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Tensile characterization and constitutive modeling of AZ31B magnesium alloy sheet over wide range of strain rates and temperatures

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ABSTRACT

Magnesium alloys are an ideal candidate due to their low density in comparison to aluminum and steel alloys when designing a vehicle with lower weight and therefore, reduced fuel consumption. It is important to characterize the strain rate sensitivity of any material that will be used in a structure which can undergo high rate deformation (as in an automobile crash) as well as during high velocity forming processes such as electromagnetic or electrohydraulic forming. Tensile tests for AZ31B magnesium alloy sheet at different strain rates were carried out using different testing techniques: (i) quasi-static strain rates tests were conducted in a range between 10^{-3} and $10^{-1}\,s^{-1}$ using a conventional electromechanical tensile testing apparatus; (ii) intermediate strain rates tests at 4.0×10^1 to $10^2\,s^{-1}$ using an instrumented falling weight apparatus; and (iii) high strain rates at 0.5×10^3 to $1.5 \times 10^3\,s^{-1}$ using a tensile split Hopkinson bar. Furthermore, quasi-static and high strain rate tests were also performed for different temperatures, from room temperature up to 250 °C. Strain rate and temperature effects are also discussed for rolling and transverse direction, to identify the variation of sheet properties with loading direction. Finally, the constitutive fitting of the stress–strain curves to the widely employed Johnson–Cook material model equation is evaluated and also a new model is proposed based on a modified J–C model to account for the variation of strain hardening with strain rate.

1. Introduction

Environmental issues and especially fuel economy are forcing automotive and aeronautics industry to develop new light materials to decrease vehicle weight. In this sense, Smith and McVay (1997) showed innovative forming technologies to manufacture light materials. Recently the interest in magnesium alloys from the transportation industries is increasing due to their low density and high specific strength. As an example of the increasing interest of the automotive industry a report written by the USAMP (2007) estimates for the year 2020 an increase in the use of Mg alloys from the actual 10–12 lb (0.3% of the weight of a vehicle) to 350 lb (12.2%). According to Doege and Dröder (2001), 25% of the current weight of an automobile corresponds to body parts and therefore, the potential use of extruded and wrought magnesium alloys could have significantly reduce vehicle weight.

However, as it has been reported by many researchers, the ductility of magnesium sheet at room temperature is very limited and therefore, the formability of magnesium alloys by conventional forming methods at room temperature is very limited. As Agnew et al. (2006) stated, if the practical formability of magnesium alloys could be improved, there would likely be a considerable increase in the use of this under-utilized material. Electromagnetic, electrohydraulic and explosive forming are three innovative technologies where sheet materials are formed at high strain rates which allows higher final deformation values. It has been shown the increase in formability by electromagnetic forming for several materials, such as copper by Balanethiram and Daehn (1994), steel by Seth et al. (2005), aluminum alloys by Imbert et al. (2004) or magnesium alloys by Ulacia et al. (2009a).

Another concern in the introduction of magnesium alloys in automotive body structures is their performance during crash events. Upon impact, the local strain rates are high within the failure sections of crash structures, underlying the importance in accounting for the material's strain rate sensitivity when numerically simulating these events.

Although in the last decades significant work has been performed in quasi-static characterization of magnesium alloys at different temperatures, little research has been carried out at high rates of strain. Ishikawa et al. (2005) concluded that the main deformation mechanism for high strain rate compression tests on Mg alloys is dislocation glide and twinning, even at elevated temperatures. Mukai et al. (2000) also studied the influence of the grain size and observed that the tensile strength and ductility of

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Mg alloys increased at high strain rates for an initial fine grain material. Yokoyama (2003) also studied the dynamic response of magnesium alloys without any remarkable increase in elongation for extruded AZ31B alloy, although the absorbed energy at high strain rates improved. Other work performed by El-Magd and Abouridouane (2003) showed an increase in the elongation for extruded AZ80 magnesium alloy under dynamic compressive loading. Previous studies have concentrated on extruded magnesium alloys which have a different initial crystallographic texture comparing to rolled sheets, they respectively develop $\langle 1\,0\,\bar{1}\,0\rangle$ and $\langle 0\,0\,0\,1\rangle$ fiber textures. Texture has a significant influence in the deformation mechanisms of materials with hexagonal close packed (hcp) crystal structures, such as magnesium and most of its alloys. A significant number of parts in an automobile are made of rolled sheets and fabricated through techniques where the main mode of deformation is tension, such as stamping or high speed electromagnetic forming. As such, the purpose of the current study is to determine the constitutive properties of rolled AZ31B sheet in tension. The yield asymmetry between tension and compression is not considered in the present study. Reader is referred to Ulacia et al. (2010) for more information regarding tension/compression asymmetry at high strain rates.

In the present work tensile deformation behavior of 1 mm thick rolled AZ31B sheet material is characterized over a wide range of strain rates, from $10^{-3}\,s^{-1}$ to $1.5 \times 10^{3}\,s^{-1}$ and at different temperatures, up to 300 °C. In order to account for the anisotropy of the mechanical properties of magnesium alloys, tensile tests were performed in both the rolling and transverse directions (respectively RD and TD). Furthermore, microstructure analysis was performed to identify differences in deformation mechanisms due to strain rate.

Temperature is a key factor during the deformation process of magnesium alloys due to its hexagonal close packed crystal structure. At quasi-static strain rate testing of Mg alloys a softening behavior is observed due to the dynamic recrystallization that occurs as it was previously observed by Ion et al. (1982). Additionally, during high rate deformation, such as that seen in electromagnetic forming and autocrash events, the material undergoes adiabatic heating which can reduce the strength of the material. It is therefore important to characterize the effect of temperature to determine its significance on material properties.

A predictive constitutive model is required for numerical simulations since material can be deforming with a different strain rate and temperature during the same event. In the current study three constitutive models are explored. Firstly, the standard Johnson–Cook model is fit to the measured data and predictions from the model are compared to the experimentally measured data. Then, a modified version of J–C material model is employed to account for the exponential dependence of stress on strain rate. Finally, a new advanced material model is proposed based on the modified Johnson–Cook model to account for the variation of strain hardening with strain rate.

2. Experimental procedures

2.1. Material

The sheet material used in this study was a commercial AZ31B-O magnesium alloy of 1 mm thickness with an average initial grain size of 10 μm. Table 1 summarizes the commercial chemical composition of the employed material. After the rolling process, the wrought material was annealed, and from the microstructure of the as-received material (Fig. 1) it can be seen that there are no twins observable in the initial microstructure.

Table 1
Chemical composition of the commercial AZ31B alloy.

Element	Zn	Al	Si	Cu	Mn	Fe	Ni	Ca	Sn	Others
wt%	0.96	2.7	0.01	≤0.01	0.21	0.002	≤0.001	≤0.01	0.00	≤0.30

(Source: Magnesium Electron).

2.2. Geometries of the employed specimens

Different specimen geometries are employed in the present study depending on the testing method. Specimens for quasi-static tests have been based on the geometry from the ASTM E8M-00 standard. In the case of the intermediate and high strain rate tests there is no standardized specimen geometry. A specimen geometry for dynamic tests was chosen to: (i) follow the mechanical response of a standard ASTM specimen at quasi-static rates, which requires long gage length and (ii) maintain uniaxial stress equilibrium during the testing, which is achieved by reducing the gage length. Therefore, an agreement between these two opposing aspects must be determined. The effect of the different specimen geometries is a point of much discussion in the high rate community and several authors have studied this effect. For instance, Huh et al. (2002) numerically studied by FE calculations the effect of length and width of gage section on the specimen response and they concluded that shorter gage lengths provide more uniform strain distribution. Curtze et al. (2006) experimentally studied the influence of specimen geometries on tensile Hopkinson bar results and compared them to numerical results. Verleysen et al. (2008) also studied the influence of specimen geometry on sheet materials using an optical technique to obtain the time evolution of the strain along the full length of the specimen. In the present study, a specimen geometry optimized in a previous work by Smerd et al. (2005) is used, with a 1.75 mm width and 12.5 mm gage length. This geometry is in agreement with the observations shown by the previously cited authors: Verleysen et al. (2008) concluded the geometry with the largest length/width ratio in their study was an acceptable approximation to the classical strain value calculations. Huh et al. (2002) observed an acceptable deviation of 2.14% between measured and calculated strain for a gage length of 12 mm. Regarding the fillet radius, Curtze et al. (2006) observed that the contribution of the deformation of the shoulders to the total deformation is decreased with increasing fillet radius. Nevertheless, these conclusions are material dependent and a detailed study of the effect of the different specimen geometries is beyond the scope of the present study.

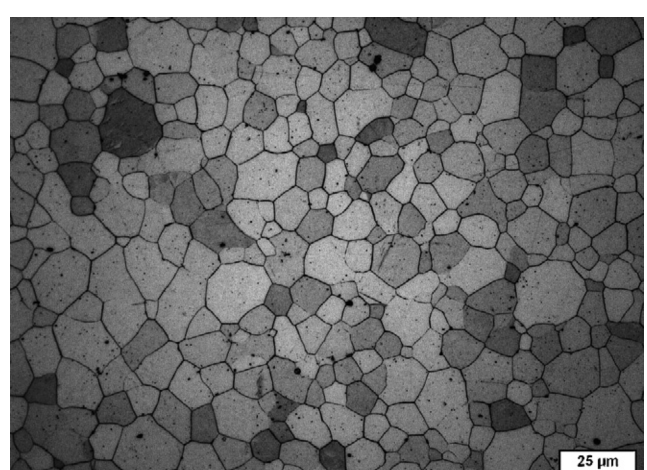

Fig. 1. Microstructure of the as-received AZ31B specimen.