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Time dependent magnesium AZ31B behavior: experimental and physically based modeling investigation

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Abstract

The need to produce vehicles with improved fuel efficiency and reduced emissions has led the automotive industry to consider use of "lightweighting" materials in the construction of automotive body and chassis systems. For automotive body structures and closure panel applications, mostly made of sheet, aluminum alloys are being introduced due to their lower densities and relatively high specific strengths, as well as their compatibility with the traditional manufacturing process that are used with steel. However, interest has been increasingly focusing on the use of sheet magnesium in the manufacturing of panels and structural components, since its density is about 40% lower compared to aluminum. Accordingly, the objectives of this study are to investigate the evolution of microstructure during thermo-mechanical processing of twin-roll cast AZ31B alloys sheets, and to examine the mechanical properties of the alloy under superplastic conditions. The rate dependent crystal plasticity model have been used and integrated using an explicit model was coupled with the Taylor polycrystal model in the aim to capture the overall behavior of our studied material.

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Keywords: AZ31 Magnesium alloys; formability; mechanical characterization; modeling; plastic behavior;

1. Introduction

Magnesium alloys are the lightest existing structural metals with densities about 1.71 g/cm^3. In addition to their low density, magnesium alloys are known to have high specific strength and good weldability (Duygulu and Agnew, 2003; Agnew and Duygulu 2005; Bettles and Gibson, 2005; Easton et al., 2006; Lou et al., 2007; Lee et al., 2008).

The effort to of the decrease fuel consumption and reduce emissions makes magnesium alloys attractive for automotive and aerospace industry. Currently, magnesium castings are used in a large number of applications including wheels, gear box housings, turbine blades, steering wheels, automotive body, chassis systems, and several others. Recently, the magnesium industry has recently begun to produce magnesium sheets in widths that are suitable for automotive sheet applications using processes

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such as twin-roll casting (TRC). This will help expand the use of magnesium alloys into a wider range of applications.

One of the challenges in forming magnesium sheets is the limited available formability at room temperature due to the hexagonal close-packed (hcp) crystal structure of magnesium (Barnett 2001; Abu Farha et al., 2007; Khan et al., 2011). However, experimental studies have shown that the formability of magnesium can be significantly improved if the material is deformed at elevated temperatures (Barnett 2001; Abu Farha et al., 2007; Khan et al., 2011). One of these processes is superplastic forming, which is a gas forming process used to form the sheet metal at elevated temperatures (greater than 0.5 of the melting temperature) and slow strain rates (typically less than 10^{-3} mm/mm/s or less). The aim of this paper is to report the preliminary findings of a study on investigating the superplastic behavior of AZ31B sheets produced by the TRC process. The paper also presents a proposed model based on single crystal plasticity to develop a numerical tool that can predict this mechanical behavior as well as the microstructure evolution under different deformation temperatures and strain rates.

2. Experimental Investigation

Twin roll cast magnesium alloy AZ31B sheets, of 3.22 mm thickness, were used to conduct tensile tests under two different strain rates: 10^{-3} s^{-1} and $5x10^{-4}$ s^{-1} and two different temperatures: room temperature (RT) and 300°C. Test specimens were machined according to the shape and size presented in Figure 1 with the major axis of each specimen aligned parallel to the rolling direction. The tests were all conducted using an electromechanical screw driven testing machine (MTS Insight 30kN) equipped with an environmental chamber.

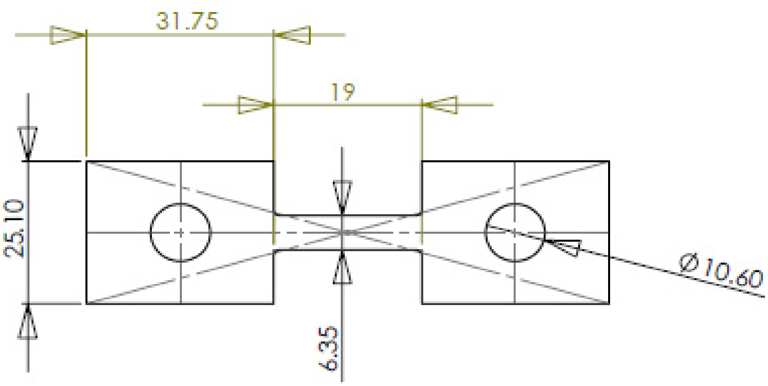


Figure 1. Geometry of the tensile sample, *dimensions are in mm*.

The stress-strain behavior of the AZ31B magnesium alloy is shown in Figure 2. At room temperature, it can be clearly seen that the tested material has limited formability with a maximum elongation to fracture of about 20%. Furthermore, the material fails in a brittle manner. When the material is tested at 300 ^{o}C, a significant increase in ductility is observed with over 80% elongation to fracture achieved at a strain rate of 10^{-3} s^{-1}.

Figure 2 also shows that the material exhibits strain rate sensitivity. At room temperature, the ultimate tensile strength increased with increasing strain rate; however, the total elongation to fracture was approximately the same for the two tested strain rates. When the temperature was increased to 300 ^{o}C, the elongation to fracture increased to about 120% when the strain rate was decreased from 10^{-3} s^{-1} to $5x10^{-4}$ s^{-1}. These observations are in line with the expected material behavior under superplastic flow conditions.

Results obtained from mechanical tests will be used to develop the material constitutive model parameters described in the Section 3 of this paper.

The microstructure of the AZ31B magnesium alloy was observed through an optical microscope. The samples were polished and then etched using a Picric acid based etchant. Figure 3a shows the a micrograph of the as received microstructure of the as-received material and Figure 3b is a micrograph of the material deformed at 300 °C at a strain rate of 10^{-3} s^{-1}. Figure 3a shows that the as-received material has equiaxed grains with grain sizes varying from the order of 1 micron to the order of 100 microns. This indicates that the sheet rolling process to produce the material was not optimized to achieve a uniform grain size. However, Figure 3b shows finer grains with a more uniform grain size than those observed in Fig 3a. This indicates that the material undergoes dynamic recrystallization during processing. In the next phase of our study, we will be performing interrupted tests to at a wider range of temperatures and strain rates to examine the recrystallization response of the material.

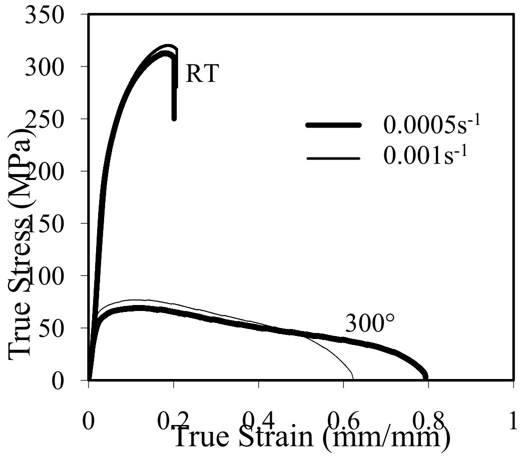
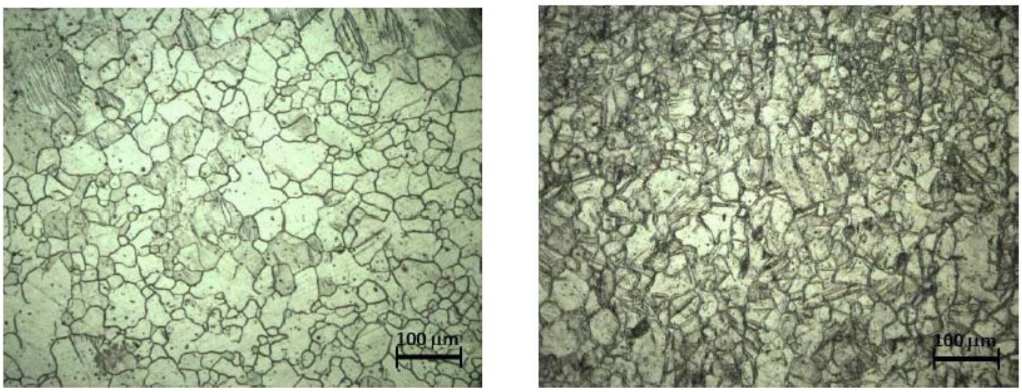


Figure 2. True stress-strain curves of the magnesium alloy AZ31 at different strain rates and different temperature.



(a) (b)

Figure 3. Micrographs showing the roll casting AZ31 magnesium alloy microstructure (a) of the as received material and (b) of a specimen tested to fracture at 10^{-3} s^{-1} strain rate and 300 °C.

3. Modeling

Constitutive equations based on the rate dependent crystal plasticity theory are proposed in this work as an attempt to describe the stress-strain behavior of the magnesium alloys. Few studies attempted to model the stress-strain behavior or the crystallographic texture evolution in hcp metals by using crystal plasticity (Lee et al., 2008). Lebenson and Tome (1993), Kalidindi, (1998), Brown et al. (2005) and Staroselky and Anand (2003) were the first to apply crystal plasticity to simulate the behavior of magnesium alloys. The two main intragranular deformation mechanisms that occur during loading are slip and twinning. The 18 slip and twinning systems that could be activated during loading as described by Staroselky and Anand (2003). These systems are defined by the vectors $\mathbf{m}^{\alpha}$ and $\mathbf{n}^{\alpha}$, where $\mathbf{m}^{\alpha}$ and $\mathbf{n}^{\alpha}$ are the unit vectors defining the direction and the slip/twinning plane normal to the α slip/twinning system, respectively. In this section the constitutive equations for the single crystal rate dependent crystal plasticity, under finite strain, are presented.

3.1. Kinematics

The deformation gradient is denoted by $\mathbf{F}$ with the Jacobian $J = \det \mathbf{F} > 0$. The time derivative of the deformation gradient is written as follows $\dot{\mathbf{F}} = \mathbf{L}\mathbf{F}$, where $\mathbf{L}$ the velocity gradient. The deformation gradient $\mathbf{F}$ is decomposed in a multiplicative manner into elastic part $\mathbf{F}^{e}$ and flow part $\mathbf{F}^{p}$ (Lee, 1969):

$$\mathbf{F} = \mathbf{F}^{e}\mathbf{F}^{p} \tag{1}$$

The velocity gradient could be written in an additive manner as the sum of elastic and plastic part:

$$\mathbf{L} = \mathbf{L}^{e} + \mathbf{L}^{p} = \mathbf{D} + \mathbf{W} \tag{2}$$

where $\mathbf{D}$ and $\mathbf{W}$ are the deformation rate tensor and the spin tensor respectively.
The slip/twinning direction in the α system could be written in the current configuration as follows:

$$\mathbf{m}^{\alpha} = \mathbf{F}^{e}.\mathbf{m}_{0}^{\alpha} \tag{3}$$

The orthogonality condition between the slip/twinning plan and direction impose the following relation:

$$\mathbf{n}^{\alpha} = \mathbf{F}^{e-T}.\mathbf{n}_{0}^{\alpha} \tag{4}$$

Flow rule:
The evolution of the plastic deformation gradient due slip and twinning dislocations is given by the sum of the shearing rates on all the slip and twinning systems:

$$\mathbf{L}^{p} = \sum_{i} \dot{\gamma}^{\alpha}\mathbf{m}^{\alpha} \otimes \mathbf{n}^{\alpha} \tag{5}$$

with $\dot{\gamma}^{\alpha}$ the slip/twin shear rate on the α slip/twinning system.

The twinning and slip will be accounted for by expressing the Cauchy stress in a mixture rule (Kalidindi, 1998):

$$\mathbf{T} = (1 - \sum_{\alpha} f^{\alpha})\mathbf{T}^{un} + \sum_{\alpha} f^{\alpha}\mathbf{T}^{twn\alpha} \tag{6}$$

The volume fraction of twinning will evolve following the given differential equation on the α twinning systems (Kalidindi, 1998; Staroselsky and Anand, 2003) :

$$\dot{f}^{\alpha} = \frac{\dot{\gamma}^{\alpha}}{\gamma^{twin}} \tag{7}$$

A local rotation of the crystal is induced by twinning and must be accounted for in each increment of our calculation.

3.2. Constitutive equations

The resolved shear stress τ^{α} on each slip/twinning system identified in the current configuration is written as follow:

$$\tau^{\alpha} = \mathbf{S} : \left(\mathbf{m}^{\alpha} \otimes \mathbf{n}^{\alpha}\right) \tag{8}$$

The Piola-Kirchhoff stress is defined as $\mathbf{S} = \mathbf{K}^{e} : \mathbf{E}^{e}$ where is $\mathbf{K}^{e}$ the forth order anisotropic tensor of the elastic moduli, $\mathbf{E}^{e} = 1/2\left(1 - \mathbf{F}^{eT}\mathbf{F}^{e}\right)$ is the elastic Green-Lagrange strain tensor. In the time dependent model the shear rate is defined in a power law and the model used is called the Pierce-Asaro-Needleman model defined as follow:

$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \operatorname{sgn}\left(\tau^{\alpha}\right)\left|\frac{\tau^{\alpha}}{s^{\alpha}}\right|^{1/m} \tag{9}$$

Where $\dot{\gamma}_0$ is the initial shear rate, in this study, the value of this parameter is assumed to be the same on all shear and twinning systems, is m the material rate sensitivity parameter. s^{α} is the slip/twinning systems resistance that is taken to evolve as follows:

$$\dot{s}^{\alpha} = \sum_{\beta} h^{\alpha\beta}\left|\dot{\gamma}^{\alpha}\right| \tag{10}$$

With $h^{\alpha\beta}$ describes the instantaneous strain hardening on the slip/twinning α system due to shearing on the system β . The Asaro and Needleman (1985) self-hardening moduli relation was used in this work.

Due to the high order non-linearity of the single crystal plasticity equations sever numerical instability occurs during integration. The explicit Euler integration need a very small time step about 10^{-8} s. several explicit and implicit integration methods have been proposed in the literature (Peirce et al., 1983; Cuitino and Ortiz, 1992; Ling, et al., 2005; Li, 2007; Dumoulin et al., 2009). In this work and as a first attempt to integrate the crystal plasticity non-linear equations the explicit Eurel integration method has been used.

4. Numerical model validation

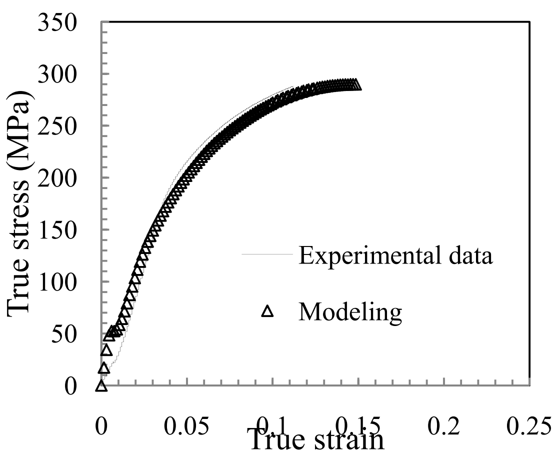


Figure 4. Comparison between numerical and experimental results of the stress-strain behavior of the magnesium AZ31 at 0.001 s^{-1} strain rate.

A polycrystal model based on the Taylor assumption was chosen to model the overall behavior of the material. A large number of random crystal orientations were selected in order to provide an average response of the material.

The modeling results are now compared to the experimental data of tensile test for a strain rate equal to 0.001 s^{-1}. The analysis is performed using the following set of parameters: $\dot{\gamma}_0 = 10^{-3} s^{-1}$, $m = 0.1$, $s_0^{basal} = 0.55MPa$, $s_0^{prismatic} = s_0^{pyramidal} = 10MPa$, $s_0^{twinning} = 18MPa$, $q = 3.4$, $h_0 = 1007.2MPa$, $s_0^{threshold} = 522MPa$. Figure 4 highlights the ability of the model to reproduce the experimental results in a satisfactory manner. While not investigated in this study, the ability of the crystal plasticity model to predict the strain rate effect was investigated and proved in several studies (i.e. Roters et al. 2010).

5. Conclusion

In this paper, the behavior of magnesium alloy AZ31B at different strain rate and temperature was conducted. The behavior of the studied material is viscoplastic, time and temperature dependent. A physically based viscoplastic model based on the crystal plasticity theory was proposed. The model takes into account the effects of slip and twin systems. An explicit integration method was used to integrate the crystal plasticity equations. The overall behavior of the material was modelled using polycrystal model based on the Taylor assumption. A comparison between the numerical simulation and the experimental data for one strain rate was provided. The capacity of the model to reproduce in an accurate manner the stress-strain behavior of the magnesium alloys was highlighted. In the continuity of this work the modelling of the time and the temperature effect will be achieved by incorporating the different physical phenomena that occurs while evolving the temperature and the strain rate.

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