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Effect of twinning and detwinning on the spring-back and shift of neutral layer in AZ31 magnesium alloy sheets during V-bend

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ABSTRACT

In order to investigate the effect of twinning and detwinning on springback and shift of neutral layer, pre-stretch (PRS) of 3% and 5%, and pre-compression (PRC) of 1%, 3% and 5% along rolling direction was conducted in an AZ31 magnesium alloy sheets at room temperature. 90° V-bending tests were performed at 423 K with various pre-strained samples. The results show that springback increases after both PRS and PRC deformation. The coefficient of neutral layer (*k-value*) decreases with the increase of the levels of PRS and PRC. After PRS, twinning in an inner compressive region during bending is restrained and tension–compression asymmetry decreased. After PRC, detwinning occurs which implying that it dominates the deformation in the outer tensile region, while in inner compressive region twinning still governs the deformation. Twinning and detwinning leads to a decrease of asymmetry mechanism between the outer and inner layers. The decrease of asymmetry mechanism after PRT and PRC results in a drop of the neutral layer offset.

1. Introduction

As the lightest structural metal, magnesium and its alloys have attracted a large number of industrial sectors due to their high specific strength and stiffness [1,2]. However, owing to hexagonal close packed (HCP) structure, magnesium shows a poor formability at room temperature. In other words, since there are limited numbers of available slip systems in magnesium crystals at low temperatures. The Von Mises Criterion requiring at least 5 independent slip systems for plastic deformation of polycrystalline metals to occur which cannot be met and limited ductility is shown [3]. Accordingly, improving the ductility and strength of magnesium alloys through different procedures has been widely investigated. Recently, pre-strain has been found to be a proper method to significantly improve the mechanical properties in magnesium alloys. Song et al. [4] and Xin et al. [5] reported that the {10$\bar{1}$2} twins-induced by pre-rolling could actually split grain crystals and thereby leads to grain refining, improving the mechanical properties of magnesium alloys. Wang and Huang [6] indicated that the twins generated by pre-compression along extrusion direction disappeared after inverse tension which resulted in improvement of plasticity in an AZ31 magnesium alloy. Zhang et al. [7] also proved that the basal texture was weakened by pre-stretch deformation and that the formability of the AZ31 magnesium alloy sheet was improved.

Being one of the most important processing techniques, bending is also known to be affected by the complex springback phenomenon. Besides, during bending, the outer-layer of the sheets is under tensile deformation while the inner-layer will be under compressive deformation. The different deformation modes result in a shift of the neutral layer during bending. For common metals like aluminum, the neutral layer shifts to the inner compressive region. However, for magnesium alloys featuring an HCP structure is opposite. Thus, as reported in the previous research [8], the asymmetry of the deformation mechanism leads to a shift of the neutral layer of the alloy to the outer tensile region. It was also proved that twinning plays an important role on the tension–compression asymmetry [9]. The more frequent the twins, the bigger the tension–compression asymmetry will be. Hence, twinning must have an important effect on the shift of the neutral layer in magnesium alloys during bending. It is well known that detwinning occurs after inverse deformation [10,11] and accordingly, during bending, springback cannot be avoided and an inverse load will be induced, leading to the concurrent detwinning behavior. To the authors' knowledge, detwinning behavior during bending has not been researched so far. In this paper, twins were induced in an AZ31 alloy by different pre-strain (pre-stretch and pre-compres-

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sion) paths and thereafter the effect of pre-strain as well as twinning–detwinning behavior on spring-back and shift of neutral layer during bending of sheets were thoroughly investigated.

2. Experimental procedure

A commercial rolled sheet of AZ31 magnesium alloy (Mg–3 wt.%Al–1 wt.%Zn) having a thickness of 3 mm was annealed at 673 K for 4 h. Rectangular specimens with a width of 30 mm and a length of 100 mm were cut from the annealed sheets. Some of the specimens were then pre-stretched along their rolling direction (RD) by 3% or 5% at a strain rate of 10^{-3} s^{-1} at room temperature. Other specimens with the same size were pre-compressed along RD by 1%, 3%, 5% as well at room temperature. The pre-strained samples were annealed at 200 °C for 2 h. In order to avoid buckling of the sheet during compression, a special mold was designed, as shown in Fig. 1. During compression, standard mineral oil was used as a lubricant.

Samples with 30 mm width and 80 mm length were cut from the pre-strained sheets and subjected to V-bending to an angle of 90° on a CMT6305-300KN electro-mechanical universal testing machine at the temperature of 423 K based on General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ) Standard GB/T GB/T232-2010 [12]. Due to poor formability of the alloy, bending was conducted at 423 K by placing the die and the specimens in a resistance furnace fitted to the testing machine. The V-punch had a radius of 9.3 mm and the initial speed of the punch was set to 10 mm/min. In order to ensure reproducibility of the experiments, for each condition three tests were carried out. In order to keep the same conditions and minimize the effect of unloading time on springback, all the specimens kept 30 s after V-bending before unloading. After V-bending, the thickness of the samples was measured using a universal goniometer. The offset of neutral layer was measured by the coefficient of neutral layer (*k* value). The coefficient (*k*-value) was the standard of offset of neutral layer. The bigger of *k*-value, the further away shifting of neutral layer from geometrical middle layer will be. If *k*-value is less than 0.5, it means neutral layer shift to compressive region during bending. If it exceeds 0.5, neutral layer shifts to the outer tensile region accordingly.

According to a theory of stamping process, the computational formula of the *k* value is given as:

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

where k, β, R_i and t are the coefficient of the neutral layer, the coefficient of incrassation, the inside bending radius and the original thickness of the sheet, respectively.

The microstructure of the samples was characterized by optical microscopy and by electron backscatter diffraction (EBSD). The optical microstructure was observed after standard metallographic preparation technique while samples preparation for EBSD consisted in mechanical grinding followed by polishing down to colloidal silica naps. Then, electro-polishing was performed using a solution of 20% nitric acid and 80% methanol with a voltage of 20V for 120 s at temperature of −30 °C. Finally, EBSD measurements were performed on a Zeiss EVO 50 SEM. The EBSD data were processed by an INCA OXFORD crystal software.

3. Results and discussion

Optical micrographs illustrating the microstructure of the AZ31 alloy at different pre-strain levels are shown in Fig. 2. The as-received microstructure consisted of large amount of equiaxial grains with an average size of 18 μm. After 3% PRS and 5% PRS some of the grains appeared to be deformed but no twins emerged. However, a large number of twins were found in the microstructure of PRC samples. The twinning lamellar structure was preserved when annealing below 473 K took place, which is consistent with previous research results [13]. By increasing the level of PRC strain, the volume fraction of twins increased as well, and, especially in 5% PRC samples, almost all the grains contained twins. The (0002) pole figures of as-received, 3% PRT and 3% PRC samples are depicted in Fig. 3. It can be observed that the as-received AZ31 plate exhibits a typical basal texture. After pre-stretch deformation, the basal texture did not change too much, however, in 3% PRC samples, a texture//RD was induced by twins. According to the EBSD maps, the twinning boundaries are (10−12) twins. It is widely accepted that the {10−12} twinning always occurs when tension is applied along the *c*-axes of most grains or when compression is applied perpendicular to the *c*-axes [14].

The load vs position curves during bending of various pre-strained samples experimentally obtained are shown in Fig. 4. As expected, the bending load increased with pre-strain deformation levels. Comparing the load–position curves in various pre-strained samples in Fig. 4(c), the bending load was higher in the PRC than in the PRT samples, even 1% PRC featured a higher bending load than 5% PRT.

The trend of springback and coefficient of neutral layer (*k-value*) after V-bending to 90° of the pre-strained samples is shown in Fig. 5. The springback value increases with increasing PRT and PRC levels. It is well known that springback is affected by both the elastic modulus and the yield stress of the material [15]. It is supposed that elastic modulus does not vary too much by pre-strain deformation. Bruni et al. [16] indicated that the decrease of springback with the increasing temperature was mainly due to the decrease of flow stress recorded on the load–stroke curves during bending, and to lower amount to decrease inelastic modulus. As shown in Fig. 4, the flow stress (which is assumed to directly depend on position of the bending load) increased with the increase of PRT and PRC levels, resulting in an improvement in

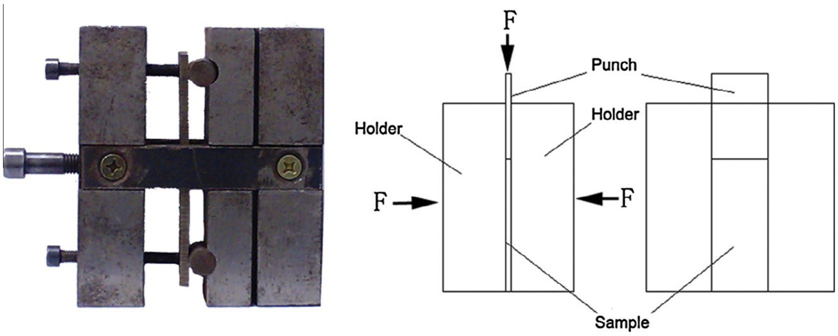

Fig. 1. The sheet compressive mold and sketch map of load.