Effect of strain rate on tensile and work hardening properties for Al-Zn magnesium alloys

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Abstract: The effect of strain rate on the mechanical behaviour of Al-Zn magnesium alloys was examined at room temperature under tensile loading with wide range of strain rate. Quasi static tensile test was performed in four different strain rates to obtain their effect on tensile properties, work hardening rate, strain hardening exponent and strength coefficient using a round shape tensile sample. Two types of Al-Zn magnesium alloys were used in this research study, i.e., AZ31 and AZ61 magnesium alloys. The yield stress and tensile strength of AZ31 were found to be strain rate dependent but not for AZ61. The elongations of AZ31 were approximately about 15% for all strain rate levels but for AZ61 the elongations were slightly decreased with increasing strain rate. For all strain rate levels, the work hardening rate of AZ61 was found to be higher compared to that of AZ31. The strain hardening exponent was decreased with increasing strain rate. In contrast, the strength coefficient was increased with increasing strain rate for both alloys. The change in fracture mode as observed from the fracture surface implies that the fracture mechanisms in AZ31 change as the strain rate increases.

Keywords: AZ61 magnesium alloy; quasi static tensile test; strain rate; tensile properties; work hardening; strain hardening exponent; strength coefficient; materials engineering; Al-Zn magnesium alloys; AZ31 magnesium alloy.

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1 Introduction

High specific strength and lightweight properties promote wider applications of magnesium alloys in automotive and aerospace industries. The lightweight property of magnesium alloys entices manufacturer to replace components of denser materials such as steel, cast irons, copper base alloys and even aluminium alloys. In addition, magnesium alloys also possess an excellent mechanical, physical and chemical properties (Ahmad and Wei, 2010; Kainer, 2003). However, in real applications, the chances of the magnesium alloys' made components to collide with other objects (i.e., accident or crash) in different impact velocities could happen in automotive and aerospace applications. The impact could cause damage and leads to catastrophic failure of the materials. Thus, it is important in particular to identify the effect of loading rate on mechanical properties of magnesium alloys to ensure the reliability and durability.

Several studies on the effect of tensile loading rate on mechanical behaviour of magnesium alloys have been reported. For example, Ahmad and Wei have investigated the tensile properties of die-cast magnesium alloy AZ91D at increased strain rates (Ahmad and Wei, 2010). Ulacia et al. (2010) have investigated the mechanical behaviour of an AZ31 magnesium sheet at high and low strain rates at elevated temperatures. They found that the strength of alloys increased with increasing strain rate (Ahmad and Wei, 2010; Ulacia et al., 2010).

The Al-Mg alloys as a good compound to be a high strength and formability material, which due to the solid strengthening and strain hardening (Gurugubelli et al., 2012). Similarly, aluminium content in magnesium alloys is also known to influence the strength of the material with the presence of precipitates in the microstructure. It allows a better hardening of magnesium alloys to indicate the high strength of material with occurrence of many dislocation pile ups against the grain boundaries for delayed fracture (Kainer, 2003; Marya et al., 2006). Strain hardening was also explained as a strengthening process of alloys by the plastic deformation. In this study, the effect of strain rate on tensile properties, work hardening behaviour, strain hardening exponent and strength coefficient of AZ31 and AZ61 magnesium alloys were investigated and compared.

2 Experimental procedure

Two types of extruded magnesium alloys, AZ31 and AZ61, were selected for the quasi static tensile tests with various strain rates. The aluminium contents in AZ31 and AZ61 are approximately 3% and 6%, respectively. In both alloys, the content of zinc is approximately 1%. The tensile test specimens with dumb-bell shape were cut from the extruded round bar of 16 mm in diameter. The gage length and diameter of the gage part of the specimen were 10 and 3 mm, respectively. All specimens were polished by using 400 to 1,500 grits emery papers to obtain the smooth surface before the tensile tests. The quasi static tensile test was conducted with strain rates of 1×10^{-4}, 1×10^{-3}, 1×10^{-2} and 1×10^{-1} s^{-1}. The strain was measured during the test until the specimen break by using a high resolution extensometer. The universal testing machine with a capacity of 100 kN was used for the tensile test. All tests were performed at room temperature and in lab air. After the tensile tests, the fracture surface was observed by using a scanning electron microscope (SEM) to identify the mode of fracture.

The data (force, area of cross section, elongation and engineering strain) obtained from the quasi static tensile test at room temperature were used to calculate the true stress, σ and true strain, ε. The true stress and true strain were calculated using the following equations (1) and (2).

$$\sigma = \frac{F}{A_T} \tag{1}$$

where F is the force and A_T the area of cross section at the force, F and

$$\varepsilon = \ln\left(1 + \frac{\mathrm{d}L}{L_O}\right) \tag{2}$$

where dL is the elongation and L_O the original gage length.

Based on the stress and strain obtained, the work hardening rate for both materials were identified by using equation (3) (Marya et al., 2006):

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{3}$$

dσ the increment of true stress

dε the increment of true strain.

By referring to the ASTM E 646-00, the tensile strain hardening exponent and strength coefficient were determined by the following power law hardening equation (4), which is called as Hollomon equation.

$$\sigma = K\varepsilon_p^n \tag{4}$$

where σ is the true stress, K the strength coefficient (stress intercept at $\varepsilon_p = 1$), ε_p the true plastic strain and n the strain hardening exponent (slope of the line) (ASTM E 646-00; Dieter, 1928; Kleemola and Nieminen, 1973).

The plotted graph was taken by the tensile data between the yield strength and ultimate strength of stress-strain curve. By obtained the logarithms of the true stress-true plastic strain curve, it can be calculated the strain hardening exponent and strength coefficient by equation (5) (ASTM E 646-00; Dieter, 1928).

$$\log\sigma = \log K + n\log\varepsilon_p \tag{5}$$

3 Results and discussion

3.1 Tensile test

The tensile properties of Al-Zn magnesium alloys are listed in Table 1 and the stress-strain curves are shown in Figure 1. Tensile strength of the AZ61 magnesium alloy was higher compared to the AZ31. The responses to the change in strain rate for both the materials were different. Referring to the stress-strain curves in Figure 1, the AZ31 shows an increase in yield stress and ultimate tensile strength with increasing strain rate. This trend was similar to the result obtained by Ahmad and Wei (2010) for die-cast magnesium alloy AZ91D. A study for the material of AZ31 + 0.5 Ca was done by Trojanova et al. and that for AZ61 magnesium alloys by Yoshida et al. They found that there occurred a rapid rise of flow stress at higher strain rates for magnesium alloys (Trojanová et al., 2012; Yoshida et al., 2005).

Figure 1 Strain rate effect on stress-strain curves (see online version for colours)

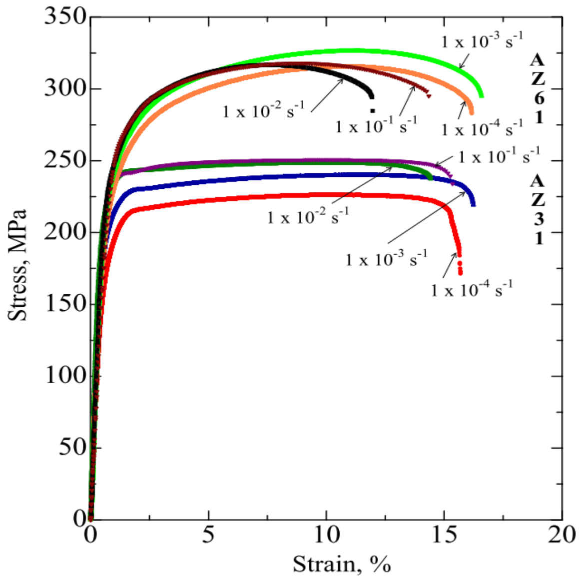


Table 1 Tensile properties of AZ31 and AZ61

	Strain rate (s^{-1})	σ_y *(MPa)*	σ_{UTS} *(MPa)*	*Elongation (%)*
AZ31 magnesium alloy	1×10^{-4}	173	226	15.7
	1×10^{-3}	191	240	16.2
	1×10^{-2}	217	249	14.4
	1×10^{-1}	204	251	15.4
AZ61 magnesium alloy	1×10^{-4}	205	316	16.2
	1×10^{-3}	219	327	16.6
	1×10^{-2}	228	317	12.0
	1×10^{-1}	221	318	14.4

For the AZ31, the elongations were approximately 15% regardless of strain rate. On the contrary, the yield stress and tensile strength increased with increasing strain rate. The increment in tensile strength compared to the yield stress was small and not significant. This indicated that the AZ31 magnesium alloy had low work hardening properties. This phenomenon is also reported by Srivatsan et al. (2008) who studied the tensile behaviour of the rapidly solidified magnesium alloy. Further, the yield and tensile strengths increased with increasing strain rate up to 1×10^{-2} s^{-1}. This might be due to the strain rate dependency of critical resolved shear stress (CRSS) of non-basal slip systems for magnesium alloy (Ulacia et al., 2010; Barnett, 2003).

In contrast, the strength of AZ61 magnesium alloy was not significantly affected by the strain rate, but the elongation was slightly decreased with increasing strain rate. The AZ61 exhibited higher work hardening rate compared to that of AZ31, which would be speculated by significant difference of tensile strength and yield stress of AZ61 as shown in Figure 1.

3.2 *Work hardening*

In this study, work hardening rate was used to show the ability of work hardening for the Al-Zn magnesium alloys. Work hardening occurs due to the dislocation movements and dislocation generation against the crystal structure of alloys. Figure 2 shows the variation of true stress and work hardening rate against true strain for both the Al-Zn magnesium alloys.

Figure 2 Work hardening rate of (a) AZ31 and (b) AZ61 (see online version for colours)

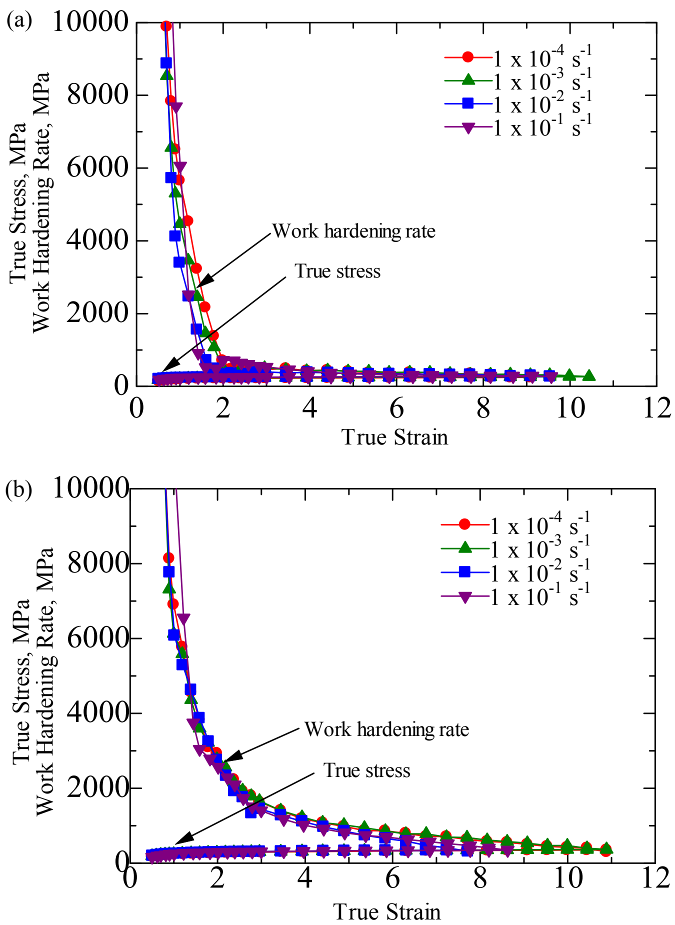
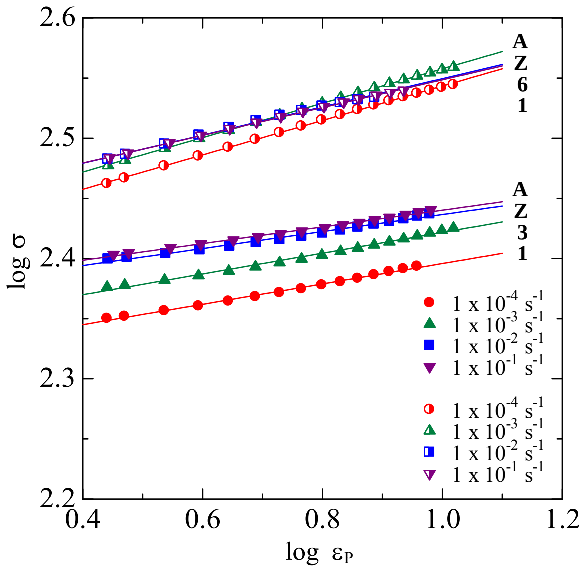


Figure 2(a) shows the work hardening rate versus the true strain curve for the AZ31 magnesium alloy. The figure shows that, for all the strain rate conditions, the work hardening significantly occurred in the early stage of deformation. The hardening process was then diminished just after the yielding, which indicated the poor strain hardening behaviour of the material. In contrast, work hardening rates for all the AZ61 specimens in different strain rate conditions were higher compared to those of the AZ31 as shown in Figure 2(b). The work hardening process in the AZ61 continues up to the level of tensile strength. The higher work hardening rate for the AZ61 was believed to be attributed to more dislocation pile-up due to blocking at the $Mg_{17}Al_{12}$ precipitates and grain boundaries compared to the AZ31 in which precipitates were very limited due to the composition of the alloy (Kainer, 2003; Kapoor and Nemat-Nasser, 1998; Kim and Chang, 2011; Tanski, 2012). However, among the AZ61 samples, the work hardening rate at 1×10^{-1} s^{-1} was slightly higher compared to those of other samples at lower strain rate.

3.3 Strain hardening exponent and strength coefficient

In Figure 2, the different of work hardening rate was not seen clearly at each strain rate levels for both the alloys. Thus, the log σ – log ε curve as shown in Figure 3 was used to evaluate the strain hardening exponent and the strength coefficient for both the alloys. These values indicate to the mechanical behaviour which corresponds to the stress-strain behaviour after yielding. The figure could also be used to study the deformation mechanisms (Kleemola and Nieminen, 1973; Zhang et al., 2006).

Figure 3 The log true σ – log true ε_p curves for AZ31 and AZ61 (see online version for colours)



The strain hardening exponent and strength coefficient evaluated for wide range of strain rate are listed in Table 2. The strain hardening exponent significantly decreased with increasing strain rate, while the strength coefficient clearly increased with increasing strain rate for both the alloys (Kulkarni and Prabhakar, 2003). The AZ61 seemed a high strength alloy with the high strain hardening exponent and strength coefficient compared to those of the AZ31. The phenomena was also explained in the discussion of work hardening rate according to the dislocation collision on the alloy itself (Kainer, 2003; Kapoor and Nemat-Nasser, 1998; Kim and Chang, 2011; Tanski, 2012).

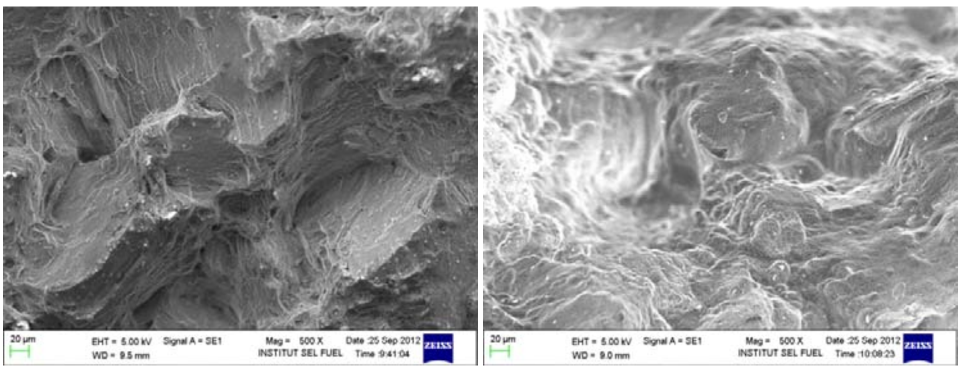
Table 2 Strain hardening exponent and strength coefficient of AZ31 and AZ61

	Strain rate (s^{-1})	*Strain hardening exponent, n*	*Strength coefficient, K (MPa)*	*Fit equation,* $\sigma = K\varepsilon_p^n$
AZ31 magnesium alloy	1×10^{-4}	0.09	204.7	$\sigma = 204.7\varepsilon_p^{0.09}$
	1×10^{-3}	0.09	216.4	$\sigma = 216.4\varepsilon_p^{0.09}$
	1×10^{-2}	0.07	232.2	$\sigma = 232.2\varepsilon_p^{0.07}$
	1×10^{-1}	0.07	234.8	$\sigma = 234.8\varepsilon_p^{0.07}$
AZ61 magnesium alloy	1×10^{-4}	0.14	251.3	$\sigma = 251.3\varepsilon_p^{0.14}$
	1×10^{-3}	0.14	259.8	$\sigma = 259.8\varepsilon_p^{0.14}$
	1×10^{-2}	0.12	270.6	$\sigma = 270.6\varepsilon_p^{0.12}$
	1×10^{-1}	0.12	271.1	$\sigma = 271.1\varepsilon_p^{0.12}$

3.4 Fracture surface of Al-Zn magnesium alloys

Examples of SEM fractographs of the tested specimens are shown in Figures 3(a) and 3(b). The fractographs revealed that the specimens tested at low strain rates exhibited intergranular fracture with clear surface steps as shown in Figure 3(a). These fracture steps and planar surfaces are believed to be the h.c.p. basal plane of crystal structure (Zhang et al., 2011). The surface morphology was changed in the specimens tested at high strain rate of 1×10^{-1} s^{-1} as observed in Figure 3(b). Here, the material fractured in relatively ductile mode which implied that the fracture mechanism in the AZ31 changed with strain rate.

Figure 3 Fracture surface of the AZ31 magnesium alloy at a strain rate of (a) 1×10^{-4} s^{-1} and (b) 1×10^{-1} s^{-1} (see online version for colours)



(a) (b)

4 Conclusions

Quasi static tensile test of AZ31 and AZ61 magnesium alloys were carried out. Based on the results obtained, the following conclusions are summarised:

a tensile strength and work hardening rate of the AZ61 were higher compared to those of the AZ31

b tensile strength of the AZ31 was dependent on strain rate but not for AZ61

c the elongations of the AZ31 were approximately 15% for all the strain rates, while those of the AZ61 were slightly decreased with increasing strain rate

d strain hardening exponent for both the alloys decreased with increasing the strain rate, while strength coefficient increased with increasing strain rate

e strain hardening exponent and strength coefficient for the AZ61 were higher than those of the AZ31

f the change in fracture surface morphology was observed, which suggested the change in fracture mechanism depending on strain rate.

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