

Article

Recrystallization and Anisotropy of AZ31 Magnesium Alloy by Asynchronous Rolling

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Abstract: In this study, the microstructure and mechanical properties of AZ31 magnesium alloy were investigated through asynchronous rolling. The results demonstrate that the rolled sample exhibits a refined grain structure with a significant presence of continuous dynamic recrystallization. Notably, as the roll speed ratio increases, the grain refinement becomes more apparent. For the sample with a roll speed ratio of 1.3, the tensile strength in the rolling direction (RD) reaches 273 MPa, while the elongation measures 20.2%. Similarly, in the transverse direction (TD), the tensile strength reaches 282 MPa, accompanied by an elongation of 18.9%. These values indicate a substantial improvement in elongation compared to conventional rolling processes. The enhanced elongation can be attributed to two primary factors. Firstly, recrystallization contributes to a grain refinement recrystallization ratio of 86%, promoting improved mechanical properties. Secondly, the recrystallized grains induce a favorable Schmidt factor, further supporting elongation. Overall, the findings of this research highlight the benefits of asynchronous rolling in refining the microstructure and enhancing the mechanical properties of AZ31 magnesium alloy.

Keywords: AZ31; asynchronous rolling; microstructure; mechanical property; texture



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1. Introduction

Magnesium alloys possess relatively low strength [1,2]; however, they exhibit significant potential for utilization in transportation systems, including automobiles and aerospace applications [3–5]. Among these alloys, AZ31 stands out as a widely employed and highly favored wrought alloy [4,6]. Nevertheless, the conventional rolling process employed for magnesium alloys tends to retain the robust substrate texture commonly observed during ingot rolling [7–9]. The resulting texture strongly influences the ductility of magnesium alloys, giving rise to anisotropic behavior within the material [10]. Asynchronous rolling (differential speed rolling), a technique involving the differential rotation of two identical rolls at varying speeds, effectively applies substantial plastic strain uniformly across the thickness of the deformed workpiece [11–13]. This process serves to weaken the development of pronounced textures during rolling. The adoption of asymmetric rolling is anticipated to yield improvements in grain refinement, mechanical properties, and formability characteristics of the alloy [14].

Ebrahim Tolouie's study [8] proposes an asynchronous cold rolling technique and investigates the microstructure and the corresponding texture evolution of AZ91 magnesium alloy. It was noted that asynchronous cold rolling was effective in activating continuous dynamic recrystallization (CDRX). Asynchronous cold rolling weakened the basal organization of AZ91 alloys, and the initial non-basal organization stimulated CDRX, resulting in a non-basal organization. Jae-Hyung Cho [15] performed Asynchronous hot rolling on AZ31B magnesium alloy. The intensity of the substrate texture decreases with increasing rolling temperature. The shear deformation produced by asynchronous rolling also reduced the substrate's strength. Synchronous rolling followed by asynchronous finish

rolling effectively reduced the substrate strength and improved the mechanical properties. The shear bands formed during hot rolling contain many twins and off-base textures, which increase the elongation. Kim [16] et al. conducted an asynchronous rolling process with upper and lower rolls on AZ31 sheets. By introducing significant shear deformation, they achieved remarkable grain refinement during the asynchronous rolling process. Ucuncuoglu et al. [17] found that the asynchronous rolling process caused changes in the microstructure, mechanical properties, and texture of thin plate AZ31 magnesium alloy, with increased shear strain leading to varying degrees of inclination in the texture peak direction of the specimens. Biswas et al. [18] conducted a study on the microstructure, texture, and mechanical properties of pure magnesium using asynchronous rolling. Their findings revealed that asynchronous rolling led to a deviation in the basal texture under the given conditions. The study conducted on Kaseem [19] reveals that the use of DSR leads to the creation of a microstructure that is notably more homogeneous, exhibiting fewer twin boundaries and a greater extent of recrystallization. This observation can be attributed to the substantial accumulation of shear strain induced by DSR, resulting in a microstructure characterized by its uniformity and a heightened propensity for dynamic recrystallization (DRX). In Watanabe's investigation [20] on asynchronous rolling conducted at various temperatures, it was determined that materials processed at lower temperatures exhibited enhanced ductility. This improvement could be attributed to subtle alterations in basal orientation and/or a reduction in grain size. The research conducted by Gong et al. reveals that the DSR-treated ZK60 plates exhibit significantly improved elongation properties, albeit with a slight decrease in tensile strength compared to the ESR-treated plates [21]. DI Zhao [22] pointed out that the improvement in anisotropy is mainly due to the weakening of matrix weave, finer grain size, and uniform organization caused by the accelerated DRX process.

Zhang [23] investigated that asynchronous rolling improves ductility due to the tilting and weakening of the matrix texture. Luo Dan [13] showed that the elongation failure rate of AZ31 alloy sheets treated by asynchronous rolling was significantly improved at room temperature compared to conventional rolling, mainly due to the attenuated basal texture. These findings suggest that the attenuation of this specific texture is attributed to the introduction of shear strain during processing. Bo Che et al. [24] studied the introduction of twinning and a second phase in AZ31 magnesium alloy samples during rapid cooling, rapid heating, and slow heating, which can significantly hinder dislocation movement and effectively coordinate deformation. Hao Chen [25] pointed out that the rolled AZ31 magnesium consists of coarse deformed grains with high energy storage, deformation twins, and recrystallized grains with free strain. Annealing increases the grain size and reduces the number of dislocations, twins, and second-phase particles.

Jia Weitao's research [26] suggests that the deformation and fracture behavior of twin roll-cast AZ31 magnesium alloy are not only highly sensitive to temperature and strain rate but also closely related to stress state. Yuzhi Zhu [27] pointed out that textured magnesium alloys typically exhibit anisotropic mechanical behavior due to the asynchronous activation of different twin and slip modes. This study focuses on the $\langle c + a \rangle$ conical slip response of rolled AZ31 magnesium alloy under two loading conditions (compression loading along the normal direction and tensile loading). Under the condition that the compression loading direction is closely parallel to the c -axis of the grain, tensile twins and substrate slip are inhibited, and $\langle c + a \rangle$ dislocations become active and tend to aggregate at grain boundaries to form dislocation walls. Humphreys and Hatherly [28] proposed that the process of dynamic recrystallization (DRX) involves minimal boundary migration and lacks a clear demarcation between nucleation and growth. As a result, this mechanism falls under the category of continuous recrystallization (CDRX) mechanisms. In a study by Yang et al. [29], the grain refinement mechanism in AZ31 magnesium alloys was investigated using multi-directional forging within a temperature range of 423 K to 623 K. It was observed that the formation of new grains was accompanied by the development of kink bands. Consequently, the DRX mechanism in this context was also classified as CDRX [1,9].

These findings indicate that the DRX mechanisms controlling AZ31 magnesium alloys are typically governed by CDRX. The grain fragmentation effect was thoroughly studied by V. N. Perevezentsev [30]. gradual substructure evolution leading to refined, highly disoriented crystals; the evolving grain fragments are called “cell blocks”.

Hot rolling under high strain is a valuable industrial technique known for its ability to refine the grain size, break up second-phase particles, and enhance the strength of magnesium alloy sheets [31]. As a result, this study focused on examining the effects of high-pressure asynchronous rolling under high strain on the evolution of the microstructure and properties of AZ31 magnesium alloy sheets. The objective was to utilize the DSR method to enhance the overall performance of AZ31 magnesium alloy sheets while reducing the intensity of the texture.

2. Materials and Methods

The material used for the rolling experiments was AZ31 magnesium alloy in the extruded state, which had undergone 12 h of solid solution at 380 °C. The composition of the material was as follows: Al—3.18%, Zn—1.21%, Mn—0.31%, Si—0.074%, Fe—0.003%, with the remaining balance being Mg. The original plate had a thickness of 10 mm, and each rolling pass resulted in an undercut of 2.5 mm. After three passes of asynchronous rolling, a final plate thickness of 2.5 mm was achieved, resulting in a total undercut of 75%.

To ensure a uniform internal temperature, the plates were subjected to a heat treatment in a furnace at 300 °C for 30 min prior to rolling. The sheet is extracted from the furnace at a temperature of 300 °C and promptly subjected to rolling, where the roller’s temperature is set at 200 °C. Upon the completion of the rolling process, the sheet’s temperature is estimated to be approximately 170 °C. The rolling process involved the upper roller speed being unchanged, with the upper roller speed being 0.8 m/s, the lower roller speed being 1, 1.1, 1.2, and 1.3 times the upper roller speed, and the corresponding samples being named R0, R1, R2, and R3, respectively.

For the room temperature tensile experiments, a SANS CMT 5000 (MTS, Shenzhen, China) universal testing machine with a strain rate of 10^{-3} s^{-1} was utilized. Tensile specimens were obtained from both the rolling direction (RD) and the transverse direction (TD). The specimens were sampled at a pitch of 15 mm and had a cross-section of $3.5 \times 2.5 \text{ mm}^2$. To prepare the sample for examining its microstructure and morphology, it is necessary to perform a series of polishing steps. Firstly, the sample should be polished using sandpaper with a grit size ranging from 400# to 2000#. This step ensures the removal of any surface irregularities and imperfections. Subsequently, the sample is polished using SiO_2 , which further enhances the surface finish. For electron backscatter diffraction (EBSD) sample preparation, the polished sample is subjected to argon ion polishing at specific parameters. This involves applying a voltage of 6 kV and a current of 2.5 mA for a duration of 1 h. The sample is positioned at a tilt angle of 6° during this process. Argon ion polishing helps refine the sample surface and prepare it for EBSD analysis. Microstructure observation and EBSD testing are conducted using specialized instruments. An electron probe microscope, specifically the JXA-8530F model (JEOL, Akishima City, Tokyo, Japan), is utilized for microstructure observation. Additionally, a scanning electron microscope, the ZEISS Sigma 500 (Carl Zeiss AG, Oberkochen, Germany), equipped with an EBSD probe, is employed for EBSD testing. During microstructure detection, a working distance of 15 mm is maintained between the microscope and the sample. EBSD analysis is performed using a sample tilt angle of 70 degrees and a voltage of 20 kV. A step size of 0.25 μm was used. Specifically, HKL Channel 5 is utilized for the calculation and analysis of the EBSD data.

3. Results

Figure 1 portrays the initial state of the AZ31 magnesium alloy prior to the rolling process. Through electron probe microanalysis (EPMA), the microstructure morphology reveals the presence of α -Mg (the primary phase) and a white second phase known as β - $\text{Mg}_{17}\text{Al}_{12}$ [32]. This second phase is composed of magnesium (Mg) and aluminum (Al),

as indicated by the energy spectrum in Figure 1b. Additionally, the β -Mg₁₇Al₁₂ phase is distributed along the extrusion direction.

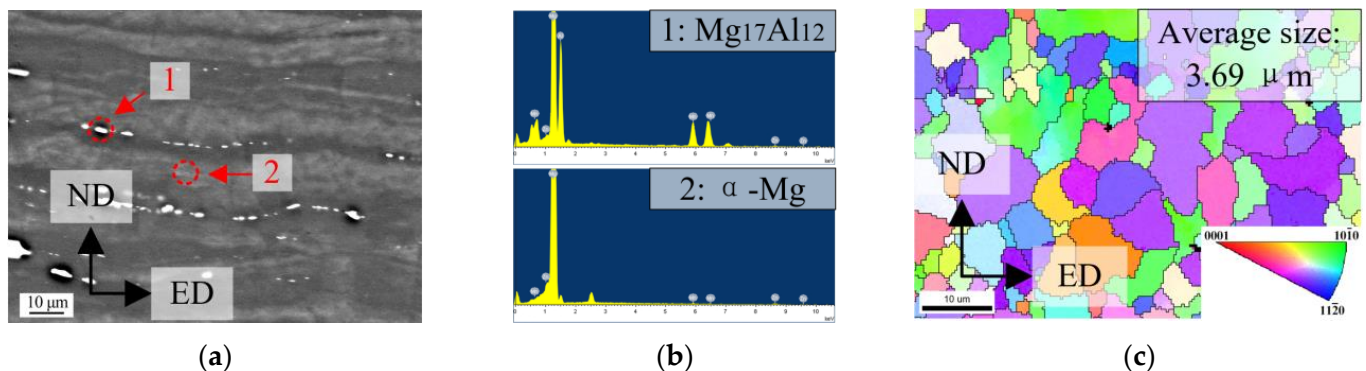


Figure 1. Microstructure of AZ31 magnesium alloy before rolling: (a) SEM of AZ31 magnesium alloy; (b) Energy spectrum of Mg₁₇Al₁₂ and Mg; (c) IPF of AZ31 magnesium.

Furthermore, Figure 1c illustrates the Inverse Pole Figure (IPF) plot obtained through EBSD (ED refers to extrusion direction). A comprehensive analysis of the plot revealed an average grain size of 3.69 μ m.

Figure 2 presents the mechanical properties of the rolled AZ31 magnesium alloy, focusing on the rolling direction (RD) and transverse direction (TD). Figure 2a displays the stress-strain curves, while Figure 2b presents the corresponding data results for the samples.

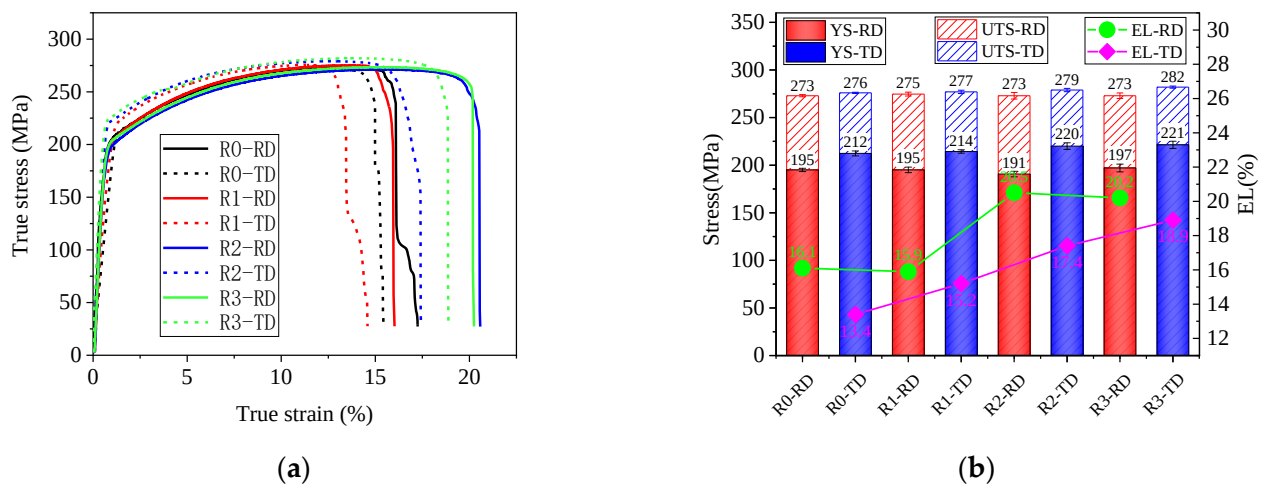


Figure 2. Tensile stress-strain curves and mechanical properties of AZ31 magnesium alloy: (a) Tensile stress-strain curves; (b) mechanical properties (YS, UTS, and EL) of rolled AZ31.

It is evident that the RD direction of the initial rolled sample (R0) exhibits a yield strength (YS) of 195 MPa, a tensile strength (UTS) of 273 MPa, and an elongation (EL) of 16.1% in Figure 2. In the TD direction, the YS measures 212 MPa, the UTS is 276 MPa, and the elongation is 13.4%. Comparing these directions, the TD direction demonstrates increased yield and tensile strengths but decreased elongation.

For the asynchronously rolled samples R1–R3, the yield strength and tensile strength in the RD direction remain almost unchanged. Similarly, the yield strength and tensile strength in the TD direction show slight increases. Specifically, the yield strength increases from 212 MPa to 221 MPa, and the tensile strength increases from 276 MPa to 282 MPa.

Moreover, the elongation in the RD direction experiences a notable increase from 16.1% to 20.5%, representing a 27.3% improvement. Similarly, the elongation in the TD direction increases from 13.4% to 18.9%, showcasing a 41.0% enhancement. These results

indicate that asynchronous rolling is a feasible technique for increasing the elongation without compromising the tensile strength and yield strength of AZ31 magnesium alloy. To further analyze the reason behind the improved elongation, a microstructural analysis was conducted.

Figure 3 exhibits the backscattered morphology of the electron probe for samples R0–R3. The image reveals the presence of not only the primary β -Mg₁₇Al₁₂ phase but also fine phases. This fine phase in the rolled sheet may originate from the original β -phase during rolling. These finely precipitated phases serve as nucleation sites for subsequent recrystallization processes.

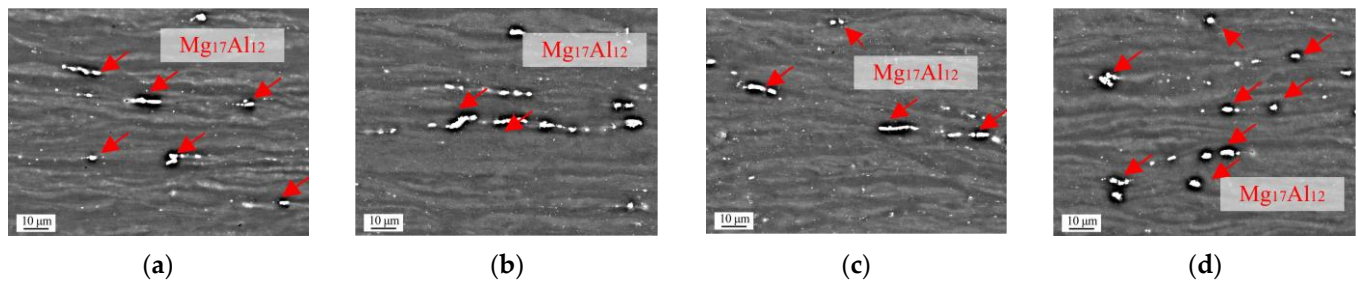


Figure 3. SEM of AZ31 rolled magnesium alloy: (a) R0; (b) R1; (c) R2; (d) R3, the red arrows point to β -Mg₁₇Al₁₂.

Figure 4 displays the IPF+ grain boundaries of samples R0–R3. The color-coded representation indicates low angle grain boundaries (LAGBs) ranging from 2° to 5° in red, LAGBs from 5° to 15° in green, and high-angle grain boundaries (HAGBs) exceeding 15° in black. The average grain sizes for the samples are 2.86 µm, 2.63 µm, 2.74 µm, and 2.41 µm, respectively. Notably, asynchronous rolling, particularly with a roll speed ratio of 1.3, significantly refines the grain size of the R3 sample.

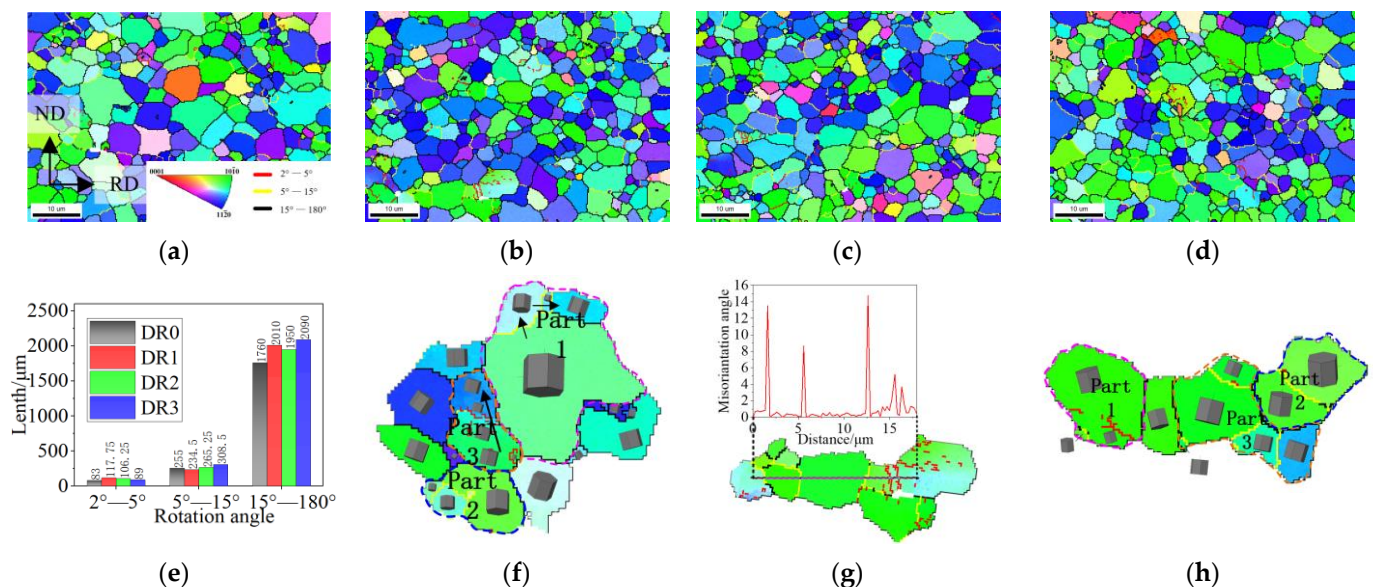


Figure 4. IPF and grain boundaries diagram of AZ31 magnesium alloy: (a) R0; (b) R1; (c) R2; (d) R3; (e) grain boundaries length of different rotation angles; (f) detail grain orientation of R0; (g) detail grain orientation of R1; (h) detail grain orientation of R3.

Figure 4e illustrates the grain boundary lengths for angles of 2–5°, 5–15°, and 15–180°. When combined with Figure 4a–d, it becomes apparent that the samples contain a considerable number of LAGBs, indicating the presence of CDRX throughout the rolling process.

Figure 4f–h provide detailed views of partial grains for samples R0, R1, and R3. In Part 1 of Figure 4f, small deflections can be observed in the grains, gradually transforming them into crystalline grains. This indicates the occurrence of continuous dynamic recrystallization [22]. Furthermore, Part 3 exhibits discontinuous grain boundaries within the range of 2–5°. In Figure 4g, the orientation differences observed in grains formed by LAGBs indicate the presence of CDRX occurring in multiple grains.

Moving on to Figure 4h, Part 1 reveals the existence of LAGBs within the grains. Parts 2 and 3 illustrate CDRX. Furthermore, it is worth noting that the second phase of the alloy serves as nucleation sites, and these heterogeneous nucleation sites are more likely to produce DDRX [22,33].

In order to distinguish between recrystallized grains and deformed grains, a grain orientation extension (GOS) diagram describing internal orientation differences was used. It seems that the GOS approach, using a threshold value of 2–5°, can only differentiate the “recently-recrystallized” grains. As dynamic recrystallization (DRX) is a continuous process, grains with a GOS value below two are considered dynamic recrystallized (DRXed) grains. In total 2–5 are sub-structured grains, and grains greater than 5° are deformed grains [34]. Figure 5 depicts the GOS of AZ31 and the Kernel Average Misorientation (KAM) diagram of the rolled AZ31 magnesium alloy. As commonly recognized, KAM maps serve as a tool to depict the localized dislocation density and strain level within the microstructure [5]. Table 1 shows the statistical values for Figure 5a–d. As can be seen from the figure, most of the grains are recrystallized, which is due to the higher deformation temperature and larger deformation. Table 1 reveals that as the rolling speed ratio increases, the proportion of recrystallized grains gradually rises while the proportion of deformed grains decreases. From the KAM diagram, it can be seen that the KAM values are higher in deformed and sub-structured grains, which indicates that the dislocation density is higher in these grains. This phenomenon can be mainly attributed to the shear force exerted by the rolls on the rolled plate during asynchronous rolling [13,18]. The shear force plays a crucial role in enhancing the degree of recrystallization in the material [19].

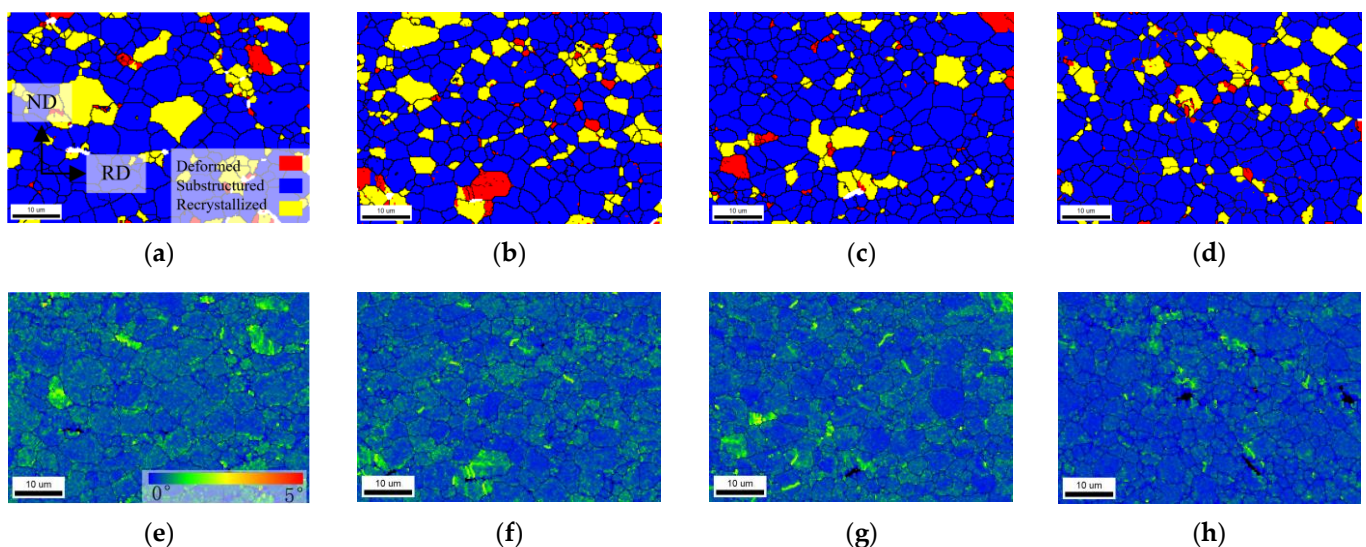
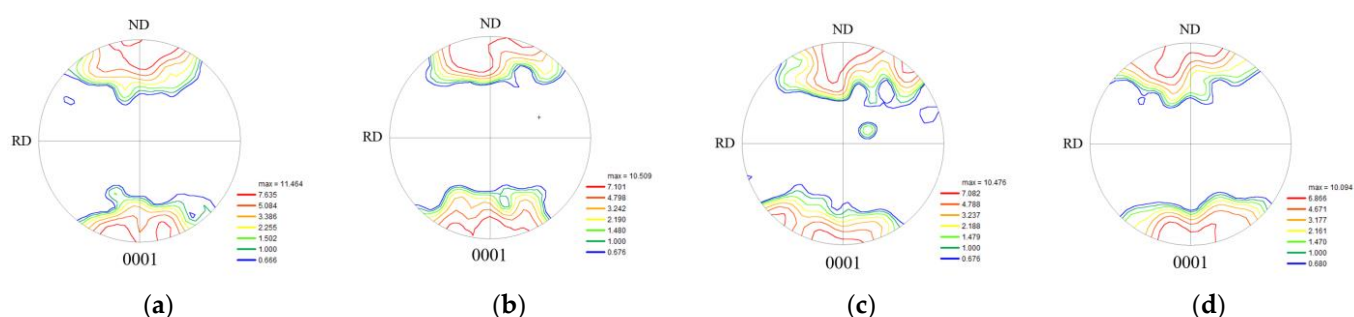


Figure 5. Recrystallization distribution of AZ31 magnesium alloy after rolling: (a) R0; (b) R1; (c) R2; (d) R3 (Red represents deformed grains, yellow represents sub-structured grains, and blue represents recrystallized grains); KAM of AZ31 magnesium alloy after rolling: (e) R0; (f) R1; (g) R2; (h) R3.

Table 1. Recrystallization fraction of rolled AZ31 magnesium alloy.

Recrystallized Fraction/%	Deformed	Substructured	Recrystallized
R0	3.07	19.25	77.68
R1	5.08	18.91	76.01
R2	3.93	9.83	86.24
R3	1.87	12.02	86.11

Figure 6 presents the Pole Figure (PF) plots of samples R0–R3. The plots reveal that all the plates exhibit weaving in the $\{0001\}$ //ND direction, with varying intensities. The maximum intensity is observed in R0, measuring 11.464, followed by R1 with 10.509, R2 with 10.476, and R3 with 10.094.

**Figure 6.** PF diagram of rolled AZ31 magnesium alloy: (a) R0; (b) R1; (c) R2; (d) R3.

Interestingly, the intensity of weaving gradually decreases as the rolling rate ratio increases. This reduction can be attributed to the deflection of grain orientation during the recrystallization process [22]. The deflection leads to the diffusion of the weave structure and subsequently decreases the intensity of weaving in the material.

Figure 7 illustrates the Schmidt factors (SFs) of samples R0–R3 in the RD and TD directions for basal plane slip, column plane slip, and conical plane slip.

In Figure 7a, the Schmidt factors of $\{0001\}$ [11–20] in the RD and TD directions are compared. It can be observed that the Schmidt factors in the RD direction are generally lower than those in the TD direction. This suggests that the post-rolling orientation is more favorable for slips in the TD direction.

Moving on to Figure 7b, the Schmidt factors of $\{1\bar{1}00\}$ [11–20] are shown. It is evident that the Schmidt factors in the RD direction are all greater than 0.4, indicating that column surface slip in the RD direction is easily initiated during the deformation process [35]. Conversely, the Schmidt factor values in the TD direction are relatively small, suggesting that activating the column surface slip system in the TD direction is more challenging.

Figure 7c presents the Schmidt factors of $\{11\bar{2}2\}$ [11–23]. Both the RD and TD directions exhibit Schmidt factors above 0.4, indicating a higher probability of initiating conical surface slip. In terms of Schmidt factors, basal slip, column slip, and conical slip can be initiated in the RD direction. However, in the TD direction, the Schmidt factor for column slip is relatively small [35]. This discrepancy in Schmidt factors may be one of the significant reasons for the differences in mechanical properties observed between the RD and TD directions.

Figure 8 shows the fracture of AZ31-rolled samples, and Figure 8a shows the fracture in the direction of RD of synchronous rolling. From the fracture morphology, it is seen that there are a large number of tough nests, from which it can be judged that the fracture mode is toughness fracture, and some second phases are shown, which play a role in strengthening during the tensile process. All the other samples also showed a large number of dimples, with finer and deeper toughness pits in Figure 8d,h, further confirming the excellent mechanical properties of the R3 samples.

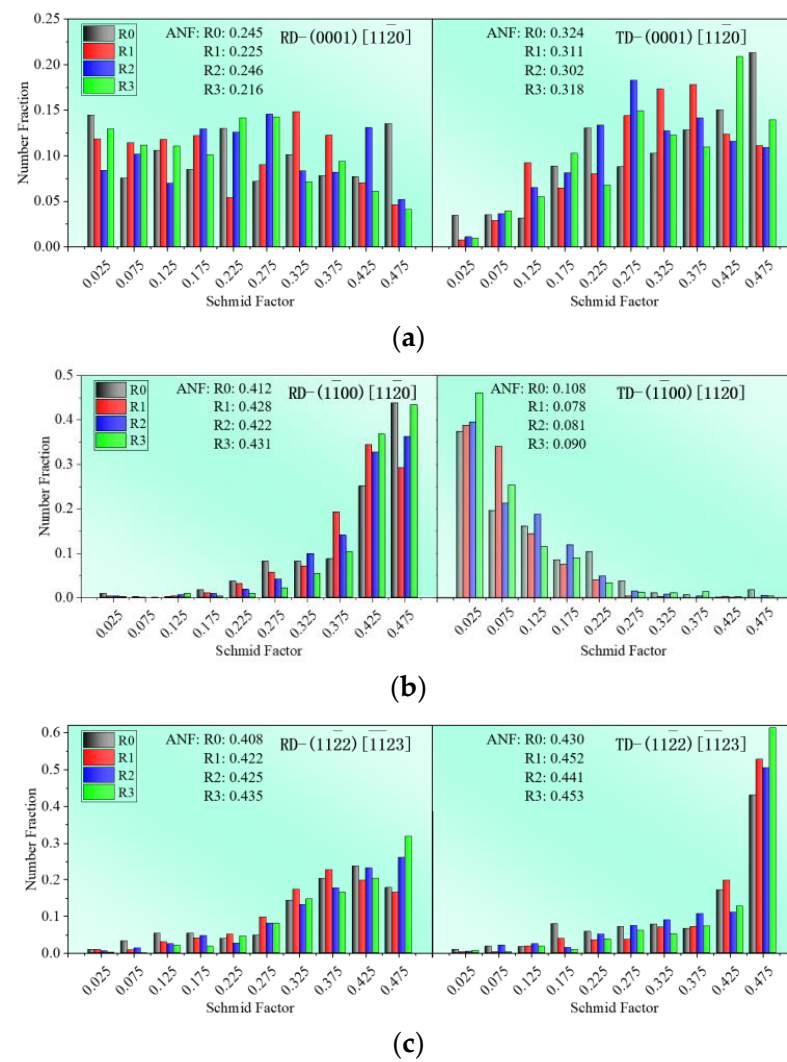


Figure 7. Schmidt factor for rolled AZ31 magnesium alloy: (a) (0001) [11–20] of RD and TD; (b) (1–100) [11–20] of RD and TD; (c) (11–22) [11–23] of RD and TD.

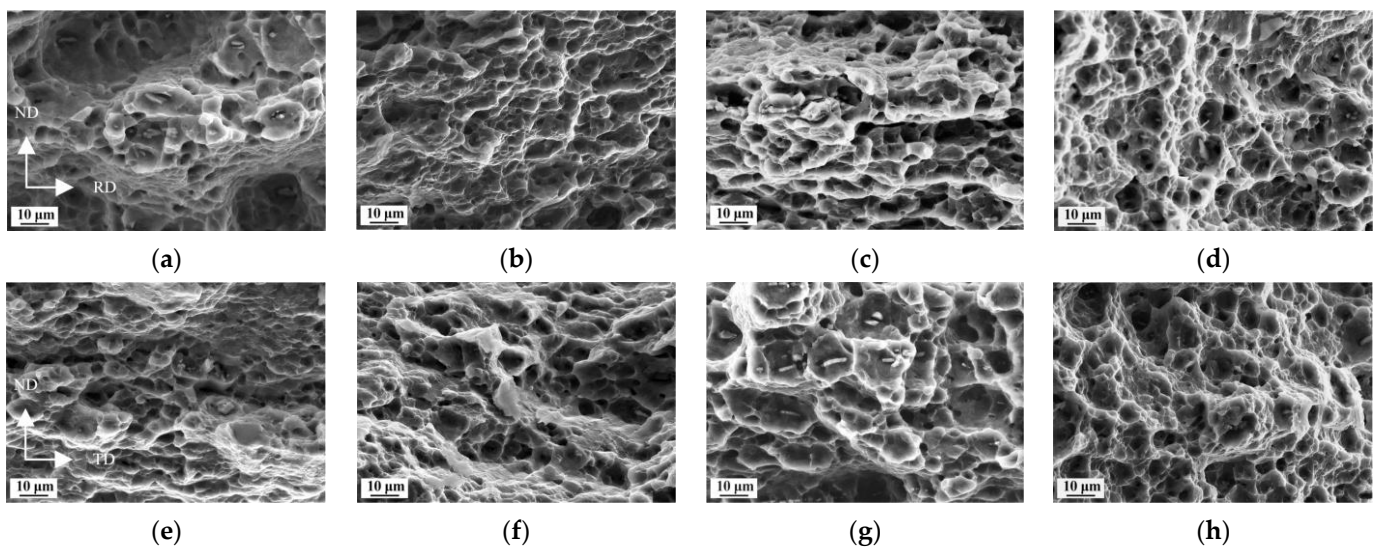


Figure 8. SEM morphology of the tensile fracture surfaces of the alloy specimens after rolled processes: (a) R0-RD, (b) R1-RD, (c) R2-RD, (d) R3-RD, (e) R0-TD, (f) R1-TD, (g) R2-TD, (h) R3-TD.

4. Discussion

The second phase of deformed magnesium alloys is generally distributed along the direction of deformation [6]. The distribution of the second phase is fairly similar between samples subjected to asynchronous rolling and synchronous rolling, with both exhibiting $\text{Mg}_{17}\text{Al}_{12}$ as the second phase and both being distributed along the rolling direction. However, a notable disparity exists in terms of grain size. In the synchronously rolled samples, the average grain size is $2.86\text{ }\mu\text{m}$; however, the samples processed by asynchronous rolling have smaller grain sizes, with $2.63\text{ }\mu\text{m}$ for the sample with a rolling speed ratio of 1.1 and $2.74\text{ }\mu\text{m}$ for the sample with a rolling speed ratio of 1.2, and the grain size of the sample with a rolling speed ratio of 1.3, in particular, is $2.41\text{ }\mu\text{m}$ for the sample with the R3. This can be explained by the fact that when the rolling process occurs, the combination of elevated temperatures, substantial pressure variations, and shear stresses caused by asynchronous rolling generates increased stresses and leads to the formation of a greater number of dynamically recrystallized (DRX-ed) grains at higher roll speed ratios [23]. The Hall-Petch relationship is a theoretical model that describes the relationship between grain size and mechanical properties in materials. According to this relationship, when the grain size decreases, the strength of the material increases. When a material undergoes dynamic recrystallization (DRX), the original coarse grains are replaced by fine grains with smaller sizes. As a result, grain boundary strengthening occurs, leading to an increase in the tensile yield strength (TYS) of the material [16,22].

It has been reported that the DRX of magnesium alloys is predominantly discontinuous dynamic recrystallization (DDRX) when the heat distortion temperature is above $250\text{ }^{\circ}\text{C}$, and below $250\text{ }^{\circ}\text{C}$, the DRX mechanism of magnesium alloys changes from DDRX to CDRX [36]. In this study, throughout the rolling process, dynamic recrystallization takes place, predominantly in the form of CDRX (Figure 4f–h). While this mechanism of recrystallization reduces the basal texture, it does not completely eradicate it [6]. Hence, the structure resulting from rolling remains intact, albeit with diminishing strength as the roll speed ratio increases.

The existence of rolled texture introduces anisotropy in the rolled plates, manifesting distinct properties along the rolling direction (RD) and transverse direction (TD) [27,35]. The yield and tensile strengths in the RD direction of the synchronously rolled R0 samples are less than those in the TD direction, and the elongation is opposite, with those in the TD direction being less than those in the RD direction. The pattern of yield strength and tensile strength in the RD direction for the other samples is consistent. The elongation in the RD direction and the elongation in the TD direction gradually increase with the increase in roll speed ratio.

Due to the pronounced anisotropy of the rolled sheet, the Schmidt factor in the RD direction is different from the Schmidt factor in the TD direction, resulting in different slip mechanisms in the RD and TD directions [6,13]. In material microstructure analysis, the Schmid factor (SF) is commonly used to characterize the deformation mechanism of magnesium alloys under different orientation conditions [2,24,27]. The SF values of basal plane slip ($\langle a \rangle$ slip) RD-(0001) [11–20] for the R0–R3 samples range from 0.21 to 0.25, which is smaller than that for a slip in the TD direction. The SF values of the prismatic slip ($\langle c \rangle$ slip) (1–100) [11–20] in the RD direction are larger and are more easily activated during deformation; however, the values in the TD direction are smaller, indicating that this slip system is more difficult to activate. The values for the pyramidal slips are all greater than 0.4, indicating that they are all easier to activate. This easier slipping of grains leads to a decrease in yield strength and an increase in elongation [24]. This would result in greater strength in the RD direction than the TD direction but less elongation in the TD direction. Therefore, the reason for the higher strength of the R3 sample than the other samples is the relatively small grain size, and the main reason for the difference in the properties of all plates in the RD and TD directions is the difference in SF.

5. Conclusions

This study used asynchronous rolling technology with large deformation to conduct rolling experiments on AZ31 magnesium alloy plates with roller speed ratios of 1, 1.1, 1.2, and 1.3 and a deformation of 75% at 300 °C. Then, detailed microstructure characterization of these rolled plates was carried out using SEM, XRD, and EBSD detection methods. The following conclusions can be drawn:

1. With an increase in the roll speed ratio, significant improvements are observed in the material's mechanical properties. In the RD (rolling direction), the elongation rate increases from 16.1% to 20.2%, while in the TD (transverse direction), it increases from 13.4% to 18.9%. Additionally, there is a slight enhancement in both the tensile strength and yield strength of the material. These improvements contribute to the overall enhancement of the material's mechanical performance.
2. During the rolling process, the deformation mechanism of AZ31 magnesium alloy is primarily continuous dynamic recrystallization, which can be attributed to the motion and accumulation of dislocations, leading to the formation of low-angle grain boundaries measuring 2–5°. Subsequently, these boundaries gradually transform into grain boundaries ranging from 5 to 15° or greater than 15°.
3. The main factor affecting the mechanical properties is the grain size; the sample with a roll speed ratio of 1.3 has the smallest grain size and the least deformed grains, and the Schmidt factor value is higher than that of other samples, which is beneficial for elongation. The Schmidt factor of (1–100) [11–20] has a significant difference in values in the RD and TD directions, which is one of the main reasons for the performance differences between the two directions.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Su, J.; Sanjari, M.; Kabir, A.S.H.; Jung, I.-H.; Yue, S. Dynamic recrystallization mechanisms during high speed rolling of Mg–3Al–1Zn alloy sheets. *Scr. Mater.* **2016**, *113*, 198–201. [\[CrossRef\]](#)
2. Zhi, C.; Lei, J.; Xing, H.; Huang, Z.; Xu, H.; Jia, W.; Ma, L. Tensile fracture prediction of AZ31 cast-rolled sheet based on hot working map. *J. Mater. Res. Technol.* **2023**, *23*, 3272–3283. [\[CrossRef\]](#)
3. Huang, Z.; Qi, C.; Zou, J.; Lai, H.; Guo, H.; Wang, J. Edge crack damage analysis of AZ31 magnesium alloy hot-rolled plate improved by vertical roll pre-rolling. *J. Magnes. Alloys* **2021**, *11*, 2151–2164. [\[CrossRef\]](#)
4. Estrada-Martínez, J.A.; Hernández-Silva, D.; Al-Samman, T. Hot Rolling of Magnesium Single Crystals. *Metals* **2021**, *11*, 443. [\[CrossRef\]](#)
5. Lee, S.W.; Kim, S.-H.; Park, S.H. Microstructural characteristics of AZ31 alloys rolled at room and cryogenic temperatures and their variation during annealing. *J. Magnes. Alloys* **2020**, *8*, 537–545. [\[CrossRef\]](#)
6. Li, Y.Q.; Li, F.; Kang, F.W.; Du, H.Q.; Chen, Z.Y. Recent research and advances in extrusion forming of magnesium alloys: A review. *J. Alloys Compd.* **2023**, *953*, 170080. [\[CrossRef\]](#)
7. Tolouie, E.; Jamaati, R. Asymmetric cold rolling: A technique for achieving non-basal textures in AZ91 alloy. *Mater. Lett.* **2019**, *249*, 143–146. [\[CrossRef\]](#)
8. Guo, L.; Fujita, F. Modeling the microstructure evolution in AZ31 magnesium alloys during hot rolling. *J. Mater. Process. Technol.* **2018**, *255*, 716–723. [\[CrossRef\]](#)

9. Chang, L.; Kang, S.; Cho, J. Influence of strain path on the microstructure evolution and mechanical properties in AM31 magnesium alloy sheets processed by differential speed rolling. *Mater. Des.* **2013**, *44*, 144–148. [\[CrossRef\]](#)
10. Huang, X.; Suzuki, K.; Saito, N. Microstructure and mechanical properties of AZ80 magnesium alloy sheet processed by differential speed rolling. *Mater. Sci. Eng. A* **2009**, *508*, 226–233. [\[CrossRef\]](#)
11. Chen, X.-M.; Lin, Y.; Chen, J. Low-cycle fatigue behaviors of hot-rolled AZ91 magnesium alloy under asymmetrical stress-controlled cyclic loadings. *J. Alloys Compd.* **2013**, *579*, 540–548. [\[CrossRef\]](#)
12. Hamad, K.; Chung, B.K.; Ko, Y.G. Microstructure and mechanical properties of severely deformed Mg–3%Al–1%Zn alloy via isothermal differential speed rolling at 453K. *J. Alloys Compd.* **2014**, *615*, S590–S594. [\[CrossRef\]](#)
13. Luo, D.; Wang, H.-Y.; Zhao, L.-G.; Wang, C.; Liu, G.-J.; Liu, Y.; Jiang, Q.-C. Effect of differential speed rolling on the room and elevated temperature tensile properties of rolled AZ31 Mg alloy sheets. *Mater. Charact.* **2017**, *124*, 223–228. [\[CrossRef\]](#)
14. Ko, Y.G.; Hamad, K. Structural features and mechanical properties of AZ31 Mg alloy warm-deformed by differential speed rolling. *J. Alloys Compd.* **2018**, *744*, 96–103. [\[CrossRef\]](#)
15. Cho, J.-H.; Jeong, S.S.; Kim, H.-W.; Kang, S.-B. Texture and microstructure evolution during the symmetric and asymmetric rolling of AZ31B magnesium alloys. *Mater. Sci. Eng. A* **2013**, *566*, 40–46. [\[CrossRef\]](#)
16. Lee, J.; Kim, W.; Jeong, H. Microstructure and mechanical properties of Mg–Al–Zn alloy sheets severely deformed by asymmetrical rolling. *Scr. Mater.* **2007**, *56*, 309–312. [\[CrossRef\]](#)
17. Ucuncuoglu, S.; Ekerim, A.; Secgin, G.O.; Duygulu, O. Effect of asymmetric rolling process on the microstructure, mechanical properties and texture of AZ31 magnesium alloys sheets produced by twin roll casting technique. *J. Magnes. Alloys* **2014**, *2*, 92–98. [\[CrossRef\]](#)
18. Biswas, S.; Kim, D.-I.; Suwas, S. Asymmetric and symmetric rolling of magnesium: Evolution of microstructure, texture and mechanical properties. *Mater. Sci. Eng. A* **2012**, *550*, 19–30. [\[CrossRef\]](#)
19. Kaseem, M.; Chung, B.K.; Yang, H.W.; Hamad, K.; Ko, Y.G. Effect of Deformation Temperature on Microstructure and Mechanical Properties of AZ31 Mg Alloy Processed by Differential-Speed Rolling. *J. Mater. Sci. Technol.* **2015**, *31*, 498–503. [\[CrossRef\]](#)
20. Watanabe, H.; Mukai, T.; Ishikawa, K. Effect of temperature of differential speed rolling on room temperature mechanical properties and texture in an AZ31 magnesium alloy. *J. Mater. Process. Technol.* **2007**, *182*, 644–647. [\[CrossRef\]](#)
21. Gong, X.; Kang, S.B.; Li, S.; Cho, J.H. Enhanced plasticity of twin-roll cast ZK60 magnesium alloy through differential speed rolling. *Mater. Des.* **2009**, *30*, 3345–3350. [\[CrossRef\]](#)
22. Zhao, D.; Chen, X.; Wang, X.; Pan, F. Effect of impurity reduction on dynamic recrystallization, texture evolution and mechanical anisotropy of rolled AZ31 alloy. *Mater. Sci. Eng. A* **2019**, *773*, 138741. [\[CrossRef\]](#)
23. Chang, L.; Cho, J.; Kang, S. Microstructure and mechanical properties of twin roll cast AM31 magnesium alloy sheet processed by differential speed rolling. *Mater. Des.* **2012**, *34*, 746–752. [\[CrossRef\]](#)
24. Che, B.; Lu, L.; Zhang, J.; Teng, J.; Chen, L.; Xu, Y.; Wang, T.; Huang, L.; Wu, Z. Investigation on microstructure and mechanical properties of hot-rolled AZ31 Mg alloy with various cryogenic treatments. *J. Mater. Res. Technol.* **2022**, *19*, 4557–4570. [\[CrossRef\]](#)
25. Chen, H.; Tang, J.; Gong, W.; Gao, Y.; Tian, F.; Chen, L. Effects of annealing treatment on the microstructure and corrosion behavior of hot rolled AZ31 Mg alloy. *J. Mater. Res. Technol.* **2021**, *15*, 4800–4812. [\[CrossRef\]](#)
26. Jia, W.; Wang, L.; Ma, L.; Li, H.; Xie, H.; Yuan, Y. Deformation failure behavior and fracture model of twin-roll casting AZ31 alloy under multiaxial stress state. *J. Mater. Res. Technol.* **2022**, *17*, 2047–2058. [\[CrossRef\]](#)
27. Zhu, Y.; Hou, D.; Chen, K.; Wang, Z. Loading direction dependence of asymmetric response of pyramidal slip in rolled AZ31 magnesium alloy. *J. Magnes. Alloys* **2022**. [\[CrossRef\]](#)
28. Rollett, A.; Humphreys, F.; Rohrer, G.S.; Hatherly, M. Chapter 11—Grain Growth Following Recrystallization. In *Recrystallization and Related Annealing Phenomena*, 2nd ed.; Humphreys, F.J., Hatherly, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2004; pp. 333–378, ISBN 9780080441641.
29. Yang, X.-Y.; Ji, Z.-S.; Miura, H.; Sakai, T. Dynamic recrystallization and texture development during hot deformation of magnesium alloy AZ31. *Trans. Nonferrous Met. Soc. China* **2009**, *19*, 55–60. [\[CrossRef\]](#)
30. Perevezentsev, V.; Rybin, V.; Chuvil'Deev, V. The theory of structural superplasticity—I. The physical nature of the superplasticity phenomenon. *Acta Met. Mater.* **1992**, *40*, 887–894. [\[CrossRef\]](#)
31. Shi, Z.; Kim, W.; Cao, F.; Dargusch, M.S.; Atrens, A. Stress corrosion cracking of high-strength AZ31 processed by high-ratio differential speed rolling. *J. Magnes. Alloys* **2015**, *3*, 271–282. [\[CrossRef\]](#)
32. Park, J.; Kim, W. Effect of differential speed rolling on microstructure and mechanical properties of an AZ91 magnesium alloy. *J. Alloys Compd.* **2008**, *460*, 289–293. [\[CrossRef\]](#)
33. Che, B.; Lu, L.; Zhang, J.; Zhang, J.; Ma, M.; Wang, L.; Qi, F. Effects of cryogenic treatment on microstructure and mechanical properties of AZ31 magnesium alloy rolled at different paths. *Mater. Sci. Eng. A* **2021**, *832*, 142475. [\[CrossRef\]](#)
34. Fu, B.; Shen, J.; Suhuddin, U.F.; Chen, T.; dos Santos, J.F.; Klusemann, B.; Rethmeier, M. Improved mechanical properties of cast Mg alloy welds via texture weakening by differential rotation refill friction stir spot welding. *Scr. Mater.* **2021**, *203*, 114113. [\[CrossRef\]](#)

35. Zhou, P.; Beeh, E.; Wang, M.; Friedrich, H.E. Dynamic tensile behaviors of AZ31B magnesium alloy processed by twin-roll casting and sequential hot rolling. *Trans. Nonferrous Met. Soc. China* **2016**, *26*, 2846–2856. [[CrossRef](#)]
36. Galiyev, A.; Kaibyshev, R.; Gottstein, G. Correlation of plastic deformation and dynamic recrystallization in magnesium alloy ZK60. *Acta Mater.* **2001**, *49*, 1199–1207. [[CrossRef](#)]

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