were measured within a length of 200 mm along both sides, the results are displayed in Fig. 5. The detailed measurement is described in our previous study [10]. The number and maximum depth of edge cracks increases significantly with the augment of tension. Among the three given tensions, 1 KN is the best tension for rolling AZ31B sheet under large strain rolling with regard to edge crack. However, the sheets rolled under 1 KN exhibit edge wave while no edge wave is observed in the sheets rolled under 3 KN and 5 KN.

![Fig. 2 – True stress vs strain curves for sheets rolled at different rolling tension.](image)

![Fig. 3 – Pole figures of rolled sheets at different rolling tension: (a)1 KN; (b)3 KN; (c)5 KN.](image)
As is seen from Fig. 1, the microstructure at the edge of the sheet is composed of coarse grains and fine grains. It is interesting to observe from the tip of the edge crack (Fig. 6(b), (d), (f)) that all the cracks propagate in the fine grain area under the tension of 1KN, 3KN, and 5KN. In addition, in front of the crack tip, large area of fine grains is observed in both sheets rolled under 3KN, and 5KN.

The inverse pole figure (IPF) map of crack tip area is shown in Fig. 7. In comparison with the OM shown in Fig. 6, it is considered that the large blank areas in the figure represents the edge crack, some small blank area are the unmarked area from EBSD. It can be seen that most of the grains are in visually red and only a few grains are in blue and green, which indicates a strong basal texture of the rolled sheets. At the crack tip area, there are both coarse and fine grains in the sheets rolled under the tension of 1KN and 3KN. While for the sheet rolled under 5KN, nearly the whole crack tip area are composed of fine grains. In addition, it is observed from of the IPF that the edge crack propagate through the grain indicating a transgranular fracture for all the three samples.

The fine grains at the crack tip area are estimated as recrystallized grains. In order to confirm this, dynamic recrystallization maps are carried out by EBSD technique and the results are shown in Fig. 8. It can be seen that the portion of subgrains (grains in yellow color) is very small in the three figures, while the recrystallized grains and deformed grains occupy the majority of the figures. The proportions of different grains are counted and calculated, the white area including both the crack area and the unmarked area are excluded from the data. The results are displayed in Fig. 9. It can be found that when the tension is 1KN, the recrystallized grains and the deformed grains are mixed around the crack tip. As the tension increases to 3KN, recrystallized fine grains are mainly distributed near the crack tip, and the coarse deformed grains

3.5. **Microstructures of the edge cracks**

The optical metallographic photograph of edge cracks in rolled sheets under different tension is shown in Fig. 6. It can be seen from Fig. 6(a), (c), (e), with the increase of tension, both the depth and width of cracks increase significantly. In the online heating rolling process, the online heating of the sheet will help to reduce the temperature difference between the edge and center. Smaller temperature difference results in more uniform deformation which will assist to reduce the edge crack. However, the tension imposed on the sheet is along RD which is perpendicular to the crack propagation. Thus, the tension will accelerate the crack propagation once the crack is nucleated due to the local stress exceeds the strength of the material. As a result, large tension will leads to more severe edge crack.
are mainly distributed far away from the crack tip. At the tension of 5KN, the whole area are mainly recrystallized fine grains with only a few fine deformed grains. In addition, the coarse grains are nearly 100% in red which are deformed grains. The fine grains are mainly in blue with a small portion in red and yellow indicating they are mainly recrystallized grains.

3.6. Fracture surface of the edge crack

The fracture surfaces of the edge cracks are shown in Fig. 10. It is to be noted that due to the small size of edge cracks in sheets rolled under 1KN and 3KN, the samples were torn manually. Before the manual tearing process, the crack tip area was marked and later used to distinguish the edge crack and the artificial crack. Thus part of the fracture surface is induced by sample preparation, as shown in Fig. 10(a) and (d), the left side of the red dashed line shows the fracture surface of edge crack, the right side of the line represents the manually torn fracture surface.

Fig. 10(a)–(c) show the fracture surface at different magnifications of the sheet rolled under 1KN. The fracture surface shows in a V-shape with the center line in the ND-TD plane as the vertex. The enlarged fracture surface indicates the edge crack is brittle. The crack tip area also show the crack is brittle. As the tension increases to 3KN, the cleavage fracture appears in most of the fracture surface indicates a brittle fracture, clear dimples are also observed near the crack tip show a ductile fracture. Thus, the fracture mode of the edge crack change from brittle at the start area to ductile near the tip area. It can be seen from Fig. 10(g)–(i) that when the tension is 5KN, the fracture surface shows mixed ductile and brittle fracture.

4. Discussion

4.1. Fracture mode of edge crack

As can be seen in Fig. 10, when the tension is 1KN and 3KN, the initial fracture is typical brittle with cleavage and the tip area show some ductile fracture with dimples. However, both of the
Fig. 7 – IPF maps of cracked area of rolled sheets under (a) 1 KN; (b) 3 KN; (c) 5 KN.

Fig. 8 – EBSD maps distinguished with DRX region (blue area), subgrains region (yellow area) and deformed region (red area) of sheets rolled under (a) 1 KN; (b) 3 KN; (c) 5 KN.

manually made fracture surfaces (right side of the dashed line in Fig. 10(a) and (d)) indicate a typical ductile fracture mode with dimples. This phenomenon indicates AZ31B sheet went through ductile deformation during the manual tearing apart the edge crack tip. On the contrary, the edge crack of AZ31B sheet initially went through brittle fracture and changed to ductile fracture at the end of fracture (fracture tip). As the tension increases to 5 KN, the edge crack initially went through a
mixture of ductile and brittle fracture and changed to ductile fracture at the crack tip.

Similar ductile fracture surface in the manually torn samples (right side of the dashed line in Fig. 10(a) and (d)) is also found in the tensile fracture surface associated with tensile twining [24]. However, the brittle fracture surface of the edge crack in this study with very large facets is different from the quasi-brittle facets in Ref. [25], brittle-like patterns related to the boundary fracture in Ref. [26]. While the fracture surface is found to be similar to the tensile fracture surface performed at very low temperature of 78 K and 4.2 K [5] and the brittle fracture surface of specimens tests with high strain rate in Ref. [27]. It is well known that Mg has very low intrinsic fracture toughness and is prone to brittle cleavage failure at a low temperature of 0 K, which is confirmed in both linear elastic fracture mechanics (LEFM) prediction and atomistic simulations [28]. Similar cleavage fracture surface of edge crack is also found in the Zhi et al.’s study [9], in which the AZ31B sheet was cross-rolled at 350 °C.

The ductile fracture mode found on the tip of edge crack in all three samples and partial ductile fracture in the initial state of edge crack in sample rolled under a high tension of 5KN is expected to be related to their higher stress state. Stress concentration is normally found at the crack tip area which can induce the ductile deformation through dislocation emission. The higher tension of 5KN applied to the sample results in higher stress in the edge area than that of samples rolled under 1KN and 3KN. According to Wu’s simulation [28], higher applied load leads to more dislocation emission thus the crack tip exhibits ductile behavior. In addition, the dislocation emission is mainly simulated at the crack tip rather than non-crack-tip area.

4.2. Edge crack occurs in the fine grains

Most of the edge cracks are found initiated and propagated in the fine grain area in this study. Except for the previously shown edge cracks in Fig. 6, many other edge cracks are also found in the fine grain area (pictures are not shown here). Figs. 7 and 8 confirm that the fine grains are mainly composed of recrystallized grains. Thus, the edge cracks in this study mainly initiated and propagated in the recrystallized grain area. This could be due to the “soft” nature of the recrystallized grain area in comparison with the coarse deformed grains. It is further evident that separate cracks away from the main edge cracks are observed in the near edge area of the sheets rolled under 3KN and 5KN, as shown in Fig. 11. All these separate cracks formed in the recrystallized grain

![Fig. 9 - Proportions of different type of grains.](image)

![Fig. 10 - Fracture surfaces of the edge cracks under different tension, (a)(b)(c) 1 KN; (d)(e)(f) 3 KN; (g)(h)(i) 5 KN.](image)
area, which indicates the recrystallized grain area is weak and susceptible to the crack initiation and propagation. Especially when the applied tension is as high as 3KN and 5KN, the small separate cracks formed along with the large edge cracks. It is suggested in rolled steel that edge crack is more likely to propagate in the soft ferrite other that strong martensite [23]. Xie et al. found that the coarse microstructure is more resistant to crack propagation than fine microstructure [29]. The numerical simulation results indicate that the mean stress is higher in the fine microstructure than that in the coarse microstructure, which results in fast crack growth rate in fine grains. In addition, Xia et al. [30] also showed that AZ31 alloys tend to deform heavily in small grain area during deformation.

5. Conclusion

In this work, different tension is applied during the on-line heating rolling of AZ31B sheets under 523 K with a single pass reduction of 40%. The conclusions from the present study are summarized below.

(1) An appropriate tension is suggested for the rolling process of AZ31B magnesium alloy sheet with respect to both edge wave and edge crack. High tension results in severe edge crack while low tension leads to edge wave.

(2) The on-line heating rolled AZ31B sheet with tension exhibit mixed microstructures of fine recrystallized grains and coarse deformed grains.

(3) Edge crack is likely to initiate and propagate in fine grain areas and the crack tip is surrounded with large portion of fine recrystallized grains.

(4) The fracture surface of edge crack show initially brittle and ductile in the crack tip as the sheets are rolled under low tension of 1KN and 3KN. As the tension increases to 5KN, the fracture surface show initially mixed ductile and brittle, the ductile fracture remains in the crack tip.

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References


Fig. 11 – Separate cracks found in the fine grain area of sheets rolled under (a) 3 KN, (b) 5 KN.


