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

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Abstract. The effect of strain rate on the mechanical behavior of Al-Zn magnesium alloys was examined in room temperature from low to high strain rates by using a Universal Testing Machine. Quasi static tensile test was performed in four different strain rates to obtained their effect on tensile properties and work hardening rate 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 elongation of AZ31 were approximately about 15% for all strain rate levels but for AZ61 the elongations were slightly decreased with increasing strain rates. For all strain rate levels, the work hardening rate of AZ61 were found higher compared to that of AZ31. The change in fracture mode as observed from the fracture surface implies that the fracture mechanisms in AZ31 change as the strain rate increases.

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 as well as good corrosion resistance [1, 2]. 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 increasing loading rate on mechanical properties of magnesium alloys to ensure the reliability and durability.

Several studies on the effect of tensile loading rates of mechanical behavior of magnesium alloys are reported. Ahmad and Wei have investigated the tensile properties of die-cast magnesium alloy AZ91D at increased strain rates [1]. Then, the mechanical behavior of an AZ31 magnesium sheet has
been investigated by Ulacia et al. at high and low strain rates with elevated temperatures [3]. They found that the strength of the alloys increased with increasing strain rates [1, 3].

In general, aluminium content in magnesium alloys is known to influence the strength of the material with the presence of precipitates in the microstructure. It allows a better work hardening rate of magnesium alloys to indicate the high strength of material with occurrence of many dislocation pile ups against the grain boundaries for delayed fracture [2, 4]. In this study, the effect of strain rates on tensile properties and work hardening behavior of AZ31 and AZ61 magnesium alloys were investigated and compared.

2. Experimental procedure
Two types of extruded magnesium alloys were selected for the quasi static tensile test with increased strain rates. The materials were AZ31 and AZ61 magnesium alloys which have different chemical compositions. 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 samples were cut from extruded bar of 16 mm in diameter to a dumb-bell shape. The gage length and diameter of the sample were 10 and 3 mm, respectively. All samples were subjected to grind polish by using 400 to 1500 grits emery papers to obtain the smooth surface before tensile tests. The quasi static tensile test was conducted with strain rates of $1 \times 10^{-4}$, $1 \times 10^{-3}$, $1 \times 10^{-2}$ and $1 \times 10^{-1}$ sec$^{-1}$. The strain was measured from the beginning of the test until the specimen break by using high resolution extensometer. The Universal Testing Machine with a capacity of 100 kN was used. All tests were performed in room temperature and lab environment. After the tensile tests, the fracture surface of samples were observed and examined by using a scanning electron microscope (SEM) to identify the mode of fracture.

The data (force, area of cross section, elongation and engineering strain) from the quasi static tensile test at room temperature were used to calculate the true stress and true strain. The true stress and true strain were calculated using formula as in equation (1) and (2).

$$\sigma_T = \frac{F}{A_T} \quad (1)$$

Here, $F$ is force and $A_T$ is true area of cross section and

$$\varepsilon_T = \ln \left( 1 + \frac{dL}{L_0} \right) \times 100 \quad (2)$$

where $dL$ is elongation and $L_0$ is original sample length

Based on the stress and strain obtained, the work hardening rates for both materials were identified by using equation (3) as follows [5]:

$$\frac{d\sigma}{d\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \quad (3)$$

d$\sigma$ : change of true stress
d$\varepsilon$ : change of true strain of material

3. Results and discussion

3.1. Tensile test
The tensile properties and behavior of Al-Zn magnesium alloys were listed in table 1 and the stress-strain curves are shown in figure 1, respectively. In overall, AZ61 magnesium alloy exhibited higher tensile strength compared to AZ31. The responses to the changes in strain rate by both materials were
found different. Referring to the stress-strain curves in figure 1, the AZ31 shows increment in yield stress and ultimate tensile strength with increasing strain rates. This trend was similar to the results obtained by Ahmad and Wei for die-cast magnesium alloy AZ91D [1]. Study for material of AZ31 + 0.5 Ca was done by Trojanova et al. and for AZ61 magnesium alloys by Yoshida et al. They found that there occurred a rapid rise of flow stress at high strain rates for magnesium alloys [6, 7].

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

*Figure 1. Strain rate effect on tensile behavior.*

For AZ31, the elongations of were approximately 15% which showed that there is no influence of strain rates on elongation. However, even though the yield and tensile strengths for all samples were different with increasing strain rate, the ultimate tensile strengths of individual AZ31 sample under certain loading velocity condition was found marginally higher than yield strength where only limited stress increment is allowed after plastic deformation. This indicated that AZ31 magnesium alloy exhibited low work hardening properties. This phenomenon is also mentioned by Srivatsan et.al who studied the tensile behavior of rapidly solidified of magnesium alloy [8]. Further, the yield and
maximum tensile stresses increased with increasing strain rate up to $1 \times 10^{-2}$ sec$^{-1}$. It is assumed that this was due to the strain rate dependency of critical resolved shear stress (CRSS) of non-basal slip systems for magnesium alloy [3, 9].

In contrast, the strength of AZ61 magnesium alloy was not significantly affected by the increasing strain rates but the elongations of samples were slightly decreased at an increased strain rate. AZ61 exhibited higher work hardening rate as compared to that of AZ31 which indicated by significant difference of ultimate tensile strength to 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 Al-Zn magnesium alloys for work hardens after the occurrence of plastic deformation. Work hardening occurs due to the dislocation movements and dislocation generation against the crystal structure of alloys. Figure 2 shows the trends of true stress and work hardening rates against true strain for both Al-Zn magnesium alloys.

![Graph of work hardening rate against increased strain rate of (a) AZ31 (b) AZ61.](image)

**Figure 2.** Graph of work hardening rate against increased strain rate of (a) AZ31 (b) AZ61.
In figure 2(a) shows the work hardening rate versus the true strain of AZ31 magnesium alloy. The figure shows that, for all the strain rate conditions, the work hardening occurred only at the early stage of deformation. The hardening process was then diminished just after the yielding which indicates the poor strain hardening behavior of the material. In contrast, work hardening rates for all AZ61 samples in different strain rate conditions were higher compared to that of AZ31 as shows in figure 2(b). The work hardening process in AZ61 continues after yielding point until to the level of ultimate tensile strength. The higher work hardening rate for AZ61 was believed to be attributed by more dislocation pile-up and blocked at the $\text{Mg}_{17}\text{Al}_{12}$ precipitates and grain boundaries as compared to that for AZ31 in which precipitates were very limited due to high purity of the alloy [2, 10, 11 and 12]. However, among the AZ61 samples, the work hardening rate at $1 \times 10^1$ sec$^{-1}$ was found slightly higher compared to that of other samples with lower strain rate conditions.

3.3. Fracture Surface of Al-Zn Magnesium alloys

SEM fractographs of samples tested at low and high strain rates are shown in figure 3(a) and 3(b). The micrographs revealed that the sample subjected to low strain rate exhibited brittle intergranular fracture with clear surface steps observed on fracture plane 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 [13]. The surface morphology is changed in the samples subjected to high strain rate of $1 \times 10^1$ sec$^{-1}$ as observed in figure 3(b). Here, the material fractured in relatively ductile mode which implies that the fracture mechanisms in AZ31 change as the strain rate increases.

4. Conclusion

Quasi static tensile test of AZ31 and AZ61 magnesium alloys were investigated. Based on the results obtained, the findings are concluded as listed below:

a. Tensile strength and work hardening rate of AZ61 were higher compared to that of AZ31.

b. Tensile strength of AZ31 was strain rate dependent but not for AZ61.

c. The elongations of AZ31 were approximately 15% for all strain rates whereas, the elongations of AZ61 were slightly decreased as the increased of strain rate.

d. The differences in fracture surface of AZ31 implies the change in fracture mechanism from low to high strain rates.

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