Standard and Strain Path Change Forming Limit Diagrams of AZ31B Magnesium Sheet at Elevated Temperatures

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Abstract. Effect of strain path change on formability and microstructural characteristics of AZ31B automotive magnesium sheet material is studied at 300°C. The standard forming tests are carried out using Nakazima tests within the environmental chamber. The strain path change tests are performed by in-plane uniaxial, plane strain and balanced biaxial pre-strained specimens in the first stage and Nakazima test in the second stage. The enhancement in the activity of prismatic and pyramidal <c+a> slip as well as a reduction in material anisotropy with increase in temperature is responsible for improvements in formability. Compared to the standard FLD, all uniaxial, plane strain, and balanced biaxial pre-strained materials exhibit higher limit strains. This rise in FLD also incorporates the effect of additional annealing during temperature rise period prior to testing which cannot be avoided with the present experimental set-up and test methodology. The pre-strain effect is reduced by additional annealing effect caused by elevated temperature soaking time. At 300°C, the pre-strained material is almost fully recovered and behaves as the as-received material. Also, significant dynamic recrystallization is observed at 300°C.

1. Introduction
Magnesium sheet as a light weight material is being actively considered for automotive body components [1-3]. However, due to the poor formability of Mg alloy at room temperature, elevated temperature forming is being considered as a viable option by many [4-6]. Also, strain paths are not always linear and proportional in real stamping operations. Therefore, the present work explores the effect of two-step strain path change on formability of a common automotive magnesium sheet alloy, AZ31, at 300°C utilizing the hemispherical punch stretching test procedure on in-plane pre-strained test specimens.

2. Test procedures and specimen geometries for HPS tests
The sheet material was a commercial magnesium alloy AZ31B of 1.58 mm thickness in strain hardened and partially annealed condition (H24 temper) which was annealed at 300°C for 15 minutes and furnace cooled to room temperature. Uniaxial tension test at different temperatures, strain rates
and sheet orientations as well as formability tests in the form of in-plane pre-strain and out-of-plane dome tests were conducted at 300°C to obtain mechanical properties of the sheet material and forming limit diagrams (FLDs) respectively. The elevated temperature test set-up consisted of a computer-controlled servo-hydraulic mechanical test system of 500 kN load capacity (MTS system) equipped with an environmental chamber from Instron (see Figure 1). An on-line optical strain measurement system (Aramis from GoM) equipped with a high resolution CCD camera was utilized to capture images of the deforming in-plane pre-strain specimens from a glass window in the environmental chamber. The environmental chamber and the tooling inside was held at the desired test temperature of 300°C for at least one hour prior to pre-straining. Large specimens were pre-strained at 300°C, then removed from the test system, and cut to the desired geometries, as described later. For dome testing of the cut pre-strained test samples, the environmental chamber with the dome test tooling in it was kept at 300°C for at least an hour. The chamber door was then opened to insert and clamp the specimen in the die. There was a drop in the chamber temperature to about 200-250°C but the temperature returned to 300°C within a few minutes of door closing. Total insertion, clamping, heating to 300°C and soaking at 300°C for the pre-strained sample geometries, prior to dome testing, was about 10 minutes. The tests were stopped at neck and the dome samples removed from the test system for imaging with a post-test optical strain measurement system (Argus from GoM) to obtain the limit strains. The time-history of the test sample for FLD determination is provided in Figure 2.

Figure 1. A photograph of elevated temperature MTS mechanical and formability test system, test set-up (left), and (b) HPS tooling inside the environmental chamber (right).
Figure 2. Time history of test sample for FLD determination.

Figure 3 shows uniaxial and plane strain pre-strain specimen geometries. Biaxial tensile pre-strain on square shaped specimen geometry (not shown) was achieved from Marciniak tests. Forming limits from pre-strained specimens were determined using Nakazima and Hecker test methods [6] based on HPS tests on a range of different, partially and fully clamped, specimen geometries to attain various strain paths (see Figure 4). Five different specimen geometries were designed to obtain strain paths from uniaxial tension to biaxial tension. The samples were clamped with a circular lock-bead along the width direction at the top and bottom edges for the first four geometries and all around 4 edges in the last (square) geometry during HPS tests.

Figure 3. Pre-strain test specimen geometries for HPS experiments, uniaxial (left), plane strain (right). Note that the biaxial tension specimen geometry is not shown here.

Figure 4. Test specimen geometries for HPS experiments.

3. Experimental results and discussion
The uniaxial stress-strain curves at 300°C for 3 different strain rates along the rolling direction (RD) as well as along 45° and transverse directions (TD) at the slowest strain rate of 0.001 s⁻¹ are shown in Fig. 5. Duplicate tests were conducted at each of the test conditions and the test were within 1%
in the stress and strain values. The effect of increasing strain rate was to increase the flow stress of the material indicating that the material exhibits significant strain rate sensitivity at 300°C. Also, the test specimens exhibited a rather small orientation effect in the in-plane flow stress of about ±2 MPa and virtually no change in the overall strain to fracture as evident from the bottom three stress–strain curves (see the small inset in Figure 5). This corresponded to the initial texture of the sheet where a strong basal texture with a slight tilt towards the rolling direction was observed [7]. Continuous strain softening occurred over a larger strain range after the early peak stress.

Figure 5. Uniaxial tensile stress-strain curves at 300°C.

Figure 6 shows the strain paths of the uni-axial tension (left), plane strain (middle) and biaxial tension (right) pre-strained test specimens from the centre of the specimen at 300°C. The plane strain path is slightly to the left of the pure plane strain path (with a maximum minor strain of −0.015). However, biaxial tensile strain path is nearly equibiaxial at 300°C. The strain paths for the different specimen geometries were consistent with the locations of the necks observed in the deformed specimens (see Figure 7).

Figure 6. Uniaxial, plane strain, and biaxial tensile strain paths of pre-strained specimens tested at 300°C.

Figure 7. Photographs of necked dome specimens from different test specimens geometries.
Figure 8(a,b) shows the FLDs of initial sheet (i.e., standard FLD) and deformed sheets after three different pre-strains at 300°C. Fig 8(a) shows the comparison of FLDs without adding the pre-strain value. Compared with the initial FLD (in red), the UT and PS pre-strains elevate the limit strains, while the BS pre-strain reduces the limit strains. Fig 8(b) shows the FLDs after adding the respective pre-strain values. This addition of pre-strain causes all three FLD curves (UT, PS and BS) to rise above the initial FLD (in red). This rise in FLD also incorporates the effect of additional annealing during temperature rise to 300°C.

Since the material is fully recovered and the dislocation structure is largely removed due to annealing at 300°C, the effect of pre-strain becomes rather small compared to lower temperatures. As explained in Li et al. [8], the pre-strained FLD (without adding the pre-strain part) could be close to the as-received FLD at higher annealing temperatures and long annealing times. The annealing reduces the effect of pre-strain because during deformation the material undergoes work hardening but during annealing the dynamic recovery is significant, so the material returns to its initial state. In the present tests at 300°C, the annealing time was long enough and temperature high enough that the material was able to completely return to its initial state (see Figure 9). It is to be noted that an annealing effect was introduced from raising the temperature and soaking the sample in the furnace. This was rather difficult to avoid in the current experimental set-up and test methodology. It is expected that the dome height or the limit strain were improved by the additional annealing.

Since the recovery of the microstructure during the specimen heating and testing period is expected...
to have some effect on material formability, several uniaxial tension tests after pre-strain were performed. It is to be noted that it typically took about 10 minutes of time to reach the test temperature after the furnace closure. Figure 10 shows the optical micrographs after pre-straining. The results are in accordance with the FLD results. The pre-strain shows only a slight effect on FLD.

![Optical micrographs from pre-straining at 300°C.](image)

Since the temperature was not constant during the soaking period, a separate study was carried out to analyze the effect of soaking time on the stress-strain curve. Different soaking times in the isothermal condition were compared. Samples were stretched to a pre-strain of 0.1 at an initial strain rate of 0.005/s and kept in the furnace for different soaking times, then stretched again. Fig 11 shows the effect of soaking time on uniaxial stress-strain response of pre-strained specimens at 300°C. When soaking time was less than 2 minutes, the reloaded stress-strain curve was almost the same as the initial one. However, stress values progressively dropped as the soaking time was increased to 5 and 10 minutes indicating recovery of the microstructure and slight changes to the work hardening characteristics of the material from annealing.

![Effect of soaking time on uniaxial stress-strain response of pre-strained specimens tested at 300°C.](image)

4. Conclusions

The effect of strain rate and strain path change on the formability of AZ31B sheet at 300°C was studied in present work. AZ31B magnesium sheet became more ductile, increasingly more strain rate sensitive, and more isotropic with increase in temperature. The formability was enhanced
dramatically at 300°C. Also, the pre-strain effect was reduced by the additional annealing caused due to unavoidable soaking of the specimen with the present experimental set-up and test methodology to reach the desired test temperature after the pre-strain. At 300°C, the pre-strained material was fully recovered to the pre-test fully annealed state. Microstructure examination confirmed that DRX was significant at 300°C.

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