Work-Hardening Behavior of a ZX10 Magnesium Alloy Sheet under Monotonic and Reverse Loadings

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Keywords: Magnesium alloy, Work hardening, Twinning, Detwinning, Reverse loading

Abstract. Magnesium (Mg) alloy sheets are expected to be used as light-weight materials for structural components because of their low density and high specific strength. However, their press formability at room temperature is poor due to the strong crystal anisotropy of the hexagonal structure and the strong basal texture especially observed in AZ series rolled Mg alloy sheets. Recently, ZX series Mg alloy sheets have been developed that weaken the basal texture, thus improving press formability at room temperature. Although the plastic deformation behavior of ZX series Mg alloy sheets should be different notably from that of AZ series Mg alloy sheets, it is not substantially understood yet. In the present study, the work-hardening behavior of a rolled Mg-1.5mass%Zn-0.1mass%Ca (ZX10Mg) alloy sheet under monotonic and reverse loadings was investigated in detail experimentally. The microstructures of prestrained samples were also measured by means of EBSD measurements. Under monotonic tension, the stress in the rolling direction is higher than that in the transverse direction. A plateau region appears only in the transverse direction. Under monotonic compression, plateau regions appear in both the rolling and transverse directions. The in-plane anisotropy is less pronounced than that under tension. Under reverse loading from compression to tension, a sigmoidal curve appears during tension regardless of the loading direction. The sigmoidal trend depends strongly on the loading direction. The mechanisms that induce the abovementioned anisotropic deformation are discussed in terms of the difference in twinning and detwinning activities.

Introduction

Magnesium (Mg) alloy sheets are expected to be used as light-weight materials for structural components because of their low density and high specific strength. Applications of Mg alloys can now be found in various components, including the housing of laptop computers and cellular phones, and automobile components [1].

Conventionally, die casting has been used to form Mg alloys. On the contrary, press forming is now expected to be used for Mg alloy sheets to improve the productivity. However, their press formability at room temperature is poor due to the strong crystal anisotropy of the hexagonal close packed (hcp) structure and the strong basal texture especially observed in AZ series rolled Mg alloy sheets. Therefore, currently warm press forming should be employed to form Mg alloy sheets, which hinders wide application for thin-walled components [2, 3].

To weaken the basal texture and to improve the press formability at room temperature, ZX series Mg alloy sheets, to which small amounts of Zn and Ca are added, have recently been developed [3-7]. Chino et al. [4-6] developed Mg-1.5mass%Zn-0.1mass%Ca (ZX10Mg) alloy sheets with characteristic texture with the $c$ axis tilted in the transverse direction (TD) through hot rolling and heat treatment, weakened the basal texture. They also showed that the room-temperature press formability could be improved compared to materials with strong basal texture. However, although the work-hardening behavior of ZX series Mg alloy sheets should also be different notably from that of AZ series Mg alloy sheets, it is not substantially understood yet; thus, it is still difficult to evaluate the formability of ZX series Mg alloy sheets.
In the present study, the work-hardening behavior of a rolled ZX10Mg alloy sheet under monotonic and reverse loadings was investigated in detail experimentally. Microstructures were also observed on prestrained samples to study twinning activities during deformation.

**Experimental Methods**

A rolled ZX10 Mg alloy sheet with 1.0 mm thickness was used. Uniaxial tensile, compressive, and reverse loading tests were conducted in the rolling and transverse directions. The following two types of strain paths were tested in the reverse loading test: compression following tension and tension following compression. In the both cases, the amount of strain during first loading was set to 0.05. Comb-shaped dies [8, 9] were used to avoid occurrence of buckling during compression. It should be noted that the through-thickness compressive stress given by the comb-shaped dies was smaller than 5% of the yield stress under tension in the RD; thus, its effect on the mechanical behavior is negligible.

Figs. 1 (a) and 1 (b) show the geometry of the sample used in the tests and the schematic of the experimental apparatus, respectively. Strain gauges (KFEM series, Kyowa Electronic Instruments Co.) were utilized to measure strains. Experiments were conducted at least twice to confirm the reproducibility of the results. Electron Back Scattered Diffraction measurements were conducted to measure the microstructures.

Figs. 2 (a) and 3 (a) show the (0001) pole figure and the inverse pole figure map, respectively, of the initial sample. The average grain diameter was approximately 19.1 µm. Two peaks tilted from the normal direction (ND) to the TD are observed, but at the same time, small peaks appeared also in the vicinity of the TD; thus, the basal texture is weaker than that of the typical AZ series rolled alloy sheets [10, 11].

![Fig. 1 Experimental setup used in this study. (a) Geometry of the sample, and (b) schematic of the experimental apparatus.](image)

**Experimental Results**

The true stress-true strain curves under tension and compression in the RD and TD are shown in Fig. 4 (a). The stress and strain are in absolute values. Under tension, a typical convex upward curve occurred in the RD. In contrast, in the TD, the yield stress as well as the total stress level were smaller than those in the RD and, moreover, a plateau region appeared at the beginning of plastic deformation.

Under compression, clear plateau regions appeared in both the RD and TD at the beginning of plastic deformation. After the plateau regions terminated, the stresses started increasing gradually for both the RD and TD. The difference in the curve between the RD and the TD was much less pronounced than that under tension. Regarding tension-compression asymmetry, the stress level as...
well as the trend of the curve were different notably in the RD, whereas in the TD the difference in the stress was much smaller and the trend of the curve was similar.

Fig. 4 (b) shows the stress-strain curves under reverse loading in the RD and TD. Under compression followed by tension, sigmoidal curves appeared after the loading direction was inverted in both the RD and TD. This trend was similar to that of AZ series rolled Mg alloy sheets [10-12]. However, the sigmoidal trend depended on the loading direction: the second increase in the stress was more pronounced in the RD than in the TD.

![Fig. 4](image1)

Fig. 2 (0001) pole figures. (a) Initial sample, and the results measured at points (b) a, (c) b and (d) c shown in Fig. 4.

![Fig. 2](image2)

Fig. 3 Inverse pole figure maps. (a) Initial sample, and the results measured at points (b) a, (c) b and (d) c shown in Fig. 4.
Fig. 4 True stress-true strain curves. The results are under (a) tension, compression, and (b) reverse loading. In (a), the stress and strain are in absolute values.

Fig. 5 Evolution of work-hardening rate. The results are under tension in (a) the RD and (b) TD, and under compression in (c) the RD and (d) TD. For the results of reverse loading, a strain at the beginning of stress reversal was set to zero in the horizontal axis. In (c) and (d), the strains are in absolute values.

To examine the evolution of work-hardening more in detail, Figs. 5 (a) and 5 (b) show the evolution of work-hardening rate as a function of strain in the RD and TD, respectively, during monotonic tension and tension following compression. The work-hardening rate was calculated using the discrete experimental data points as $\frac{\Delta \sigma}{\Delta \varepsilon}$ for constant time interval. Specifically, $\Delta \varepsilon$ was less
than 0.005 except for the very beginning of deformation. This time interval was used to reduce scattering in the work-hardening rate as much as possible with keeping the trends unchanged. It should be noted that, for the results of reverse loading, a strain at the beginning of stress reversal was set to zero. In the RD, a clear peak appeared at a strain of approximately 0.05 under reverse loading, whereas the work-hardening rate evolved very gradually under monotonic tension. The work-hardening rate at large strains tended to become similar regardless of the loading path.

In contrast, in the TD, the evolution was very similar regardless of the loading path except for the very beginning. These results show that an in-plane anisotropy was exhibited in the strain-path dependency under tension.

Under tension followed by compression, the compressive stress after stress reversal was larger in the RD than in the TD. This trend is seemingly different from that of monotonic compression (Fig. 4 (a)), although the trend of the curve was similar between monotonic compression and compression following tension.

Figs. 5 (c) and 5 (d) show the evolution of work-hardening rate as a function of strain in the RD and TD, respectively, during monotonic compression and compression following tension. It should be noted that the strains are in absolute values. The evolution was very similar regardless of the loading path except for the very beginning in both the RD and TD. These results show that tensile prestrain induced the in-plane anisotropy of the stress level under compression with keeping the work-hardening behavior unchanged.

**Discussion**

Some characteristic behaviors, which are usually not observed in AZ series rolled Mg alloy sheets [e.g., 13], were exhibited in the ZX10 Mg alloy sheets. More specifically, the strong in-plane anisotropy occurred under tension and reverse loadings, the slight plateau region appeared under the TD tension, and the sigmoidal curve after the loading direction was inverted from compression to tension was much less pronounced in the TD than that in the RD. The difference in the initial texture between the ZX10 and AZ-series rolled Mg alloy sheets would be one of the reasons that induce these behaviors. In this section, the characteristic trends in the work-hardening behavior of the ZX10 Mg alloy sheet are discussed in terms of the mesoscopic deformation.

**Uniaxial tension.** The mechanism that a plateau region appeared only in the TD (Fig. 4 (a)) is discussed. As explained earlier, small peaks appeared in the vicinity of the TD in the initial texture (Fig. 2 (a)). It is hypothesized that, under tension in the TD, the grains whose basal planes oriented near the TD tended to be subjected to tensile stresses in the c axes; thus, extension twinning can be active. Because it is understood that large activity of twinning induces a plateau region in a stress-strain curve [10-12], twinning activities in these grains would result in the plateau region. In contrast, because twinning activities in these grains were negligible under tension in the RD, a plateau region did not appear under RD tension.

To verify the hypothesis, the (0001) pole figures measured at points a and b shown in Fig. 4 (a) are shown in Figs. 2 (b) and 2 (c), respectively. The corresponding inverse pole figure maps are shown in Figs. 3 (b) and 3 (c), respectively. As the tensile deformation progressed in the TD, the peaks appeared near the TD tended to decrease and, alternatively, the peaks near the ND tended to increase. This texture evolution suggests that the c axes initially oriented near the TD tended to rotate toward the ND due to twinning activity. The results measured at point c in Fig. 4 (a) are shown in Figs. 2 (d) and 3 (d). In contrast to the results under TD tension, the pole figure remained almost unchanged from the initial one, suggesting that twinning activity was negligible when the sample was subjected to RD tension. These results are consistent with the abovementioned hypothesis. It is further presumed from these results that the stress level was smaller in the TD than in the RD because the critical resolved shear stress of extension twinning is smaller than that of nonbasal slip systems, especially prismatic slip which is presumed to be active during tension [10-12].

**Uniaxial compression.** For the grains whose basal planes oriented near the ND, extension twinning can be active under both RD and TD compression because in either case the grains tend to be subjected to tensile stresses along the c axes. In contrast, for the grains whose basal planes oriented
near the TD, the stress state would be different between RD and TD compression. Specifically, the grains tend to be subjected to tensile and compressive stresses in the c axes under RD and TD compression, respectively. Therefore, it is presumed that twinning activity is more pronounced under RD compression than under TD compression. Nevertheless, the in-plane anisotropy of the stress-strain curve was much less pronounced than under tension, suggesting that the effect of the difference in the twinning activity between RD and TD compression on the work-hardening behavior was not significant. The hypothesis on the twinning activity will be verified experimentally in our future work.

**Reverse loading.** Firstly, the mechanisms that the in-plane anisotropy appeared after reverse loading from compression to tension are discussed. In previous studies for AZ series rolled Mg alloy sheets, it was explained that the sigmoidal curve appears after the loading direction is inverted from compression to tension because of the shift from detwinning-dominated deformation to slip-dominated deformation [10, 11]. The same mechanism would hold for the present results. Because twinning activities during compression would be more pronounced under RD compression than TD compression as explained earlier, detwinning activities after reverse loading would also be larger under RD loading. It is presumed that the pronounced detwinning activities resulted in a clearer sigmoidal curve under RD loading.

On the other hand, under TD loading, twinning was active even under tension, as observed in Figs. 2 (b) and 2 (c). Therefore, it is presumed that not only less pronounced detwinning activity but also pronounced twinning activity in the initial stage of reverse loading resulted in less pronounced shift of the deformation mode than under RD loading. Moreover, the stress level under TD tension was smaller than that under RD tension as shown in Fig. 4 (a). As a result, a sigmoidal trend was much less pronounced and the stress level was smaller than those under RD loading.

Next, the results under reverse loading from tension to compression are examined. Comparing the stress-strain curves between monotonic compression and compression following tension, the yield stress under reverse loading was larger than that of monotonic compression in the RD, while it was similar to that of monotonic compression in the TD, suggesting that the effect of tensile prestrain on the yield stress was more pronounced in the RD than in the TD. The tendency that the yield stress under compression increases with the tensile prestrain was also observed in an AZ31 Mg alloy sheet [14]. The yield stress in the TD was smaller than that of the RD presumably because detwinning was active in grains in which extension twinning was active during tension. The abovementioned hypotheses on the twinning activity will be verified experimentally in our future work.

In the present study, we focused our attention on the anisotropy in the texture to explain the strong anisotropy in the stress-strain curves. On the other hand, Wang et al. [7] recently reported that crystal anisotropy in Mg-Ca-Zn alloys was reduced compared to pure Mg, and activation of different slip systems and cross slip between basal and prismatic dislocations affected the formability of Mg-Ca-Zn alloys. These microscopic properties would also affect the work-hardening behavior of this material. The correlation between the work-hardening behavior and the microscopic properties will be further discussed by means of crystal plasticity simulations in our future work.

**Summary**

In the present study, the work-hardening behavior of a rolled Mg-1.5mass%Zn-0.1mass%Ca (ZX10Mg) alloy sheet under monotonic and reverse loadings was investigated in detail experimentally. The microstructures were also measured on prestrained samples by means of EBSD measurements. The following conclusions were obtained.

(1) Under monotonic tension, the stress in the rolling direction is higher than that in the transverse direction. A plateau region appears only in the transverse direction.

(2) Under monotonic compression, plateau regions appear in both the rolling and transverse directions. The in-plane anisotropy is less pronounced than that under tension.

(3) Under reverse loading from compression to tension, a sigmoidal curve appears during tension regardless of the loading direction. The sigmoidal trend depends strongly on the loading direction.
The differences in twinning and detwinning activities depending on the loading path, which results from the strong in-plane anisotropy in the initial texture, would be one of the mechanisms that induce the abovementioned anisotropic deformation.

Acknowledgements

The authors would like to acknowledge Mr. Sohei Uchida of the Osaka Research Institute of Industrial Science and Technology for help of the EBSD. This study was supported by the Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (KAKENHI) Grant number 20H02480 and the Amada Foundation Grant number AF-2019004-A3.

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