Effect of strain rate on the shift of neutral layer in AZ31B alloys during V-bending at warm conditions

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1. Introduction

Due to the high specific strength, stiffness and low density, magnesium alloys have a great potential in various structural applications, such as automotive, aerospace [1]. However, Mg alloys feature poor ductility owing to its HCP structure and limited numbers of activated slipping systems at lower temperatures, which cannot fulfill the Von-Mises Criterion [2]. Accordingly, at this condition, twinning plays an important role to coordinate the deformation along prismatic direc-tion. This results in the typical tension-compression yield asymmetry which makes the forming processes of Mg alloys more complex [3]. It is well known that during bending of a sheet the outer region is strained under tensile mode, while the inner region undergoes compressive deformation. Thus, the tension-compression asymmetry should occur between two sides, resulting in a shift of the neutral layer. Shifting of neutral layer has an important effect on the spring-back. In order to forecast the springback accurately, it is necessary to quantify the offset value of the spring-back during bending.

Zachariah et al. [4] indicated that the strain rate plays an important role on tension-compression asymmetry of an AM30 Mg alloy in the form of extruded rod. However, the effect of strain rate on tension-compression asymmetry of Mg sheets and the related shift of the bending neutral layer has rarely been considered. Therefore, in this paper these features have been thoroughly investigated. Since Mg alloys are not very sensitive the strain rate effects at room temperature and possess poor formability, in this investigation, the V-bending tests have been conducted at warm conditions [5].

2. Experimental procedure

Commercially AZ31B alloy sheets with a thickness of 3mm were cut into rectangular specimens with 80 mm length and 30 mm

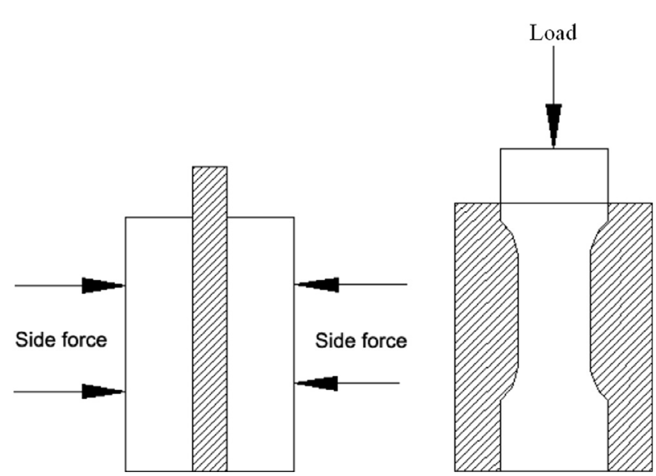

Fig. 1. Schematic view of the mould used in compression tests.

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width along rolling direction (RD). 90 °V-bending tests were conducted with strain rate of 10^{-2} s^{-1}, 10^{-3} s^{-1} and 10^{-4} s^{-1} at 423 K. Each V-bending testing condition was repeated for five specimens. According to the theory of stamping process [6], the offset of neutral layer was measured by the coefficient of neutral layer (k-value). The bigger k-value, the more marked is the shifting of neutral layer from the geometrical central layer. The computational formula for the k-value is given as follows:

$$K = 0.5\beta^2 - (1-\beta)R_i/t \tag{1}$$

where k is the coefficient of the neutral layer, β is the coefficient of incrassation ($\beta = t_1/t$, t_1 is the thickness after bending), R_i is the inner bending radius, and t is the original thickness.

Besides, tensile and compressive tests on AZ31 Mg sheets along RD were conducted at the same strain rate levels of 10^{-2} s^{-1}, 10^{-3} s^{-1} and 10^{-4} s^{-1} at 423 K. For both tension and compression tests, the sheets were cut using a mechanical wire into standard tensile-type specimens with 28 mm gauge length and 12.5 mm gauge width along RD. During compressive tests, the specimens were clamped using a special mould made of steel to avoid lateral instability and the load was stopped after a total strain to 5% both in tensile and

Table1
k-value measured in specimens tested at different strain rates

Strain rate/s^{-1}	10^{-2}	10^{-3}	10^{-4}
K-value	0.611 ± 0.004	0.598 ± 0.003	0.587 ± 0.005

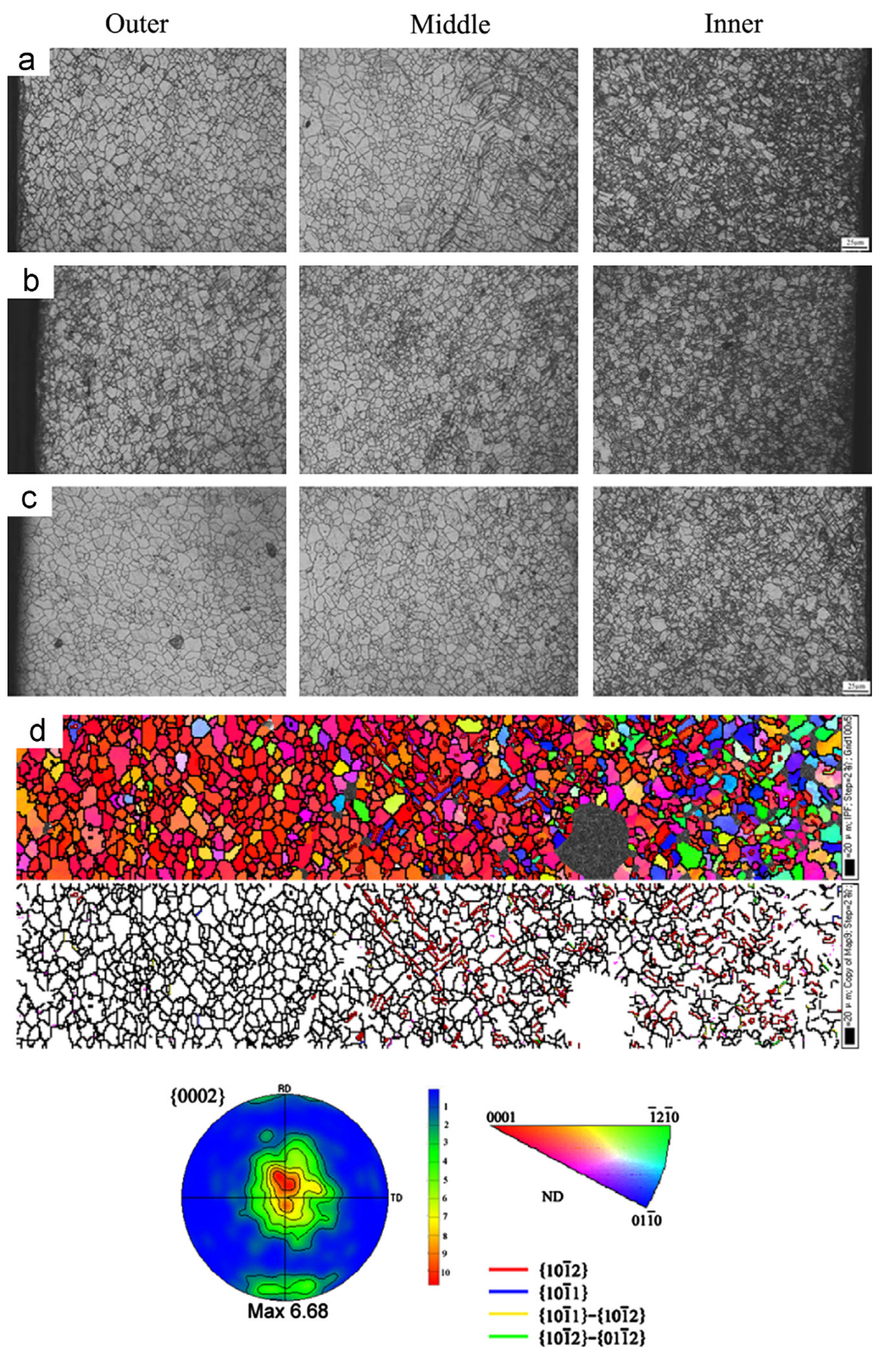

Fig.2. Microstructure of AZ31B alloy after V-bending at different strain rates: (a) 10^{-2} s^{-1}; (b) 10^{-3} s^{-1} and (c) at 10^{-4} s^{-1}, (d) the IPF map and twin boundary maps at 10^{-2} s^{-1}.

compressive tests. The schematic diagram of specimens used for compression testing is shown in Fig.1. Mineral industrial oil was used as a lubricant during compressive tests to reduce friction.

After tests, the microstructure and texture were examined by a metallographic microscope and by electron backscatter diffraction (EBSD).

3. Results and discussions

Table1 shows the modification of k-value on AZ31 Mg alloy during V-bending with different strain rates at 423 K. All k-values of samples V-bent at different strain rates exceed 0.5, which means that the neutral layer of Mg sheets shifts to outer tensile region. Besides, k-value decreases as the strain rate decreases. In previous research, it was already demonstrated that the tension-compression asymmetry resulted in a neutral layer shift in Mg alloys. Considering that during V-bending, the outer region was under tensile deformation while the inner region was under compressive deformation, this resulted in an asymmetric deformation mechanism between two sides. The bigger of the tension-compression asymmetry, the larger the offset of neutral layer will be [7].

The microstructures of the specimens observed in the bending region after straining with different strain rates are shown in Fig.2. Equiaxed grains are distributed in the outer bending region while a large amount of twins appears in the inner region. EBSD map in the middle region of specimens after V-bending at the strain rate of 10^{-2} s^{-1} is also shown in Fig.2 (d). A distinction between the twinned region (right) and the untwinned regions (left) is clearly observed in the microstructure. According to the EBSD map, the twins are {10–12} tensile twins. However, the same figure shows that the volume fraction of {10–12} twins decreases in both inner and middle region as strain rate decreases. In previous research [8], during IE tests on AZ31 sheet at 473 K, twins even occurs at 10^{-1} s^{-1} while no twins emerge as strain rate decreasing which is consistent to this phenomenon. It is supposed this might be caused by the dynamic recovery occurring during bending at 423 K. Conrad et al. [9] showed that strain-hardening coefficient in an AZ31 Mg alloy decreased with increasing deformation temperature. They attributed this softening effect to a dynamic recovery process. At higher strain rates, there will be higher stress concentration and less time for the dynamic recovery. The softening effect is expected to be less evident, which lead to a more marked activity of twinning during compression. Con=versely, as the strain rate decreases, there is more time for softening effects and stress concentration can be released easier resulting in a decrease of the volume fraction of twins. Besides, the dividing line between twinned and non-twinned material becomes less clear with decreasing strain rate.

The decrease of k-value with decreasing strain rates should be related to the evolution of tension-compression asymmetry. During bending, the outer region of the specimen (extrados of the V-bent zone) can be regarded as strained under tension along the RD, while the inner region (intrados of the V-bent zone) can be regarded as compressed along the RD.

Fig. 3 shows the microstructure of tension and compression tested samples of AZ31 Mg sheets along RD at different strain rates at 423 K. The EBSD maps of as-received alloy and of samples compression tested at 10^{-2} s^{-1} are also shown in Fig.3 (g), (h). It can be observed that no twins appear in the microstructure during tension along RD. However, large amount of twinning lamellas become visible after

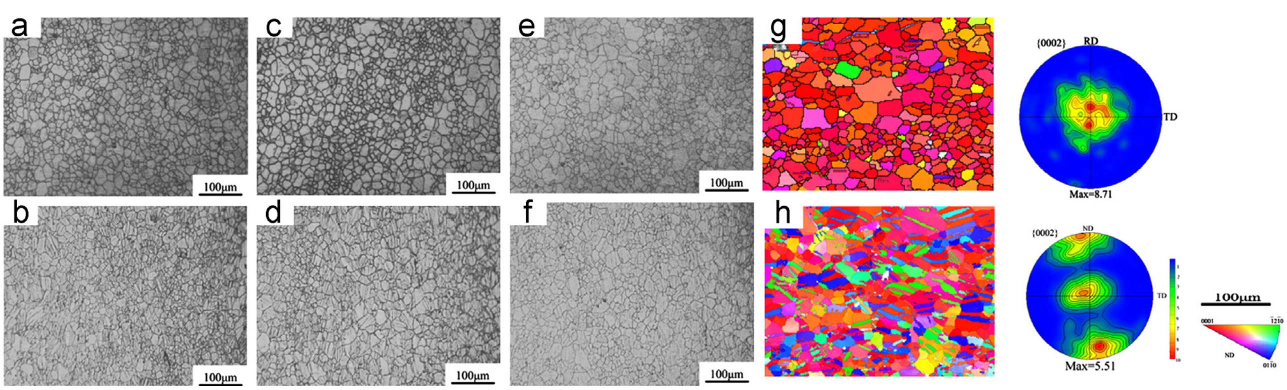

Fig.3. Microstructure of AZ31B alloy at different strain rates: (a) tension at 10^{-2} s^{-1}; (b) compression at 10^{-2} s^{-1}; (c) tension at 10^{-3} s^{-1}; (d) compression at 10^{-3} s^{-1}; (e) tension at 10^{-4} s^{-1}; (f) compression at 10^{-4} s^{-1}, EBSD map: (g) as-received, (h) compressed at 10^{-2} s^{-1}.

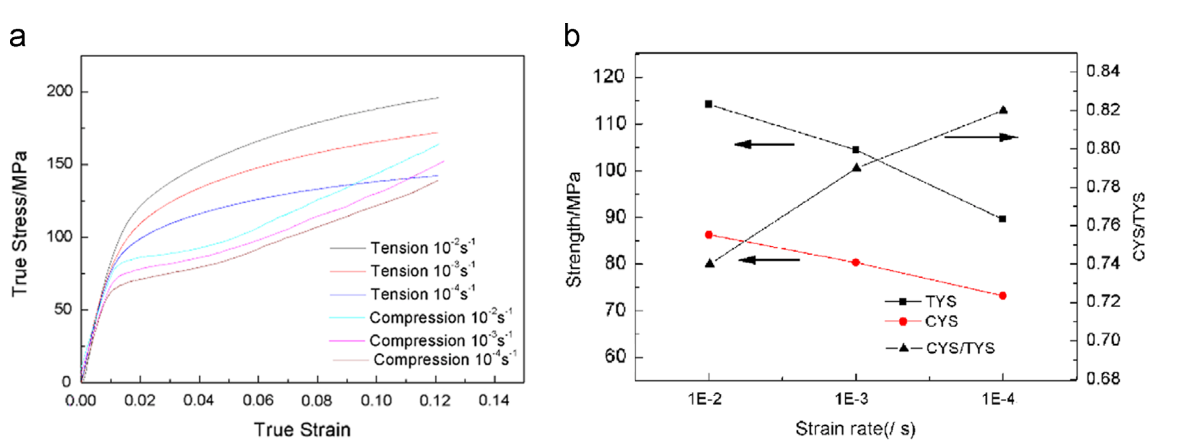

Fig.4. (a) True stress versus strain curves of AZ31B alloy sheets (b) tension and compression yield strength along RD with different strain rates at 423 K.

compression and the volume fraction of twins decreases as the strain rate decreases. According to EBSD map, the twinning boundaries are {10–12} tensile twinning. Due to the emerging of {10–12} twinning, a textured RD was induced with intensity decreasing down to 5.51, while in the as-received samples, the main basal texture had an intensity of 8.71. Yin et al. reported that the {10–12} tensile twinning becomes active when compression perpendicular to c-axis of Mg grains is applied [10]. At 423 K, softening effects are induced by dynamic recovery and, as the strain rate decreases, softening effects will be enhanced so that twinning behavior is restrained.

The trend of yield strength after tension (TYS) and compression (CYS) tests and of the yield strength ratio (CYS/TYS) at different strain rates are shown in Fig.4. It is revealed that the TYS and CYS decrease as the strain rate decrease. However, the CYS/TYS ratio increases. At a strain rate of 10^{-2} s^{-1}, CYS/TYS ratio reaches a value of 0.73, while it increases to 0.82 when the strain rate reduces to 10^{-4} s^{-1}. This again confirms that the tension-compression asymmetry weakens at lower strain rates. So k-value decreases as the strain rate decreases during bending at 423 K.

4. Conclusions

In this study, the effect of strain rate on the shift of neutral layer at 423 K was investigated under V-bending condition. As the strain rate decreases from 10^{-2} s^{-1} to 10^{-4} s^{-1}, the coefficient of neutral layer (k-value) decreases accordingly. It was demonstrated that this behavior was mainly due to the weakening of the tension-compression asymmetry found at lower strain rates. At 423 K, dynamic recovery may occur and the softening effects are induced. As the strain rate decreases, the softening effects are enhanced and twinning is therefore restrained.

Acknowledgments

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