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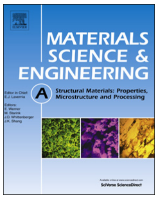

Plastic deformation and ductility of magnesium AZ31B-H24 alloy sheet from 22 to 450 °C

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ABSTRACT

Mg alloy AZ31B-H24 sheet was investigated through microstructural characterization and mechanical testing. Tension tests were conducted across a broad range of strain rates for temperatures from 22 up to 450 °C, as were gas-pressure bulge tests for several forming pressures at 350 °C. Tensile data were used to calculate flow stresses, tensile elongations, activation energies for creep and the Lankford coefficient, or R-value. The AZ31B material exhibits strong plastic anisotropy ($R=7$) at room temperature because of its basal crystallographic texture. Plastic anisotropy decreases with increasing temperature but demonstrates no sensitivity to strain rate until recrystallization occurs. Upon recrystallization, the R-value becomes sensitive to strain rate and continues decreasing with increasing temperature until it reaches a minimum ($R=1$–3) near approximately 300 °C. Plastic anisotropy at these high temperatures is greatest at the fastest strain rate. This sensitivity to strain rate is attributed to a competition between dislocation-climb creep, which produces anisotropic flow and dominates at fast strain rates, and grain-boundary-sliding creep, which produces isotropic flow and dominates at slow strain rates. The mechanistic understanding developed for plastic flow in AZ31B was implemented in a material constitutive model for deformation at 350 °C. A new aspect of this model is the inclusion of dislocation pipe diffusion as a potential accommodation mechanism for dislocation-climb creep. This model was validated against independent gas-pressure bulge test data through the predictions of a finite-element-method simulation, and the model provided quite accurate predictions of the experimental data.

1. Introduction

Magnesium alloys, the lightest of all structural metals, are of great interest to vehicle manufacturers because of their potential to provide significant vehicle mass reduction. Mass reduction is desired to improve vehicle performance, particularly for mandated fuel economy goals [1]. While Mg alloys have found commercial success primarily in cast components and, more recently, in extrusions [2], wrought Mg sheet has seen only minimal application in vehicle components. An important reason for this is the low formability typical of Mg alloys at room temperature, which precludes the use of room temperature stamping operations. The reasons for low formability are found in the complex materials science of the hexagonal close-packed (HCP) crystal lattice of Mg. At room temperature, only two unique basal slip systems and a single non-basal system are active in Mg, and high stresses are needed to activate the non-basal systems. These are not sufficient to meet the Taylor criterion [3] for strain compatibility between grains, which requires the activation of at least five independent systems. Fracture at incompatible boundaries precedes large plastic deformation and produces low polycrystalline ductility. Improved room-temperature ductility will result if the recrystallization texture is softened and the activity of otherwise inactive deformation mechanisms is thereby increased, such as by increasing $\left\{10\bar{1}1\right\}10\bar{1}2$ contraction twins, $\left\{10\bar{1}1\right\}\left\{10\bar{1}2\right\}$ double twinning, and pyramidal $c+a$ dislocation slip. Because non-basal slip systems are activated at elevated temperatures [4,5], the ductility of Mg increases significantly as temperature increases. Through this effect, hot and warm forming offer potential routes to successfully produce complex components from wrought Mg sheet. Successful commercial Mg sheet forming can be conducted at hot temperatures, as exemplified by the recent success with hot gas-pressure forming of wrought Mg AZ31B sheet [6,7]. However, substantial research activity continues to be focused toward improving ductility in Mg alloys at lower temperatures, and this is with good reason. A decrease in forming temperature from the 450 °C minimum typical of hot gas-pressure forming technologies

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might lead to several practical advantages. These include considerable savings in energy for component production, easier part handling, reduced need for high-temperature lubricants and potentially improved surface finish through reduced orange peel.

Plastic anisotropy is typically significant in Mg sheet materials, even at elevated temperatures. This is commonly the result of a strong basal texture developed during sheet rolling [8]. Carpenter et al. demonstrated that plastic anisotropy must be accounted for to accurately predict the forming of Mg AZ31B sheet at 450 °C [9]. In their study, plastic anisotropy was measured from uniaxial tension tests across a wide range of strain rates and then modeled for simulations using the Lankford coefficient, also known as the *R*-value. Plastic anisotropy in Mg AZ31B was reasonably approximated as normal anisotropy at 450 °C. The resulting material constitutive model enabled accurate finite-element-method (FEM) simulations of gas-pressure forming, which involves multiaxial stress states. It was shown that accounting for plastic anisotropy is essential to accurately predict deformation under stress states that are more complex than uniaxial tension. The success of this material constitutive model was also based upon incorporation of the deformation mechanisms that control plastic flow in Mg AZ31B at 450 °C, dislocation-climb (DC) creep and grain-boundary-sliding (GBS) creep. Carpenter et al. evaluated the changes in *R*-value with strain rate only at 450 °C. Agnew et al. [10] studied the effect of a change in temperature on the *R*-value in Mg AZ31B from room temperature up to 250 °C, but they did not study the effect of strain rate or higher temperatures. Thus, data are needed for the *R*-value at temperatures between 250 and 450 °C and for its variation with strain rate below 450 °C.

The present investigation is intended to expand our knowledge of and predictive capabilities for the plastic deformation of wrought Mg AZ31B sheet from room temperature up to 450 °C across a wide range of quasi-static strain rates. It was designed to build upon previous studies by producing new data for temperatures and strain rates not previously addressed. A particularly important contribution of the present investigation is the evaluation of plastic anisotropy through the *R*-value along with the evaluation of other parameters important to plastic flow, such as the flow stress, strain hardening, the activation energy for plastic flow and the stress exponent. Tension tests were conducted at constant true-strain rates of 10^{-3}, 10^{-2} and $10^{-1}\ \mathrm{s}^{-1}$ from 22 to 450 °C. Additional tension tests were conducted at 350 °C for strain rates from 10^{-4} to $3 \times 10^{-1}\ \mathrm{s}^{-1}$ to aid the construction of an accurate material constitutive model for that temperature. Gas-pressure bulge tests were conducted at 350 °C for pressures from 1.4 to 2.2 MPa. Finite element method (FEM) simulations were conducted for the gas-pressure bulge tests using a material constitutive model constructed solely from the tension test data. In this manner, the material constitutive model was validated against data independent of those used in its construction. The predictions from FEM simulations are found to agree closely with the gas-pressure bulge test data.

2. Experimental procedure

The material evaluated in this investigation is a commercial Mg AZ31B rolled sheet supplied in the H24 temper. The as-received thickness of the sheet material was 2 mm, and the composition is provided in Table 1. This is the same material studied by Carpenter et al. [9] at 450 °C. The recrystallization and grain-growth behaviors of this material were previously reported by Antoniswamy et al. [11] for temperatures up to 450 °C. Recrystallization occurred at temperatures of approximately 200 °C and higher, with only partial recrystallization observed after short annealing times ($\leq$ 15 min) at 200 °C. Grain size, reported as the geometric mean of lineal-intercept grain sizes measured along three orthogonal directions [12], increased with recrystallization temperature. Grain size increased from 5.3 μm after recrystallization at 250 °C to 9.2 μm after recrystallization at 450 °C. Grain growth in this material following recrystallization is quite modest at temperatures up to 450 °C [11]. These grain sizes are representative of those in the present investigation. The microstructure of this material after annealing at 150 °C for 20 min is shown in the optical photomicrograph of Fig. 1(a). A pole figure showing the strong basal texture of this sheet material after the same annealing treatment is provided in Fig. 1(b). The data for this pole figure were acquired from electron backscatter diffraction (EBSD) analysis.

Specimens were produced for tensile testing by electrical discharge machining of a "dog-bone" geometry with a gage length of 25 mm, a gage width of 6 mm, a shoulder radius of 3.2 mm and a 2-mm thickness equal to that of the material as received. Tensile testing was conducted in a three-zone resistance furnace attached to a computer-controlled servohydraulic test frame. Specimens were heated and held

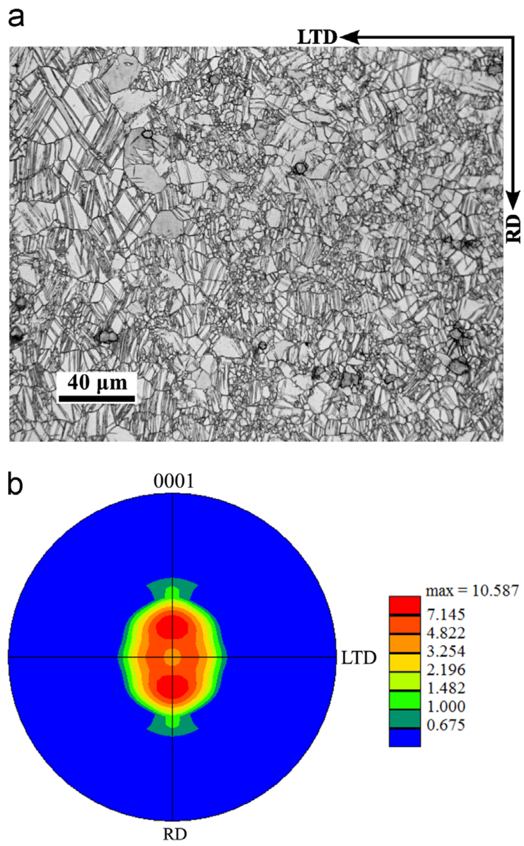

Fig. 1. (a) An optical photomicrograph shows the microstructure in the AZ31-H24 material after annealing at 150 °C for 20 min. (b) A pole figure generated from EBSD data shows the strong basal texture in the AZ31B-H24 material after annealing at 150 °C for 20 min. The color key indicates intensity in multiples of random. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
The Mg AZ31 sheet material composition is shown in wt%.

Al	Zn	Mn	Fe	Cu	Ni	Si	*Ca*	Be	Sr	Ce	Ti	Mg
3.1	1.0	0.42	0.006	0.003	< 0.003	< 0.1	< 0.01	< 0.005	< 0.005	< 0.01	–	bal.