# Twin-Slip Interaction at Low Stress Stage Deformation in an AZ31 Mg Alloy

Peng Chen, Bin Li, Duke Culbertson, and Yanyao Jiang

**Abstract**

Extruded magnesium alloys with strong basal texture present tension and compression asymmetry. Dislocation slip dominates plastic deformation during tension along the extrusion direction (ED), whereas twinning is the main contributor to plastic strain when compressed along the ED. In this work, an extruded AZ31 Mg alloy was prestrained by tension along the ED to 5 and 10% of total strain, followed by compression, in order to investigate twin-slip interaction. The results show that the yield stress in compression only slightly increases with increasing prestrain. Notably, the hardening rate at the low stress stage during compression remains almost unchanged, compared to specimens without prestrain. Our results suggest that the contribution of twin-slip interaction to hardening is negligible in deformation of Mg alloys.

**Keywords**

Magnesium alloy • Prestrain • Twin-slip interaction
Work hardening

## Introduction

Deformation twinning and dislocation slip are two important modes during plastic deformation in hexagonal-close-packed (hcp) metals. Especially, the $\{10\bar{1}2\}10\bar{1}\bar{1}$ twinning mode is the most prevalent twinning mode in hcp metals [1–4]. The favorable stress state for the $\{10\bar{1}2\}$ extension twinning can be achieved by tension along c-axis or compression perpendicular to c-axis. In situ neutron diffraction [5–8], in situ X-ray diffraction [9] as well as acoustic emission [6, 10] studies on early stage of plastic deformation in Mg alloys reveal that $\{10\bar{1}2\}$ extension twinning accounts for a major portion of the plastic deformation. Recent measurement of contribution of $\{10\bar{1}2\}$ twinning to plastic strain in an extruded Mg alloy also indicated that $\sim 90\%$ of the plastic strain comes from $\{10\bar{1}2\}$ twining during low stress stage deformation [11]. Extruded Mg alloys with strong basal texture exhibit tension-compression asymmetry. Yield stress and strain hardening behavior are largely dependent on the dominant mechanism of plastic deformation. During tension along the extrusion direction (ED), dislocation slip dominates plastic deformation. However, when compressed along the ED, $\{10\bar{1}2\}$ twinning is the main contributor during early stage of plastic deformation in Mg alloys. Thus, the yield strength under ED compression is lower than that under ED tension. Also, the strain hardening rate is higher during ED tension compared with ED compression.

A number of researchers investigated the influence of prestrain on flow curve and work hardening behavior [12–16]. Slip-slip [17–20], twin-twin [21–23] and slip-twin interactions [24–27] during deformation were studied. The slip-slip interaction take place during plastic flow, especially when it is accomplished by dislocation glide on multiple slip systems. The interaction generally gives rise to a reduction in mobile dislocations, thus promoting work hardening [28]. The sub-grains resulted from twinning and twin-twin interaction also provide a strengthening mechanism, which is attributed to the dynamic Hall-Petch effect [29]. The twin-slip interaction is a more complex mechanism and still not well understood. Serra et al. [30] considered twin-dislocation interaction as an important hardening mechanism because twin boundaries hinder subsequent slip and twinning deformation. Proust et al. [31] proposed that during the preloading, <a> and <c+a> dislocations are

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introduced. These dislocations may act as barriers to twin nucleation or/and twin propagation. El Kadiri and Oppedal [32] developed dislocation transmutation theory, which hypothesizes that dislocations inside parent are incorporated and transmuted into immobile defects in twins, promoting latent hardening. Some researchers suggest when lattice dislocations meet with a twin boundary, dislocation dissociation will occur, which is also a mechanism for enlarging or shrinking the twin domain [33].

The current work aims to investigate twin-slip interaction by taking the advantage that slip and twinning dominated deformation can be activated separately by controlling the loading direction on extruded specimens. By pre-tension of extruded specimens to various levels of plastic strain, dislocations of different density are first introduced. Then the deformation is changed to compression such that twinning is activated. As such, twin-slip interaction and its contribution to strain hardening can be studied without ambiguity.

## Experimental Method

An extruded, commercially obtained AZ31B Mg alloy was used for the current investigation. The circular extruded bar had a diameter of 38.1 mm. Dog-bone specimens were machined from the extruded bar with the gage section along the extrusion direction. The specimens had a gage length of 13.0 mm and gage diameter of 9.0 mm. An Instron load frame with a loading capacity of 25 kN was used to conduct the experiments. The specimens were carefully aligned to avoid triggering early buckling. Lubrication was applied between the moving surfaces. The extruded AZ31 Mg alloy was first prestrained by tension along the ED to 5 and 10% of total strain, respectively, followed by consecutive compression along the ED. The reason we did not pre-tensile the specimen to higher strain levels lies in that the fracture strain is approximately 12% for the material under tension. The mechanical experiments were conducted in strain-control mode at a strain rate of $8 \times 10^{-4}$ at ambient temperature.

For electron backscatter diffraction (EBSD) scans, cylindrical specimens with a thickness of 5 mm were sectioned in the middle of the gage section perpendicular to the ED. The specimens were ground mechanically down to 1200/4000 grit number on SiC sand papers, followed by electrochemical polishing with a solution of 5% nitric acid, 0.5% perchloric acid and 94.5% ethanol at 20 V for $\sim$20 s. EBSD scans were conducted on a JEOL 7100F field emission scanning electron microscope (SEM) with an Oxford HKL Channel 5 instrument. An acceleration voltage of 20 kV and a working distance of 25 mm were used. For better statistics and analysis of the twinning behavior, at least three different regions were scanned by EBSD with a step size ranging from 0.5 to 1 μm for each companion specimen. All the EBSD scans were performed on a cross-section perpendicular to the ED or the loading axis.

## Results and Discussion

The initial grain structure and the texture of the as-extruded specimens are shown in Fig. 1a, b, respectively. The as-received AZ31B presents a typical rod-texture in which the (0001) basal pole is nearly perpendicular to the ED, and the $\{10\bar{1}0\}$ pole presents a strong intensity along the ED. Intensity peaks appear at $\sim$4 and 10 o'clock positions in (0001) PF in Fig. 1b, which is likely due to the inhomogeneity in microstructure and the region for EBSD scan off the center of the extruded bar.

The stress-strain curves for 5% prestrain and 10% prestrain are displayed in Fig. 2. Firstly, we prestrained the specimens to 5% and 10% total strain in tension, then subjected the specimens to compression. The red dots denote strain levels at which the compression was interrupted and EBSD scans were performed on the specimens. The

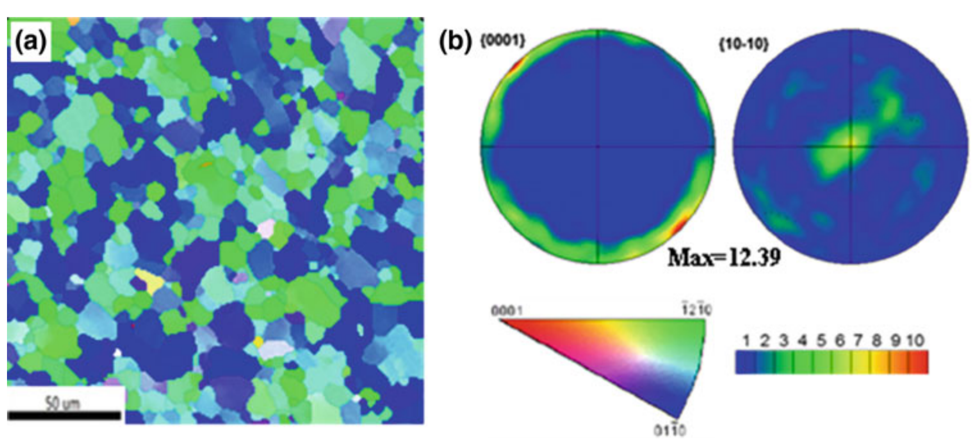


**Fig. 1** Initial texture of as-extruded AZ31 alloy. The scanned surface is perpendicular to the ED. **a** Inverse pole figure (IPF) map. **b** Pole figures. The basal plane is mostly parallel to the ED, which is a typical rod-texture in extruded Mg alloys

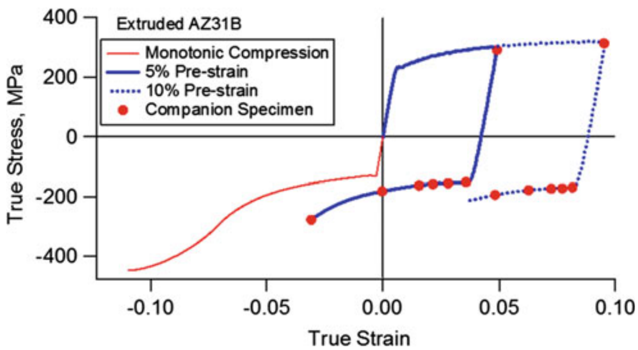


**Fig. 2** Stress-strain curves of monotonic compression (thin solid line), 5% pre-strained (solid line) specimen and 10% pre-strained (dash line) specimen. The red dots denote strain levels at which the compression was interrupted for EBSD analysis

influence of prestrain on the compression behavior is shown in Fig. 3 which compares the stress-strain curves for 0% (i.e. monotonic compression), 5 and 10% prestrains.

Several important features can be noted in Fig. 3. First, the yield stresses in compression of the prestrained specimens are slightly higher than the specimen without prestrain. As the prestrain increases, the yield stress in compression slightly increases. In our most recent measurements of twin volume fraction at low stress stage compression of extruded AZ31 specimens [11], we observed that at plastic strain ~0.25%, deformation twinning has already been activated but with a low volume fraction. The main contributor to plastic strain is dislocation slip. But the twin volume fraction rapidly increases as the strain increases. During the low stress stage deformation, twinning accounts for 80–90% contribution to the plastic strain. Thus, the increase in yield stress in Fig. 3 can be attributed to the hardening effect of the pre-existing dislocations generated in prestraining.

Second and most interestingly, it can be observed that the hardening behavior during the low stress stage deformation remains almost identical. Figure 4 plots the hardening rate in the three scenarios. The difference between the zero-prestrain, 5% prestrain and 10% prestrain specimens is obvious. The prestrained specimens present slightly lower hardening rates if compared to the un-prestrained specimen. This raises a question as to what a role twin-slip interaction plays in the hardening. Twin-slip interaction has been considered as an important contributor to the increase in hardening rate during twinning and after twinning [13, 30, 34, 35]. Dynamic Hall-Petch effect [36–38] has been proposed as one of the mechanisms that contributes to strain hardening when twinning is activated along with dislocation slip. Twin boundaries act as new grain boundaries that reduce the effective grain size and the mean free path of dislocations. However, our experimental results indicate that the contribution of twin-slip interaction to the hardening is negligible.

The EBSD results in Fig. 5 show the evolution of extension twins of the specimens with and without prestrain. In the zero-prestrain specimen (Fig. 5a), which is under monotonic compression at low stress stage of plastic deformation in an extruded Mg alloy [11], $\{10\bar{1}2\}$ twinning is activated at very early stage of plastic deformation, the density of twins increases rapidly with increasing strain. The specimen with 5% prestrain (Fig. 5b) presents a similar trend: as the plastic strain increases, the twin volume fraction increases. However, for the 10% prestrained specimen, substantial difference in twinning behavior upon subsequent tension was observed, that is, twin nucleation is retarded by the pre-introduced dislocations. It can be observed that at $\varepsilon_p$ = 1.22% (Fig. 5c), twins with a very low density are activated. However, after nucleation, the twin volume

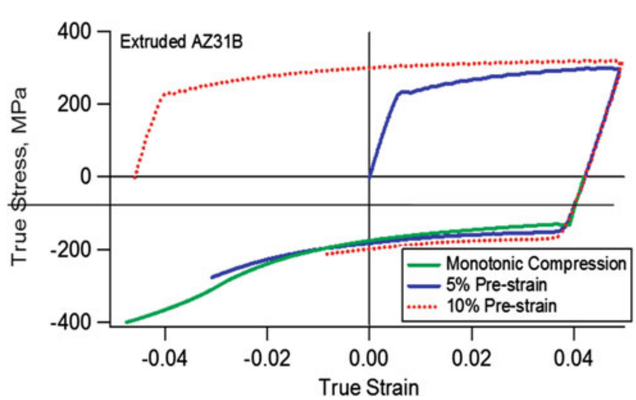


**Fig. 3** Comparison of stress-strain curves for 0% (monotonic compression), 5 and 10% prestrain. The yield stress under compression only slightly increases with increasing pre-strain. However, the hardening rate at the low stress stage during compression remains almost the same

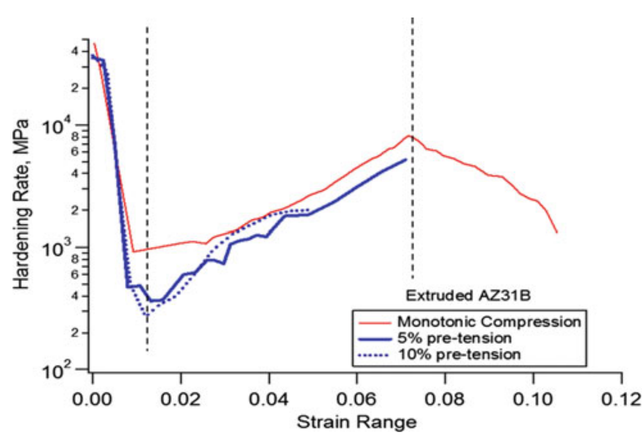


**Fig. 4** The strain hardening rate as a function of true strain during compression along the ED. After yielding, the strain hardening rates present the lowest value which is attributed to the twin nucleation. It is worth noting that the prestrained specimens present lower hardening rate than monotonic compression (0% prestrain)

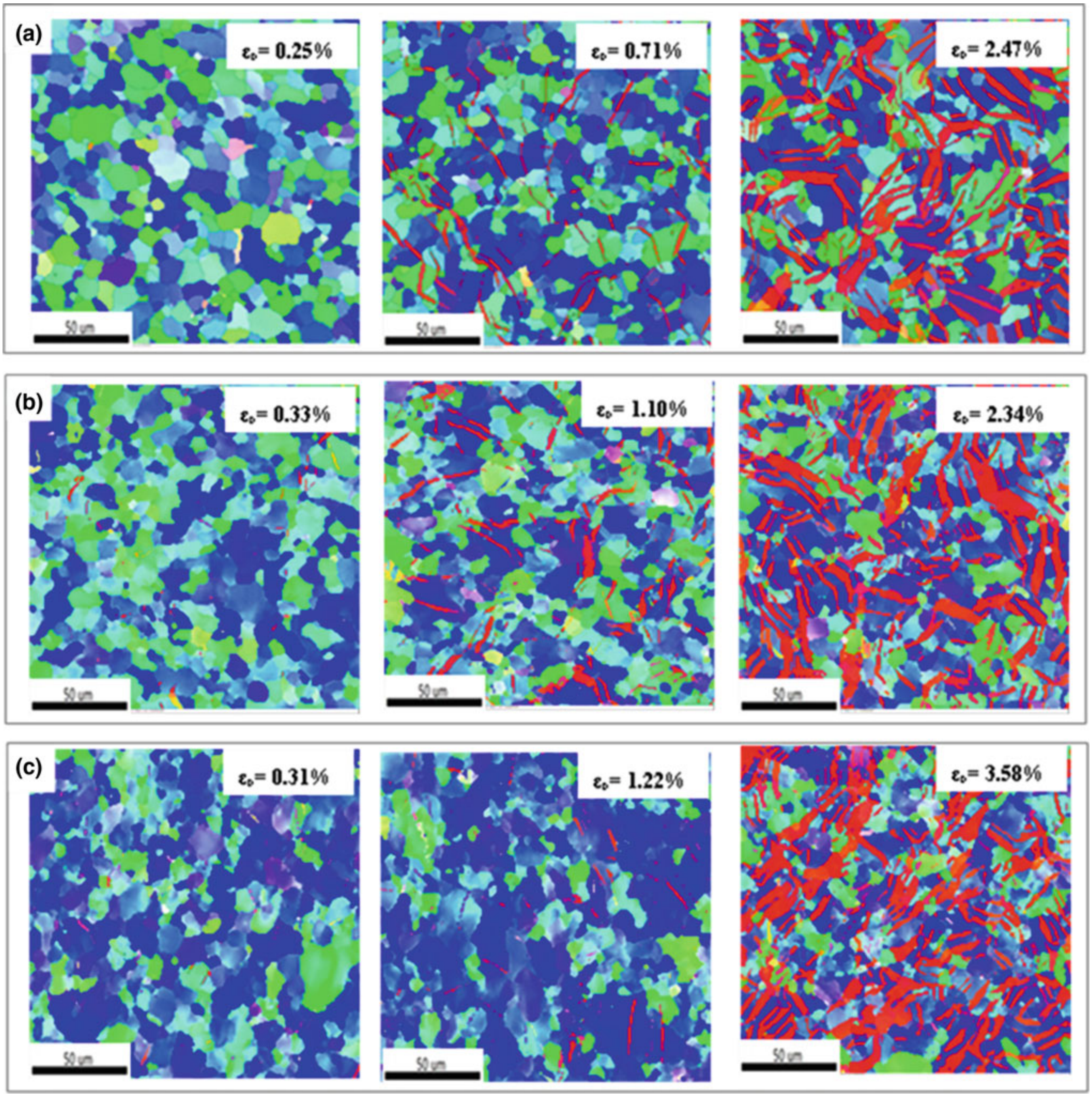


**Fig. 5** Inverse pole figure (IPF) maps at selected plastic strain levels for: **a** 0% pre-strain (monotonic compression); **b** 5% pre-strain; **c** 10% pre-strain. Compared with 5% pre-strain and monotonic compression, the number of twins is less at the early stage ($\varepsilon_p < 2.18\%$). Obviously, twin nucleation is impeded under 10% pre-strain

fraction rapidly increases as does in the zero-prestrain and the 5% prestrain specimens. Mahajan [39] reported that prestraining of iron prior to shock-loading inhibits the formation of shock twins, there are a lot of mobile dislocations, fewer twins are required to accommodate plastic strain. Boucher and Christian [40] studied the influence of prestrain on deformation twinning in niobium single crystals, it is found that prestrain is effective in suppressing twinning at temperatures down to 77 K. These dislocations induced by prestrain may increase the energy barriers for twin nucleation. This would explain the increase of the stress corresponding to the onset of twinning with increasing prestrain. Since conventional EBSD is unable to resolve dislocation type and density, transmission electron microscopy (TEM) and computer simulations are needed to reveal how twinning interacts with slip in our future work.

Skrotzki [41] reported that in γ-TiAl, one part of the possible glide dislocations remains completely unaffected by the twin interface when these dislocations come across twin boundary. Zhu et al. [42] found that there is no energy change (barrier) when 90° partial pass the twin boundary by cross-slip in bcc metals. Hence, the twin boundary will not necessarily act barriers for dislocation slip. Recently, Li and Ma [43] showed that $\{10\bar{1}2\}$ twinning in Mg alloy is actually mediated by atomic shuffling. A large deviation between the actual twin boundaries and the theoretical $\{10\bar{1}2\}$ twinning plane was also observed [44]. More recently, Li and Zhang [45, 46] showed that the twinning shear of $\{10\bar{1}2\}10\bar{1}\bar{1}$ mode can only be zero because the twinning plane is not an invariant plane and thus no shear deformation mediated by twinning dislocations can occur on the twinning plane. These new findings, along with our experimental observations, call for reconsideration of the nature of twin-slip interaction in Mg alloys and other HCP metals. Computer simulations may be needed to resolve the mechanisms.

## Conclusion

By prestraining in tension of extruded AZ31B specimens, we investigated twin-slip interaction during plastic deformation. The results show that the yield stress in compression only slightly increases with increasing prestrain. However, the hardening rate at the low stress stage during compression remains almost unchanged, indicating that the contribution of twin-slip interaction to hardening is negligible in deformation of Mg alloys.

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