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Significantly improvement in formability and ductility of AZ31 Mg alloy by differential temperature rolling

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1. Introduction

Mg alloys are the lightest structure material. Applying Mg alloys as engineering components is a promising method to increase fuel efficiency and cut carbon dioxide emissions in the automobile industry. However, since the hexagonal crystal (HCP) structures of most Mg alloys, the limited slip systems result in poor plasticity in room temperature (RT) [1,2]. The poor plasticity has severely restricted their possible application as load-bearing parts. Optimizing the plasticity of the wrought Mg alloys is one of the key research targets for all researchers in the Mg alloys [3–5].

The plasticity of Mg alloys can be enhanced by promoting dislocations slip and suppressing twinning. With the grain size...
reduced, the twin activation stress increases [6]. Due to its HCP structure, the grain size greatly influences on the dislocation slip and twinning [7,8]. Many efforts have been made to improve the plasticity of Mg alloys, such as alloy composition optimization, grain size refinement, and texture control. Adding rare earth elements to Mg alloys is one of the effective methods to improve plasticity. Rare earth elements such as Gd, Ce et al. are considered as beneficial elements in developing high plasticity Mg alloys [9–12]. In recent years, microalloying in Mg alloy has attracted more and more attention. Scholars have found that small addition of Ca, Al, and Zn significantly improve the plasticity of Mg alloys [13–15]. Nan Xia et al. [16] found that adding dilute Ca element can enhance the plasticity of Mg–1Zn–0.2Zr alloy. Addition 0.39 wt.% Ca in Mg–1Zn–0.2Zr can weak macro-texture and activate <c+a> slip and (10T2) twinning.

Grain refinement is an effective method to improve the plasticity of Mg alloys. Hucheng Pan et al. [17] reported that grains of the Mg–1.0Ca–1.0Al–0.2Zn–0.1Mn (wt.%) alloy can be refined to sub-micron scale. The alloy exhibits a relatively high yield strength of 425 MPa, while the elongation research is 11%. The excellent strength and plasticity balance result from sub-micron grains, nano-precipitates, and low-angle grain boundaries. Fakhar et al. [18] reported that fine-grained ZK6 Mg alloy showed low-temperature super-plasticity with a strain rate sensitivity index of 0.57 at 523 K and 0.62 at 573 K. Li et al. [19] found that appropriate combination of aging treatment and refined grains can improve not only tensile strength but also plasticity.

Wrought Mg alloys often show strong basal texture or fiber texture, which leads to mechanical properties anisotropy and aggravates the plasticity of Mg alloys [20]. Extensive efforts have been devoted to randomizing the deformation texture of Mg alloys, which has been proven effective in promoting plasticity in Mg alloys [21,22]. The texture evolution is dependent on recrystallization behavior during the plastic deformation process. Shear strain and deformation temperature are key factors that affecting texture formation in thermomechanical processing [23]. Asymmetric deformation techniques, such as asymmetric rolling [24,25], asymmetric extrusion [26–28], bending [29], and cross rolling [30,31] are frequently reported methods in the texture modification of Mg alloys. During asymmetric rolling techniques, shear deformation is introduced throughout the sheet thickness. The shear strain leads to the inclination of the (0001) plane, inducing the orientation of the recrystallized grains becomes random. Thus, the (0001) basal texture is effectively weakened.

Differential temperature rolling (DTR) is a novel rolling technique in which the temperature of upper and lower roller is different during rolling. DTR is used to manufacture clad plates in that the melting points of two metals that are very different such as Ti/Al [32] and Fe/Al [33]. Meanwhile, the temperature difference between upper and lower rollers greatly influences on microstructure inhomogeneity in thickness direction [34]. Dynamic recrystallization (DRX) can be promoted in high-temperature region, while DRX in low temperature region may be hindered for the insufficient driving force. For Mg alloy, the existence of a temperature gradient between rollers has a significant influence on grain rotation in DRX and can also change the metal flowing that may result in a unique texture. It is believed that the optimized DTR technique can weaken the strong basal texture of Mg alloys after the rolling process.

In this work, a commercial as-rolled AZ31 Mg alloy sheet was selected as the object to investigate the mechanical properties and microstructure evolution during the DTR process. The AZ31 Mg alloy was chosen because it is the most commonly used commercial alloy among Mg alloys. This selection offers some benefits. Firstly, the process of the AZ31 Mg alloy can be expanded, allowing for further optimization of its properties. Secondly, this choice emphasizes the universality of the process, suggesting its potential suitability for other Mg alloy systems. The origin of the enhancement in plasticity and microstructure optimizing mechanism of the DTR process will also be discussed.

### 2. Experiments

The Mg alloy sheet used in this study was a cast-rolled AZ31B sheet provided by Shaxi Yinguang Huasheng Magnesium Co., Ltd, PRC. The thickness of the as-received AZ31 sheet was 1 mm. The chemical composition is 3.02wt.% Al, 0.93wt.% Zn, 0.31wt.% Mn and the balance Mg measured by the X-ray fluorescence spectrometer (XRF, Shimadzu XRF1800).

The schematic diagram of DTR equipment was shown in Fig. 1. The temperature controller was equipped on the upper roller and lower roller to regulate temperature during rolling processes. Different temperatures of the upper and lower rollers were designed to achieve DTR. The DTR parameters were listed in Table 1 as follows: Route 1, the temperature of the upper roller was an ambient temperature of 25 °C, while the lower roller was 200 °C, named RT-200. Route 2, the temperature of the upper roller was 100 °C, while the lower roller was 200 °C, named 100–200. Contrasting case, the temperatures of the upper and lower rollers were ambient temperature of 25 °C, named RT–RT, which is represented to the traditional cold roller rolling. Before DTR, the specimens were homogenized at 400 °C for 2 h. The rollers were pre-heated and kept in the target temperature. The specimens were pre-heated at 200 °C for 30 min. Then, the samples were sent to a rolling mill with a 3 m/min rolling speed. All the specimens were rolled with different DTR parameters at the same reduction of 10%. After the DTR process, the sheets were...
annealed at 400 °C for 5 min to eliminate the deformation structure.

The mechanical properties of the samples were evaluated by the tensile test and Erichsen test. The tensile test was performed under a constant strain rate of $1 \times 10^{-3}$ s$^{-1}$ with the load direction parallel to the rolling direction. The yield stress was determined as the 0.2% offset. The gauge length of the tensile sample was 25 mm. The cross-section of the tensile sample was 0.5 mm $\times$ 3 mm. A hemispherical punch with a diameter of 20 mm was used for standard Erichsen tests at room temperature. In Erichsen tests, the blank holder force was 10 kN, and the punch speed was 5 mm/min.

Microstructures of as-rolled samples were investigated by optical microscope (OM) and Electron Backscatter Diffraction (EBSD). EBSD tests were carried out on the JSM-7800 F field emission scanning electron microscopy at 20 kV acceleration voltage with an emission current of 3.0 nA. Oxford Instruments Naordlys Nano EBSD system was used for data acquisition. EBSD data were analyzed by the OIM Analysis software. The observation plane of the OM and EBSD sample was in the RD-ND plane.

3. Results

3.1. Original microstructure

Fig. 2 shows the OM image and the maro-texture of the as-received AZ31 Mg alloy. After homogenization at 400 °C for 2 h, the grains present a uniform distribution with an average grain size of 21 μm. No deformed grains or ribbon grains, indicating that the grains in the as-received AZ31 Mg alloy are completely recrystallized. From the macro-texture in Fig. 2(b), the as-received AZ31 Mg alloy exhibits a typical basal texture, which means the (0001) planes of the grains are mainly parallel to the RD. The maximum texture intensity reaches 10.27. The formation of the basal texture is mainly due to the few slip systems in Mg alloys with HCP crystal structure [35,36].

3.2. Mechanical properties

Fig. 3 shows the tensile properties of as-rolled AZ31 Mg alloys with various DTR parameters. The corresponding mechanical property and the Erichsen values are listed in Table 2. The Erichsen value is used to evaluate the formability and anisotropy of the sheet. After the rolling process, the RT–RT sample shows poor ductility and formability. The fracture elongation (FE) and the Erichsen value are only 3.5% and 0.23 mm, respectively. This indicates that the cold roller significantly damages the ductility and formability of AZ31 Mg alloy sheet, which is not conducive to further deformation processing. After the DTR process, the ductility and formability are improved when the roller temperature increases. For the single roller temperature increase to 200 °C, the FE and the Erichsen value of the RT-200 sample are 16.4% and 0.83 mm, respectively. This indicates that the cold roller significantly damages the ductility and formability of AZ31 Mg alloy sheet, which is not conducive to further deformation processing. After the DTR process, the ductility and formability are improved when the roller temperature increases. For the single roller temperature increase to 200 °C, the FE and the Erichsen value of the RT-200 sample are 16.4% and 0.83 mm, respectively. The ductility and formability can be further enhanced with the other roller temperature increased to 100 °C. Meanwhile, the DTR process decreases the tensile yield strength (TYS) and ultimate tensile strength (UTS). It should be that the DTR process is beneficial to release dislocations during the plastic deformation process, thereby reducing work hardening and improving plasticity.

After annealing treatment (denoted as AT), the plastic deformation ability of the as-rolled sheet is recovered. Compared with the as-rolled state, the ductility and formability are further improved in three samples. Especially the RT-200/AT sample obtain the best enhancement, in which FE and Erichsen values are 32.4% and 4.49 mm, respectively. On

![Fig. 2](image_url) — The OM image (a) and the macro-texture (b) of the as-received AZ31 Mg alloy.
The mechanical properties and Erichsen value for the DRXed grains and deformation twins can be annealed to obtain higher plasticity. If further large deformation is required, the DTR treated sheet can be annealed to achieve continuous deformation during ordinary processing without the need for intermediate annealing. The DTR process to achieve continuous deformation during ordinary processing can significantly improve the plasticity and formability of the RT sample, the DTR samples have a significant increase in yield strength and ultimate tensile strength compared to the traditional cold roller rolling. In the case that two rollers are at RT, a symmetric shear band is formed within the sheet due to the plastic deformation and the gradient temperature induces different deformation resistance during the plastic deformation. According to Shin et al. [37], the slip resistance of Mg alloy decreases obviously at high temperatures. The reduction of the non-basal slip resistance can induce more dislocation to coordinate plastic deformation. Thus, plastic deformation in the low temperature region is difficult to coordinate, and thus forms a shear band with a large angle (Fig. 4(b)). On the contrary, shear bands formed in the high temperature region show a small angle (Fig. 4(e)). With the temperature differential decrease, the symmetry of the shear band appears again, as shown in Fig. 4(c, f). Therefore, the DTR process is characterized by asymmetric deformation, and the larger the temperature difference, the more significant the asymmetry.

Due to the severe deformation microstructure is hard to identify by the EBSD technology, the annealed sample is conducted to clarify the microstructure evolution during the DTR process. The EBSD results of the RT-200 sample after annealing are presented in Fig. 5. After annealing at 400 °C for 5 min, the deformation microstructures, such as deformation twins and shear bands, are basically eliminated. The microstructure is composed of grains in various sizes. For the region close to the RT roller, grains are mainly refined grains, containing some coarse grains, as shown in Fig. 5(a). In the central region, there are more coarse grains and fewer fine grains as shown in Fig. 5(b). For the region close to the 200 °C roller, as shown in Fig. 5(c), the grains are similar to the region close to the RT roller. The grain size distributions of three samples are displayed in Fig. 6. In the three samples, the central region has the finest grains with a size smaller than 5 μm, while the most grains with a size larger than 5 μm. The number fraction of grains with size smaller than 5 μm from the low temperature region to the high temperature region is 0.76, 0.67 and 0.73, respectively. In addition, grains with grain size greater than 20 μm are present only in the central and high temperature regions.

From the pole figure, three regions exhibit a weak (0001) basal texture compared to the original state. The maximum pole intensity gradually increases from the low temperature region to the high temperature region, which is 6.02, 6.92 and 7.21, respectively. Although the three regions exhibit basal texture, the grain orientations in all three regions are deflected to ND due to the DTR process. This phenomenon can be observed in the pole figure of the (10–10) and (11–20) plane. This grain deflection should be correlated with the shear bands. It can be seen from the IPF diagram that both fine and coarse grains present a particular directional distribution. For example, in Fig. 5(a and c), fine grains and coarse grains show a zone-like distribution. In Fig. 5(b), the distribution of fine grains is directional. This particular grain distribution is discussed in detail in Section 4.

### Table 2 - The mechanical properties and Erichsen value of as-rolled alloys.

<table>
<thead>
<tr>
<th>Sample</th>
<th>TYS (MPa)</th>
<th>UTS (MPa)</th>
<th>FE (%)</th>
<th>Erichsen value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT-RT</td>
<td>300</td>
<td>313</td>
<td>3.5</td>
<td>0.23</td>
</tr>
<tr>
<td>RT-200</td>
<td>275</td>
<td>304</td>
<td>16.4</td>
<td>0.83</td>
</tr>
<tr>
<td>100–200</td>
<td>231</td>
<td>286</td>
<td>20.8</td>
<td>1.21</td>
</tr>
<tr>
<td>RT-RT/AT</td>
<td>174</td>
<td>248</td>
<td>17.9</td>
<td>1.13</td>
</tr>
<tr>
<td>RT-200/AT</td>
<td>171</td>
<td>255</td>
<td>32.4</td>
<td>4.49</td>
</tr>
<tr>
<td>100-200/AT</td>
<td>174</td>
<td>258</td>
<td>28.6</td>
<td>3.66</td>
</tr>
</tbody>
</table>

Fig. 3 – Tensile curves of as-rolled AZ31 Mg alloys.

Fig. 4 shows the OM images of the DTR sample section in contact with rollers of different temperatures. For the RT–RT sample, part of dynamically recrystallized (DRXed) grains is found on the surface contacted with RT rollers, as shown in Fig. 4(a, d). Many deformation twins are in the region away from the surface, indicating that twinning is the dominant deformation mechanism during the rolling process. With the increment of the roller temperature, the DRXed grains and deformation twins also can be observed after the DTR process. Meanwhile, the fraction and grain size of DRXed grains is both increased. Compared to the RT–RT sample, the DTR samples present more DRXed grains and fewer deformation twins. This indicates that DRX can be better induced to coordinate the plastic deformation, effectively reducing the twinning. The reduction of the twin fractions can effectively reduce the work-hardening effect. This also explains the reason for the strength decrement after the DTR process.

For the DTR process, a gradient temperature is formed in the sample compared to the traditional cold roller rolling. In the case that two rollers are at RT, a symmetric shear band is formed within the sheet due to the plastic deformation and the gradient temperature induces different deformation resistance during the plastic deformation. The reduction of the non-basal slip resistance can induce more dislocation to coordinate plastic deformation. Thus, plastic deformation in the low temperature region is difficult to coordinate, and thus forms a shear band with a large angle (Fig. 4(b)). On the contrary, shear bands formed in the high temperature region show a small angle (Fig. 4(e)). With the temperature differential decrease, the symmetry of the shear band appears again, as shown in Fig. 4(c, f). Therefore, the DTR process is characterized by asymmetric deformation, and the larger the temperature difference, the more significant the asymmetry.

Due to the severe deformation microstructure is hard to identify by the EBSD technology, the annealed sample is conducted to clarify the microstructure evolution during the DTR process. The EBSD results of the RT-200 sample after annealing are presented in Fig. 5. After annealing at 400 °C for 5 min, the deformation microstructures, such as deformation twins and shear bands, are basically eliminated. The microstructure is composed of grains in various sizes. For the region close to the RT roller, grains are mainly refined grains, containing some coarse grains, as shown in Fig. 5(a). In the central region, there are more coarse grains and fewer fine grains as shown in Fig. 5(b). For the region close to the 200 °C roller, as shown in Fig. 5(c), the grains are similar to the region close to the RT roller. The grain size distributions of three samples are displayed in Fig. 6. In the three samples, the central region has the finest grains with a size smaller than 5 μm, while the most grains with a size larger than 5 μm. The number fraction of grains with size smaller than 5 μm from the low temperature region to the high temperature region is 0.76, 0.67 and 0.73, respectively. In addition, grains with grain size greater than 20 μm are present only in the central and high temperature regions.

From the pole figure, three regions exhibit a weak (0001) basal texture compared to the original state. The maximum pole intensity gradually increases from the low temperature region to the high temperature region, which is 6.02, 6.92 and 7.21, respectively. Although the three regions exhibit basal texture, the grain orientations in all three regions are deflected to ND due to the DTR process. This phenomenon can be observed in the pole figure of the (10–10) and (11–20) plane. This grain deflection should be correlated with the shear bands. It can be seen from the IPF diagram that both fine and coarse grains present a particular directional distribution. For example, in Fig. 5(a and c), fine grains and coarse grains show a zone-like distribution. In Fig. 5(b), the distribution of fine grains is directional. This particular grain distribution is discussed in detail in Section 4.
Fig. 7 shows the DRX distributions of the as-annealed RT-200 sample in different regions. The three regions exhibit a highly recrystallized grain structure. The number fractions of the DRXed grains from the low temperature region to the high temperature region are 96.5%, 97.3%, and 94.6%, respectively. The deformation structure shows a gradually increasing trend. In the low temperature region, as shown in Fig. 7(a), the deformed grains are mainly fine grains, indicating that recrystallization has not yet been completed. The deformed grains in the central region and the high temperature region are coarse and fine grains, illustrating that some grains have the possibility of secondary recrystallization.

4. Discussion

In this work, the AZ31 Mg alloy sheets processed by the DTR process present good plasticity and formability compared with the traditional cold roller rolling. In particular, the optimization effect achieved under the condition of large temperature difference is significantly improved. The origin of the performance improvement and microstructure optimizing mechanisms are discussed below.

4.1. Origin of the enhancement in ductility and formability

The enhancement of plastic deformation ability is related to grain orientation. Texture weakening is an effective way to improve the plastic deformation ability of Mg alloys. The EBSD results exhibit that the texture intensity of the DTR sample is weakened in both low and high temperature surfaces compared to the original state of the AZ31 sample. The relationship between grain orientation and dislocation activation can be understood by the Schmid rule [38]:

\[ \sigma_y = m \tau_{cress} \]

where \( \sigma_y \) is the yield stress, \( m \) is the Schmid factor, and \( \tau_{cress} \) is the activation stress of the slip system. For the strong basal texture Mg alloy, the Schmid factor of the basal \( \langle a \rangle \) slip is small in the deformation along the RD direction, indicating that the basal \( \langle a \rangle \) slip is hard to activate at this situation. As is known to all, basal \( \langle a \rangle \) slip is the most critical slip mode for the HCP metal [39]. Thus, Mg alloys with strong basal texture present poor plasticity. After DTR deformation, the grain orientation of a part grain is tilted, and which c-axis of the grain deviates from the ND. These grains have a large Schmid
factor for the basal <a> slip when the deformation direction is along the RD. More basal <a> slip can be activated to coordinate the plastic strain. It is also reported to be able to induce non-basal slip after the texture weakening \cite{16,40}. Therefore, after weakening the texture by the DTR process, it is helpful to improve the amount of basal <a> slip. It may even activate the non-basal slip to coordinate plastic deformation, and obtain better plastic deformation ability.

The activation of the dislocations provides excellent work-hardening effect, which is beneficial to promote the improvement of plasticity and formability. To further compare the plugging of dislocations in different states, the tensile curve is processed with the following formula \cite{41,42},

\begin{align}
\epsilon_T &= \ln(1 + \epsilon_E) \\
\sigma_T &= \sigma_E(1 + \epsilon_E) \\
\theta &= \frac{d\sigma_T}{d\epsilon_T}
\end{align}

where the $\epsilon_E$ and $\sigma_E$ is the engineering strain and stress, the $\epsilon_T$ and $\sigma_T$ is the true strain and stress, and the $\theta$ is the work-hardening rate. According to the Equal 2–4, the true strain–stress and work-hardening curves can be obtained, and related images are displayed in Fig. 8. In the plastic deformation stage, the work-hardening rate of the samples after DTR rolling is relatively close. However, the annealed samples showed a higher work-hardening rate. Meanwhile, the annealed sample presents a region resembling a yield plateau. The work-hardening rate in this region is low and then increases rapidly. The RT-200 sample exhibits the strongest work-hardening effect. This should be closely related to the shear deformation during DTR. The non-

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**Fig. 5** – The EBSD results of the as-annealed RT-200 sample in different regions (a, d) IPF and pole figure close to the RT roller (b, e) IPF and pole figure of the center, and (c, f) IPF and pole figure close to the 200 °C roller.

**Fig. 6** – Grain size distribution of the as-annealed RT-200 sample in different regions.
uniform deformation between the high and low temperature regions is larger for the RT-200 sample during DTR due to the larger temperature difference. This non-uniform deformation provides a prerequisite for the subsequent recrystallization of the weakened texture. The RT-200/AT sample shows the best texture weakening effect, and reaches the highest work-hardening rate in the 6 samples.

In order to further illustrate the optimization of AZ31 Mg alloy by DTR process, the mechanical properties and formability of AZ31 reported in literature were compared. The statistics are shown in Table 3, including traditional rolling, bending and corrugated wide limit alignment (CWLA) [43–45].

In this work, the ductility and formability of AZ31 Mg alloy optimized by DTR process are superior to the traditional rolling and annealing process. At the same time, these properties can be compared with some pre-twinned processes, bending processes and CWLA processes after rolling annealing. The AZ31 Mg alloy prepared by DTR process can improve plasticity and formability without sacrificing yield strength and tensile strength. Especially for the pre-twinned process, the induced twins greatly reduce the TYS. Although the formability is improved, the reduction of TYS is also very significant. Therefore, the AZ31 Mg alloy material prepared by DTR process has excellent mechanical properties, and has the advantage of short preparation process. The process equipment is close to the traditional rolling, and the DTR process can be realized only by modifying the conventional equipment.

4.2. Microstructure optimizing mechanism of DTR process

The reason of texture weakening during DTR is closely related to the optimization of the microstructure. To further analyze the microstructure optimizing mechanism, grains in different regions of RT-200 sample are analyzed, related images as shown in Fig. 9. Grains are divided into fine grains (<5 μm) and coarse grains (>10 μm). In Fig. 9(a1-a4), the fine grains are most in the area close to the low temperature surface, showing a trend of distribution along the RD. In the region far from the surface, coarse grains appear, and the grains show a certain directional distribution. In the region near the center, the number of fine grains is less than that near the surface, and the grain distribution exhibits a larger angle from the RD. Meanwhile, there are more coarse grains near the center, which are also distributed along a direction. For the high temperature region, the fine and coarse grains show an

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Fig. 7 – The DRX distributions of the as-annealed RT-200 sample in different regions, (a) the region close to the RT roller, (b) the center region, (c) the region close to the 200 °C roller.

Fig. 8 – (a) True strain–stress curves and (b) work-hardening rate curves of the as-rolled samples.
alternate layered distribution. The distribution of both coarse and fine grains presents an angle that is smaller than that of the fine grains in the central region.

Due to the different temperature of the upper and lower rollers, the recrystallization behavior of the microstructure is different. The effect of temperature on recrystallization behavior can be evaluated by the Z parameter [46,47],

\[
Z = \frac{Q}{RT}
\]

where \( \dot{\varepsilon} \) is the strain rate, \( Q \) is the activation energy, \( R \) is the gas constant, and \( T \) is the deformation temperature. When the deformation temperature decreases, the \( Z \) parameter increases. Large \( Z \) parameter means the DRX degree is low, which hinders the recrystallization process. For the cold roller and

<table>
<thead>
<tr>
<th>Alloy</th>
<th>State</th>
<th>TYS (MPa)</th>
<th>UTS (MPa)</th>
<th>FE (%)</th>
<th>IE (mm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31</td>
<td>As-rolled</td>
<td>160</td>
<td>250</td>
<td>15.3</td>
<td>2.79</td>
<td>[43]</td>
</tr>
<tr>
<td></td>
<td>pre-twinned and annealing</td>
<td>88.2</td>
<td>249</td>
<td>20.3</td>
<td>5.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pre-twinned, shear deformation and annealing</td>
<td>90.5</td>
<td>299</td>
<td>28.5</td>
<td>5.63</td>
<td></td>
</tr>
<tr>
<td>AZ31</td>
<td>Roll-annealed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bending at 250 °C, annealed</td>
<td>158</td>
<td>325</td>
<td>9.8</td>
<td>3.49</td>
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<tr>
<td></td>
<td>Bending at 300 °C, annealed</td>
<td>152</td>
<td>319</td>
<td>10.0</td>
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<tr>
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<td>Bending at 350 °C, annealed</td>
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<td>310</td>
<td>11.0</td>
<td>4.34</td>
<td></td>
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<tr>
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<td>Roll-annealed</td>
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<td></td>
<td>CWLA</td>
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<td>257</td>
<td>15.5</td>
<td>2.3</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>CWLA, and annealed at 250 °C</td>
<td>164</td>
<td>293</td>
<td>16.3</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CWLA, and annealed at 300 °C</td>
<td>150</td>
<td>284</td>
<td>20.2</td>
<td>4.4</td>
<td></td>
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<tr>
<td>AZ31</td>
<td>RT-200/AT</td>
<td>171</td>
<td>255</td>
<td>32.4</td>
<td>4.49</td>
<td>This work</td>
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<td></td>
<td>100-200/AT</td>
<td>174</td>
<td>258</td>
<td>28.6</td>
<td>3.66</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9 – The selected grains (with grain size less than 5 \( \mu m \) and over than 10 \( \mu m \)) and related KAM maps of the various region in RT-200/AT sample (a1-a4) the region close to the RT roller (b1-b4) the center region (c1-c4) the region close to the 200 °C roller.
the hot roller, the region of the sample near the cold roller leads a high Z parameter, and the region near hot roller have a relative low Z parameter. After DTR process, the sample surface contacted with hot roller presents a high DRX degree, while the surface contacted with cold roller shows low DRX degree. The Kernel Average Misorientation (KAM) value enables the analysis of local misorientation differences in the grain, which can evaluate the DRX degree. There is almost no local misorientation in the coarse grains, the KAM value is equal to 0. The local misorientation is observed in the fine grains of the three regions. Further quantitative analysis of the KAM value is list in Fig. 10. The higher KAM value in the central region indicates that the central region suffers a large deformation before recrystallization. This is mainly due to the difference in roller temperature generates the asymmetric deformation, leading to a large strain in the central part. As a result, the central region shows a gradient distribution of grains, with fine grains in the upper half and coarse grains in the lower half. The distribution direction of the grains shows an angle to the RD.

The fine grain region formed by shear band nucleation significantly effect on weakening texture. In order to identify the mechanism of shear bands on the texture weakening, the overall OM image of the RT-200 sheet thickness direction and related microhardness are shown in Fig. 11. From Fig. 11(a), the shear bands formed during the deformation of DTR exhibit a zone-like distribution. The angle tilt of the shear band formed in the low temperature region is large, while the angle in the high temperature region is small. It is worth noting that the central part is not perfectly symmetric, but exhibits a similar inclination angle as the low temperature region. In terms of hardness of Fig. 11(b), the hardness of the low temperature region is high, indicating that the degree of work-hardening is high. This work-hardening has a high driving force to promote static recrystallization. In addition, the hardness of the shear band is also higher than the center, indicating that the shear band is a stress concentration area, which can improve the stored energy. The hardness in the high temperature region is relatively uniform distribution, and the hardness value is slightly lower than that in the low temperature region. This indicates that a part of recrystallization occurs during the DTR process, which consumes a part of the accumulated dislocations, allowing the hardness to decrease and the microstructure to become more uniform.

This microstructure difference and the gradient distribution of hardness impact the subsequent static recrystallization behavior. The relationship between strain energy and recrystallization nucleation can be understood as follows [48],

\[ E > 4K_1 \gamma_S/L \]

where \( E \) is the strain energy, \( \gamma_S \) is the grain boundary energy, and \( L \) is the boundary length before bulging, and \( K_1 \) is the proportionality factor. Recrystallization nucleation is efficiently stimulated when the strain energy exceeds grain boundary energy. After the DTR process, a large fraction of dislocations and twins occur in the AZ31 alloys. Especially, the defects in RT-200 sample with large temperature differences exhibit a trend of gradient distribution. The gradient trend in the 100–200 sample with more minor temperature differences was gentler. This indicates that the RT-200 sample has higher storage energy and can form more recrystallized nuclei sites during the subsequent static recrystallization process. Meanwhile, the shear bands are enriched with dislocations, which is the potential recrystallization nucleation core. In the annealing process, the high-energy shear band regions are also preferentially nucleated, forming the grain structure with zone-like distribution.

For the annealing process after DTR, the grain nucleation and growth occur together. Under the thermal activation, the grain nuclei forms in the high storage energy region, while the DRXed grains start growth. The shear bands belong to the nucleation process, and fine grains are formed in the shear bands. In the DRXed grain regions, grain growth occurs and forms coarse grains. In this way, a bimodal grain structure composed of coarse and fine grains is formed. Due to the action of the cold roller and hot roller, the distribution of shear bands presents a gradient distribution. Near the cold roll, the number and the angle of shear bands are both large, and more fine grains with an angle away from RD are formed. In the high temperature region, more grains are DRXed grains, and the angle of the shear band is low. After shear band nucleation, it shows more coarse grains and forms an alternate layered distribution with the fine grains.

The grain orientation of the shear band nucleation and the DRXed grains after annealing is further analyzed as shown in Fig. 12. Line B is the fine grain formed by the shear band nucleation, and Line A is the coarse grains formed by the DRXed grain growth. The fine grains show a larger misorientation difference, while the coarse grains are relatively small. The large misorientation difference of fine grains is mainly due to various types of dislocations in the shear band. According to Jiang et al. [49], the basal <a> slip, prismatic <a> slip, and pyramid 〈c+a〉 slip can be found in the shear band. The basal dislocation motion forms the typical basal texture. The motion of non-basal dislocations can weaken the basal texture [50]. Thus, grains nucleated in shear bands have random orientations. These grains can coordinate plastic strain in the tensile deformation along the RD.

![Fig. 10](image-url) – The KAM value of the fine grains in different regions.
In general, the DTR process creates a cross-shear zone that induces asymmetric deformation and enhances the plasticity and formability of AZ31 alloy. To provide a more comprehensive understanding of this microscopic process, Fig. 13 illustrates a schematic diagram of the DTR process. As the material undergoes deformation from the cold and hot rollers, a temperature gradient field is generated within the material. The low temperature region experiences a large strain, resulting in work-hardening and material hardening. The middle part, close to the hard region, forms shear bands with a large angle from RD due to the difficulty of deformation. These shear bands contain a significant number of dislocations and twinning, which facilitate subsequent static recrystallization. The high temperature region forms more DRXed grains, which can coordinate some of the strains and form the soft region. However, in the soft region, shear bands with a smaller angle from RD are formed because DRX can coordinate strain. This microstructure difference caused by the cross-shear zone has a significant impact on the subsequent static recrystallization. After static recrystallization, the microstructure of the material from the low temperature region to the high temperature region is as follows: the fine grain region parallel to RD, the zone-like grain region with an angle far from RD, and the alternate layered distribution of the coarse and fine grains (grains show an angle from RD). As an asymmetric deformation technique, the DTR process has the capability to create a unique hierarchical

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Fig. 11 – The OM image (a) and related hardness distributions (b) of the RT-200 sheet. The observation position is in the RD-ND plane.

Fig. 12 – The misorientation distribution in fine grains and coarse grains along the direction of grain distribution, (a) the IPF map with line A and B marked, (b) the misorientation distribution of line A and B, (c) related IPF of fine grains, and (d) related IPF of coarse grains.
structure. The current literature mainly focuses on texture weakening, which has a good effect on improving plasticity and formability [51–53]. However, the grain refinement and the composition of the hierarchical structure have not been addressed. Moreover, this unique microstructure activates more deformation modes during plastic deformation, effectively improving the plasticity and formability.

5. Conclusions

In this work, we conducted the DTR process on AZ31 alloys and investigated the microstructure evolution and mechanical properties. The results demonstrate that the DTR process significantly enhances the plasticity and formability of AZ31 Mg alloy. Specifically, the ductility and formability of the RT-200 sample are comparable to those of the traditional cold rolling and annealing combination process, with FE and Erichsen values of 32.4% and 4.49 mm, respectively. The improvement in ductility and formability is mainly attributed to the texture weakening resulting from the temperature gradient formed during the DTR process. This gradient leads to the formation of a bimodal grain structure composed of fine and coarse grains, exhibiting a gradient distribution due to the different deformation modes between the low and high temperature regions. The resulting microstructure includes a fine grain region parallel to RD, a zone-like grain region with an angle far from RD, and an alternate layered distribution of coarse and fine grains. This unique microstructure activates more deformation modes during plastic deformation, effectively improving the plasticity and formability of the material.

The properties of AZ31 Mg alloy treated by DTR process are comparable to those achieved by the traditional cold rolling and annealing combination, making it a promising method for achieving continuous deformation during hot rolling. Furthermore, the excellent plasticity and formability of the Mg alloys after the DTR process enable them to be processed twice, further promoting the application of Mg alloys.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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