Materials Science & Engineering A 591 (2014) 69–77

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of pre-strain on work-hardening behavior of magnesium alloy sheets upon cyclic loading

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ARTICLE INFO

Article history:
Received 20 September 2013
Received in revised form
24 October 2013
Accepted 25 October 2013
Available online 31 October 2013

Keywords:
Magnesium alloy sheet
In-plane cyclic loading
Pre-strain
Twinning
Work-hardening

ABSTRACT

This paper reports the effect of pre-strain on the work-hardening behavior of rolled AZ31 magnesium alloy sheets during in-plane cyclic loading. The work-hardening behavior of the alloy remained almost unchanged when tensile strain was applied before cyclic loading. However, the work-hardening behavior was significantly affected when a compressive strain was applied. First, the resulting stress–strain curve was not sigmoidal upon tension in some cases, depending on the magnitudes of the applied compressive pre-strain owing to the inversion of the loading direction from tension to compression before the second increase in the work-hardening rate. In other words, a sigmoidal stress–strain curve certainly arose upon tension when compressive pre-strain was applied and the loading direction was not inverted from tension to compression. It was found that the strain at the beginning of the second increase had a high correlation with the volume fraction of twins. Second, the change in the rate of work-hardening at the beginning of tension became sharp as compressive pre-strain increased, probably owing to the effect of activation of detwinning on the stress–strain curve, which became increasingly significant as the compressive pre-strain increased the volume fraction of twins.

1. Introduction

Mg alloys have attracted a great deal of attention because of an increasing demand for lightweight materials to reduce CO_2 emission from transport equipment. In general, Mg alloys used for components are made by die casting and thixoforming. Because press forming of sheet metal is an efficient process to manufacture thin-walled structural components, press forming of Mg alloy sheets has received much attention, and many studies on the press formability of Mg alloy sheets have been carried out [1–11]. However, the number of structural components manufactured by press forming of Mg alloy sheets is still small. One of the reasons is that the deformation behavior of Mg alloy sheets is significantly different from those of conventional metal sheets used for structural components. For instance, rolled Mg alloy sheets show asymmetric deformation between tension and compression, exhibit nonlinear deformation during unloading, and display strong anisotropic work-hardening behavior through successive changes in the shapes of their yield loci. Such characteristic deformations in Mg alloy sheets are the result of magnesium's hexagonal close-packed (HCP) structure, which exhibits significant crystal anisotropy and allows easy activation of direction-dependent [10 – 12] deformation twinning. Therefore, many studies have been carried out to understand the work-hardening behavior as well as the formability of Mg alloys [12–23].

During press forming, a metal sheet is often subjected to cyclic loading such as cyclic bending–unbending processes. Consequently, the deformation behavior under cyclic loading conditions have been extensively studied in various metals used for structural components, including aluminum alloys and steels [24–27], and in Mg alloys [21,28–36]. These past studies on Mg alloys focused particularly on their fatigue properties, studied using a very large number of cycles and a relatively small strain amplitude. A literature survey of the past studies on fatigue properties can be found in [21].

During press forming, a metal sheet is subjected to several cycles during which large plastic strains arise accordingly, showing that cyclic-loading conditions necessary for the study of press forming would be different from those used for study of fatigue properties. In our previous study [21], the work-hardening behavior of a rolled Mg alloy sheet was investigated under in-plane cyclic tension–compression conditions with relatively high strain amplitudes and small cycle numbers. The effects of twinning and detwinning on the work-hardening behavior were also investigated. In summary, we found that the work-hardening behavior was asymmetrical between tension and compression as follows: the rate of work-hardening in the later stages of compression increased as the number of cycles increased, whereas rate in the

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http://dx.doi.org/10.1016/j.msea.2013.10.083

later stages of tension decreased. It was also found that the work-hardening behavior could be explained in terms of twinning and detwinning. The work-hardening behavior was also affected by the strain amplitude of cyclic loading.

In our previous study [21], we also showed that the work-hardening behavior remained unchanged when a tensile pre-strain was applied before a cyclic loading test was carried out, while they were significantly affected when a compressive pre-strain was applied. In particular, the sigmoidal shape in the stress–strain curve that generally occurs upon tension following compression did not arise when a pre-strain of −4% was applied before the cyclic loading test with a strain amplitude of 6%. These results indicated that the work-hardening behavior might be subjected to significant changes by the loading history of the sample. However, the experiments were carried out only with the conditions of a strain amplitude of 6% and pre-strains of 4% and −4% in the previous study. Therefore, changes in the work-hardening behavior as a function of the pre-strain are not yet understood. Particularly, changes in the stress–strain curve during inversion of loading from compression to tension in one cycle depending on the pre-strain and the strain amplitude are not clear, which hinders an accurate prediction of the work-hardening behavior.

In the present paper, the effect of pre-strain on the work-hardening behavior under in-plane cyclic tension–compression was investigated. We focused our attention on the effect of pre-strain on the work-hardening behavior upon tension following compression. Cyclic loading tests were carried out with strain amplitudes of 2%, 4%, and 6% after pre-strains of 4%, 0%, −2%, −4%, −5%, and −6% were applied. Metallographic observations using an optical microscope were also used to examine the correlation between the twinning activity and the work-hardening behavior.

2. Experimental procedures

2.1. Material

In the present study, commercial rolled AZ31B Mg alloy sheets (Mg–3% Al, 1% Zn, Osaka Fuji Corporation) of two thicknesses were used, 0.8 and 1 mm. The sheet with a thickness of 0.8 mm was the same as that used in our previous study [21]. The material with a thickness of 1.0 mm was used in additional experiments where very large compressive pre-strains were applied, which will be explained in detail in Section 4. Sheets with thicknesses of 0.8 and 1.0 mm are referred to as A and B, respectively. The mechanical properties of the sheets obtained from uniaxial tension tests are shown in Table 1. A sample preparation procedure was the same as in our previous study [21]. The geometry of the specimen used is shown in Fig. 1. The specimens were machined parallel to the rolling direction, and were annealed at 350 °C for 1.5 h before conducting the experiments.

2.2. Experimental procedure of in-plane cyclic loading test

The experimental procedure for the in-plane cyclic loading test was the same as that used in our previous study [21], and has been explained briefly as follows. Comb-shaped dies were used to suppress buckling during compression [37]. A photograph of the experimental setup is shown in Fig. 2. The compressive forces in the thickness direction were applied through the elastic forces of four coil springs. The magnitude of the compressive force was 5 kN, which was much smaller than the 0.2% proof stresses of the sheets. Mineral hydraulic oil with a nominal kinetic viscosity of 32 cSt at 40 °C was used as a lubricant.

The experiment was carried out at an initial strain rate of $6.67\times10^{-4}\,s^{-1}$ at room temperature. A strain gauge was used to measure strains in the loading direction during the test. The cyclic loading test was carried out with strain amplitudes of 2%, 4% and 6% after pre-strains of 4%, 0%, −2%, −4%, −5% and −6% were applied. The definitions of the strain amplitude ε_S and the pre-strain ε_P are described in Fig. 3 where a stress–strain curve with a strain amplitude of 6% and a pre-strain of −2% is shown. Because of the capacity limitation of the experimental setup, the maximum

Table 1
Mechanical properties of sheet materials obtained by a uniaxial tension test[a].

Material	Thickness/mm	E/GPa	$\sigma_{0.2}$/MPa	σ_T/MPa	$r_{10\%}$	$r_{15\%}$	F/MPa	n
A	0.8	40	168	264	2.25	2.79	478	0.225
B	1	42	158	255	2.38	3.05	478	0.252

[a] The true-stress–strain curve is approximated with $\sigma = F\varepsilon^n$.

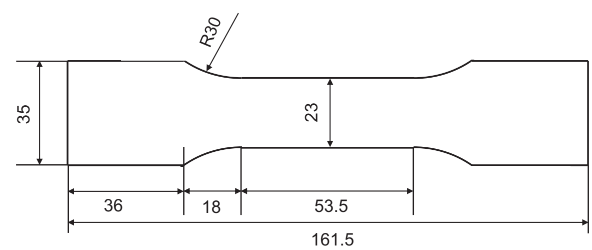

Fig. 1. Geometry of a specimen used in the cyclic loading test.

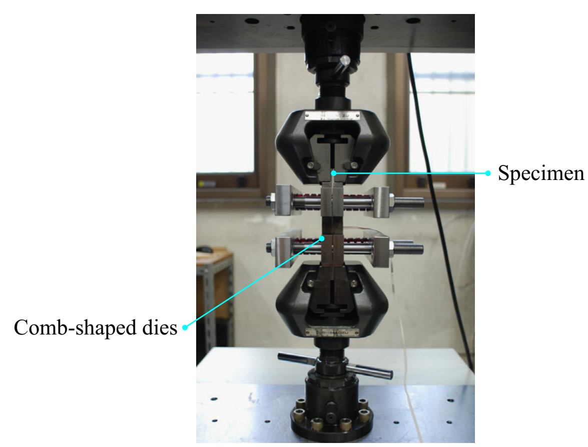

Fig. 2. Photograph of the experimental setup for the cyclic loading test.

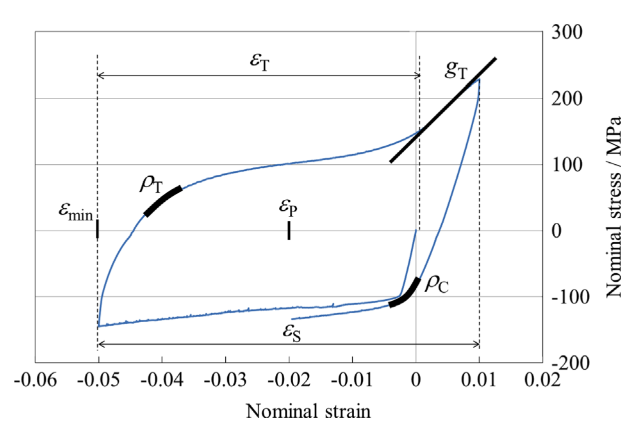

Fig. 3. Symbol definitions. Stress–strain curve of material A with a strain amplitude of 6% and a pre-strain of −2% is shown.