EFFECT OF STRAIN RATES ON TENSILE PROPERTIES AND FRACTURE TOUGHNESS DETERMINATION OF EXTRUDED Mg-Al-Zn ALLOYS

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KESAN KADAR TERIKAN TERHADAP SIFAT-SIFAT TEGANGAN DAN PENENTUAN KELIATAN PATAH BAGI ALOI Mg-Al-Zn TERSEMPRIT

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ABSTRACT

Extruded Mg-Al-Zn alloy is a lightweight and high strength magnesium alloy that is becoming a preferred material to be used as a structural component in automobiles. During a crash event, an automobile structure is subjected to dynamic loading. The magnesium alloy structures must be able to maintain its integrity and provide adequate protection in survivable crashes. Besides static tensile properties, tensile properties at high strain rates of extruded magnesium alloys and their fracture behaviour are some of the important parameters to be considered in design in ensuring the durability and reliability of automobile structures. In this study, the effect of strain rates on tensile properties and work hardening behaviour were evaluated for extruded Mg-Al-Zn alloys. Further, the fracture behaviour at different loading rates and the effect of temperature on fracture toughness of Mg-Al-Zn alloys were investigated. The extruded Mg-Al-Zn alloys used in this study were AZ61 and AZ31 magnesium alloys. Tensile tests under low and high strain rates were carried out using a universal testing machine and high strain rate tensile tester, respectively. The high strain rate tensile tester was designed and fabricated in-house to fulfil the requirement of tensile test under high strain rate ranging from 100 to 600 s\(^{-1}\). Work hardening behaviour for low strain rate tensile specimen was determined by referring to the ASTM E646. To obtain the fracture behaviour of both alloys at different loading rates, three-point bending fracture test was conducted on pre-cracked specimens. Standard test methods i.e. ASTM E1820 and JSME S001 were referred to determine the elastic-plastic fracture toughness \(J_{IC}\) value of AZ31 and AZ61 alloys. The \(J_{IC}\) value obtained were then used as a standard reference value to identify a proper groove depth of a single side-grooved specimen. The side-groove depths evaluated were 25\%, 35\% and 50\%. The proper depth of the side-grooves is confirmed after the \(J\) value obtained from the side-grooved specimen test method is identical to the \(J_{IC}\) value that of the standard test method. The side-grooved specimen with proper groove depth was then used to determine the \(J_{IC}\) value of AZ61 alloy at high temperature. From the results, the tensile strengths were gradually increased with increasing strain rates. However, at above 200 s\(^{-1}\), the tensile strength increased significantly to more than 600 to 800 MPa. In addition, the work hardening rate for AZ61 was found higher compared to that of AZ31. Both alloys exhibited significant elastic-plastic fracture behaviour at different loading rates. It was found that 50\% side-grooves depth is appropriate enough to produce valid \(J_{IC}\) value using a single specimen. This finding is very useful especially in determining \(J_{IC}\) value in a condition where standard multiple specimen test method is difficult to be conducted such as in high temperature environment. The \(J_{IC}\) values of AZ31 and AZ61 at room temperature were 19 and 25 kJ/m\(^2\), respectively. Meanwhile, the \(J_{IC}\) value of AZ61 at 150 °C was found twice higher than the \(J_{IC}\) value at room temperature.
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NOMENCLATURE

Symbols

\( a \)  
  crack length

\( \Delta a \)  
  crack growth

\( \frac{da}{dN} \)  
  fatigue crack growth rate

\( A \)  
  area

\( A_o \)  
  original cross section area of test specimen

\( A_f \)  
  final cross section area of test specimen

\( A_r \)  
  area of cross section at force

\( A_{max} \)  
  area under the curve up to maximum load \((P_{max})\) point

\( A_{specimen} \)  
  actual area under the curve of testing specimen

\( A_{total} \)  
  total area under the curve of test

\( A_{jig} \)  
  area under the curve of testing jigs

\( b \)  
  remaining crack ligament

\( B \)  
  specimen thickness

\( B_N \)  
  net specimen thickness

\( B_e \)  
  effective thickness

\( B_{e1} \)  
  effective thickness 1

\( B_{e2} \)  
  effective thickness 2

\( B_{e3} \)  
  effective thickness 3

\( \beta \)  
  second phase

\( d \)  
  displacement

\( d_l \)  
  length of long diagonal

\( d_s \)  
  side-grooves depth
\( ds \) increment of the contour path
\( E \) Young’s modulus
\( F \) force
\( f(\alpha) \) geometry factor
\( g \) acceleration of gravity (9.81 m/s\(^2\))
\( h \) drop weight height
\( J \) \( J \)-integral
\( J_C \) critical \( J \)-integral
\( J_{IC} \) fracture toughness \( J_{IC} \)
\( K \) stress intensity factor
\( K_s \) strength coefficient
\( K_Q \) critical stress intensity factor
\( K_I \) mode I stress intensity factor
\( K_{Id} \) dynamic fracture toughness
\( K_{IC} \) fracture toughness \( K_{IC} \)
\( \Delta K \) stress intensity factor range
\( K_m \) mean stress intensity factor
\( K_{min} \) minimum stress intensity factor
\( K_{max} \) maximum stress intensity factor
\( L_o \) original gage length
\( L_f \) final gage length
\( dL \) increment of elongation
\( m \) mass
\( Mg_{12}Al_{12} \) precipitation
$n$ strain hardening exponent

$P$ load

$P_Q$ critical load

$P_5$ load at intersection of 95% slope on load-displacement curve

$P_{\text{max}}$ maximum load

$P_y$ load point at 0.2% offset from the linear slope on load-displacement curve

$R$ stress ratio

$S$ span length

$\Delta s$ displacement of loading points

$T$ outward traction vector on $ds$

$u$ displacement vector at $ds$, $x$, $y$, $z$ of the rectangular coordinates

$\nu$ impact velocity or high strain rate

$w$ loading work per unit volume

$W$ specimen width

$W_p$ work done

$Y$ geometry factor

$\epsilon$ elongation

$\epsilon_T$ true strain

$\epsilon_e$ true elastic strain

$\epsilon_p$ true plastic strain

$\Delta \epsilon_T$ increment of true plastic strain

$\sigma_y$ yield stress

$\sigma_{\text{UTS}}$ tensile strength
\( \sigma_f \)  
flow stress

\( \sigma_c \)  
critical stress

\( \sigma_T \)  
true stress

\( d\sigma_T \)  
increment of true stress

\( \Gamma \)  
path of the integral around the crack tip

\[ T \left( \frac{\partial u}{\partial x} \right) \, ds \]  
work input rate from the stress field into the area enclosed by \( \Gamma \)
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCP</td>
<td>hexagonal close packed</td>
</tr>
<tr>
<td>CRSS</td>
<td>critical resolved shear stress</td>
</tr>
<tr>
<td>UTM</td>
<td>universal testing machine</td>
</tr>
<tr>
<td>LVDT</td>
<td>linear variable differential transformer</td>
</tr>
<tr>
<td>MSDS</td>
<td>material safety data sheet</td>
</tr>
<tr>
<td>CT</td>
<td>compact tension</td>
</tr>
<tr>
<td>SENB</td>
<td>single edge notched bending</td>
</tr>
<tr>
<td>EDM</td>
<td>electrical discharge machining</td>
</tr>
<tr>
<td>ASTM</td>
<td>American society for testing and materials</td>
</tr>
<tr>
<td>JSME</td>
<td>Japan society of mechanical engineers</td>
</tr>
<tr>
<td>LEFM</td>
<td>linear elastic fracture mechanics</td>
</tr>
<tr>
<td>EPFM</td>
<td>elastic-plastic fracture mechanics</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
</tr>
<tr>
<td>SHPB</td>
<td>split Hopkinson pressure bar</td>
</tr>
</tbody>
</table>
MAGNESIUM ALLOYS have been attractive to engineers due to their lightweight and high specific strength properties as compared to aluminium and medium-strength steel alloys (Smith 1998). The specific strength of alloys is measured based on the strength to the weight ratio, while the lightweight property refers to the density of alloys. In this regard, magnesium alloys have been used in electric and electronic appliances as well as automotive applications. In automotive applications, these parameters are beneficial to reduce fuel consumption, enhance the energy efficiency of engines and reduce emissions. In addition, magnesium alloys are also excellent in machinability, castability, recyclability and high damping capacity. Hence, magnesium alloys attract the automobile manufacturers to use these alloys as components and structures for replacing the conventional materials such as steel, cast iron and aluminium (Gaines 1995; Mordike & Ebert 2001; Kainer 2003; Watarai 2006). Magnesium has been used since the 1930s in the Volkswagen (VW) Beetle. Nowadays, automobile manufacturers such as Volkswagen, Audi, DaimlerChrysler (Mercedes-Benz), Toyota, Ford, BMW, Jaguar, Fiat, Hyundai, and Kia Motors Corporation generally use magnesium alloys as components and structures (Gupta & Sharon 2011). However, utilisation of magnesium alloys in automotive applications is still limited compared to that of conventional materials (Luo 2002).

The most popular magnesium alloys used as automobile components and structures are AZ (Mg-Al-Zn), AM (Mg-Al-Mn), ZK (Mg-Zn-Zr) and WE (Mg-Y-RE) series magnesium alloys. This is due to the best properties of magnesium alloys
for certain applications are governed by the combination of alloying element contents. In the present study, Mg-Al-Zn series magnesium alloys have been used. The main elemental contents of Mg-Al-Zn alloys are aluminium and zinc. These main elements are beneficial for enhancing the strength of alloys (Kainer 2003). In addition, Mg-Al-Zn alloys are characterised as low cost, a good strength and good ductility alloy. Due to its ductile property, Mg-Al-Zn alloys are easy to produce in the shape of extruded and simple forged products. Therefore, extruded and simple forged products of Mg-Al-Zn alloys are used as components and structures in automobile applications (Becker & Fischer 2004).

Mechanical properties are referred to when choosing a good potential material especially for application in automobile concerned with the safety parameter and quality assurance. Mechanical properties comprise hardness, tensile properties, flexural strength, fracture toughness etc. Excellent mechanical properties refer to the potential material related to the durability and reliability of materials. In the present study, the potential materials such as Mg-Al-Zn alloys are beneficial for use in automobile applications to prevent or reduce the impact of critical damage in the case of accident. Mg-Al-Zn alloys are also ductile material (Becker & Fischer 2004) beneficial in automobile applications to prevent or reduce the critical crashes due to high energy absorption capability. However, application of Mg-Al-Zn alloys in extreme conditions is believed to give influenced on the mechanical properties. In general, extreme conditions are referred to the condition such as high loading rate, impact loading response, elevated temperature conditions etc. Tensile strength is significantly strain rate dependent for many materials. At the same time, tensile strength is also temperature dependent for pure and magnesium alloys (Chino 2002; Feng et al. 2014; Kim & Chang 2011; Ulacia et al. 2011). In case of accident, a high loading rate with impact response is significantly applied to the vehicle. Elevated temperature is commonly subjected to automobile components and structures since the powertrain applications such as transmission cases are operated up to 175 °C, while the engine blocks and engine pistons up to 200 °C and 300 °C, respectively (Luo 2002; Luo 2004; Gupta & Sharon 2011). Therefore, engine surrounding temperatures
could rise up to more than 100 °C. Hence, knowing the effect of extreme conditions on mechanical properties is for Mg-Al-Zn alloys are important.

1.2 PROBLEM STATEMENT

As mentioned, magnesium alloys have several advantages when used as components and structures in automobile applications. However, the utilisation of magnesium alloys in automobile applications is still limited compared to that of conventional materials (Luo 2002). This is because the conventional used are of significantly high strength materials beneficial for reducing or preventing critical crashes during accidents. Consequently, studies in obtaining the mechanical properties of those materials are also widely reported (Mutoh 1987; Yi & Xiao-Wei 1988; Kobayashi et al. 1997; Zhang & Shi 1992; Kong et al 2011). Thus, many automotive manufacturers are still using conventional materials in automotive applications.

Several series magnesium alloys are used in automotive application. For example, car body parts, crankcase, seat frame and wheel are made from AZ31, AZ91, AM60 and ZK30 magnesium alloys, respectively (Fink 2003; Friedrich & Mordike 2006; Becker & Fischer 2003). Commonly, these components and structures are subjected to high and different velocities, impact loads and then critical crash during accident. Hence, mechanical properties of magnesium alloys under impact response are required to refer prior to applying the potential magnesium alloys in automotive applications. In addition, it is important to understand these impact fracture properties to understand the material response after being subjected to similar actual situations during accident. However, in previous studies, most mechanical properties are reported under testing at static response and fatigue loads in the case of vibration in service applications (Chamos et al. 2008; Somekawa et al. 2008; Khan et al. 2006). Moreover, these fracture properties are not appropriate for crash design and impact fracture properties are preferable.

For magnesium alloys, mechanical properties of these alloys such as hardness and tensile properties are well known. In previous studies, many researchers reported
the tensile properties of magnesium alloys tested at high strain rates using the Split Hopkinson pressure bar (SHPB) tester (Kurukuri et al. 2012; Kurukuri et al. 2014; Ahmad & Wei 2010; Hasenpouth et al. 2009; Yokoyama 2003; Ulacia et al. 2010; Ulacia et al. 2011; Feng et al. 2014). However, high strain rate tensile tests using free fall principle with drop weight event are rarely investigated. Only Hasenpouth et al. (2009), Kong et al. (2011) and Zabotkin et al. (2003) conducted such studies. Additionally, this experimental technique has never been performed to extruded magnesium alloys to obtain the high strain rate tensile properties. It is very important to simulate the impact loading during collision and its effect to the material of the structures and components.

Sajuri (2005) reported that brittle magnesium alloys are referred to cast magnesium alloys, while ductile magnesium alloys refer to wrought magnesium alloys. However, the brittleness and ductility of magnesium alloys are also depending on the alloying element contents (Kainer 2003). Many of cast and wrought magnesium alloys that have been developed are generally used in automotive applications. For example, automotive parts that are made by the casting process include gearbox housing, crankcase and cylinder head cover. Examples of automotive parts that are made by the wrought process include the wheel, bumper support beam and car body parts (Fink 2003; Friedrich & Mordike 2006; Becker & Fischer 2003; Gaines et al. 1995). Generally, wrought magnesium alloys have good formability and high ductility for forging, extrusion and rolling processes.

In determining the $K_{IC}$ and $J_{IC}$ values, different fracture toughness test methods are conducted. In comparison, $K_{IC}$ test method is easier than that of $J_{IC}$. In addition, the $J_{IC}$ test includes several test methods such as multiple specimen method, unloading compliance method and side-grooved specimen method. Among these test methods, the most complicated test is multiple specimen method while the simplest test method is side-grooved specimen test method (Mutoh 1987; Yi & Xiao-Wei 1988). Multiple specimens method requires at least four pre-cracked specimens, while elastic unloading compliance test requires only a single pre-cracked specimen. However, the elastic unloading compliance method is still complicated because it requires numerous
unloading steps during testing. Thus, single side-grooved specimen test method is the simplest and convenient test method, especially in conducting tests at high temperature (Mutoh 1987; Gnanamoorthy et al. 1995) or in high loading rate conditions. In addition, the study of $J_{IC}$ for ductile magnesium alloys is rarely reported, being only reported by Somekawa et al. (2008) and Bargabagallo & Cerri (2004). Subsequently, determination of fracture toughness $J_{IC}$ of extruded magnesium alloys at high temperature using simple side-groove specimen method has not been done in previous studies. Nevertheless, all methods obtained fracture toughness complying with plane strain conditions.

Considering the application of magnesium alloys in engine compartment where temperatures can rise up to more than 100 °C during operation, it is also essential to determine fracture toughness at high temperature conditions. However, multiple specimen method and unloading compliance method are difficult to conduct under such conditions. Therefore, side-grooved specimen test method is preferable and can be easily performed in high temperature conditions. In high temperature condition, tensile strength could significantly decreases and ductility increases, and consequently the temperature the brittle magnesium alloys could fracture in ductile manner at high temperature. Therefore, the $K_{IC}$ test becomes invalid and the $J_{IC}$ test is preferable.
1.3 **HYPOTHESIS**

Based on the problem statement, the main research hypotheses of the current study have been summarised based on expectation result of tensile properties and fracture toughness $J_{IC}$ under extreme test conditions for Mg-Al-Zn alloys. The result expectations of hardness and work hardening properties are also included. Thus, the research hypotheses have been listed as follows:

(i) Strain rate is dependent on tensile properties, work hardening rate, strain hardening exponent ($n$) and strength coefficient ($K_s$). Subsequently, loading rate is dependent on fracture behaviour of Mg-Al-Zn alloys.

(ii) Elastic-plastic fracture mechanics (EPFM) approach is considered to obtain the fracture toughness $J_{IC}$ since the ductile fracture behaviour of Mg-Al-Zn alloys.

(iii) Hardness, tensile properties and fracture toughness $J_{IC}$ of AZ61 magnesium alloy are higher compared to that of AZ31 magnesium alloy.

(iv) Temperature is dependent on fracture toughness $J_{IC}$ of AZ61 magnesium alloy.
1.4 RESEARCH OBJECTIVES

The main objective of this research is to obtain the tensile properties and fracture toughness $J_{IC}$ of ductile Mg-Al-Zn alloys under several test methods and conditions as listed in the following sub-objectives:

(i) To determine the effect of low and high strain rates on tensile properties of Mg-Al-Zn alloys.
(ii) To determine the effect of strain rate on work hardening rate, strain hardening exponent ($n$) and strength coefficient ($K_s$). Consequently, to investigate the effect of loading rate on fracture behaviour of Mg-Al-Zn alloys.
(iii) To determine the fracture toughness ($J_{IC}$ value) of Mg-Al-Zn alloys.
(iv) To determine a proper side-grooves depth for validate $J_{IC}$ value of a single side-grooved specimen test method by comparing to $J_{IC}$ value of standard fracture toughness test method.
(v) To determine the fracture toughness ($J_{IC}$ value) of AZ61 magnesium alloy at room and high temperatures.

1.5 RESEARCH SCOPE

The mechanical properties of Mg-Al-Zn alloys are crucial for choosing the potential alloys to be used in automobile application. In the present study, the important mechanical properties of tensile strength and fracture toughness for AZ31 and AZ61 magnesium alloys are obtained using the tensile test and fracture toughness test. The tensile and fracture toughness tests are also conducted under extreme test conditions to understanding the effect of extreme test conditions on mechanical properties of alloys. In addition, Vickers hardness test is also conducted to determine the material’s resistance to localized plastic deformation of AZ31 and AZ61 alloys.

In the current study, most tests are performed by referring to the American Society for Testing and Materials (ASTM) and Japan Society of Mechanical Engineers (JSME) recommendations. Standard ASTM E8 is referred to when
conducting the tensile test at two different strain rates of low and high loading responses in lab air condition. The tensile test under low strain rate is performed under four different strain rates of $1 \times 10^{-4}$, $1 \times 10^{-3}$, $1 \times 10^{-2}$ and $1 \times 10^{-1}$ s$^{-1}$ using the universal testing machine (UTM) of 100 kN load capacity. Meanwhile, the tensile test under high strain rate is carried out under strain rates of 100, 200, 400 and 600 s$^{-1}$ using the high strain rate tensile tester of 125 kN load capacity. The high strain rate tensile tester is designed and fabricated in-house to fulfil the requirement of tensile test at high strain rate. This is because the UTM is unavailable to perform the tensile test at high strain rate condition. Hence, the tensile properties of AZ31 and AZ61 alloys under low and high strain rates could be determined. In addition, the effect of low strain rate on work hardening rate, strain hardening exponent ($n$) and strength coefficient ($K_s$) are also obtained in the present study. The standard ASTM E646 is referred to evaluate the $n$ and $K_s$ of AZ31 and AZ61 alloys.

For fracture toughness, generally refer to the two approaches of LEFM and EPFM. LEFM related to the brittle fracture behaviour with small-scale yielding at the crack tip. EPFM is relevant for ductile fracture behaviour that exhibits a large-scale yielding at the crack tip. However, the EPFM approach is used due to result of three-point bending fracture test under different loading rates of 5, 50 and 500 mm/min confirm the elastic-plastic fracture behaviour of the AZ31 and AZ61 alloys. In this study, recommendations by ASTM E1820 and JSME S001 standards are followed to determine the fracture toughness $J_{IC}$ of ductile AZ31 and AZ61 alloys. Further, the specimen used for determining the $J_{IC}$ value was a pre-cracked single edge notched bending (SENB) specimen.

The fatigue pre-crack on SENB specimen was done following ASTM E399 standard. Fracture toughness test was conducted based on ASTM E1820 and JSME S001 standards. To identify the effect of temperature for Mg-Al-Zn alloy on $J_{IC}$ value of AZ61 magnesium alloy, fracture toughness test was conducted at 150 °C using a single side-grooved specimen test method. The fractographs of all tested specimens were captured using the stereo microscope and scanning electron microscope (SEM).
1.6 THESIS OUTLINE

This thesis is divided into five chapters. The first chapter describes the research gap highlighting the importance of investigating the mechanical properties of Mg-Al-Zn alloys. Good mechanical properties of Mg-Al-Zn alloys are then promoted for a wider application in the automobile industry.

The second chapter reviews the relevant literature on tensile properties and fracture toughness for magnesium alloys and conventional materials determined under extreme test conditions. Results of the work hardening rate, strain hardening exponent ($n$) and strength coefficient ($K_s$) for magnesium alloys and several metallic materials are also discussed. The simplicity and convenience of side-grooved specimen test method to obtain the fracture toughness is also discussed.

Chapter 3 explains the experimental procedure of tensile and fracture toughness tests under extreme test conditions. The work hardening rate, strain hardening exponent ($n$) and strength coefficient ($K_s$) are then analysed to understand the tensile ductility of materials. In-house development of high strain rate tensile tester is also described to test tensile strength under high strain rates. This includes a discussion on the proper method for obtaining the fracture toughness using the side-grooved specimen test method. Procedures for fractography, metallography and hardness tests are also included in this chapter.

Chapter 4 exhibits the results and present the analysis of the results of tensile and fracture toughness tests of Mg-Al-Zn alloys under extreme test conditions. Work hardening rate, $n$ and $K_s$ of Mg-Al-Zn alloys are included. The fracture behaviour and fracture mechanisms of these alloys are also discussed. Next, fracture toughness for ductile Mg-Al-Zn alloys is determined based on the elastic-plastic fracture mechanics (EPFM) approach. Other than that, the average grain size and Vickers hardness of Mg-Al-Zn alloys are reported in this chapter.
The research findings have been summarised in the chapter 5 including the contribution of the research and suggestion for future studies. In this study, side-grooved specimen test method is validated to determine the fracture toughness of Mg-Al-Zn alloys with simple and convenient test method especially under extreme test conditions.
2.1 MAGNESIUM

Magnesium (Mg), an alkaline earth metal, is the sixth most abundant element in the earth crust and third most abundant dissolved mineral in seawater. Magnesium has a glossy silver colour, is ductile, and easily reacts with chemical substances such as oxygen, nitrogen, carbon dioxide or water (Golabczak 2011). Magnesium is classified as a light material compared to other engineering metals with two-thirds of the density of aluminium and one-quarter of iron. The density of magnesium, aluminium and iron at 20 °C are 1.74 g/cm$^3$, 2.70 g/cm$^3$ and 7.86 g/cm$^3$, respectively (Gaines 1995; Joksch 2003; Kainer 2003). However, the density of magnesium is reduced to 1.65 g/cm$^3$ at melting temperature of 650 °C. The crystal structure of magnesium is a hexagonal close packed (HCP) structure with c/a ratio of 1.624 at room temperature (Friedrich & Mordike 2006). Major slip systems of HCP structure for magnesium are shown in Figure 2.1.
2.2 MAGNESIUM ALLOYS

Magnesium has several advantages such as the lowest density among all conventional materials, high specific strength, and good castability and machinability. However, several disadvantages of magnesium include low mechanical strength, low formability at low temperature, poor creep resistance at elevated temperature and low corrosion resistance. For these reasons, magnesium fails to meet the requirements of many technical applications. Thus, alloying development is required to improve the properties of magnesium by adding other alloying elements (Mordike & Ebert 2001; Kulekci 2008). Many alloying elements are used with sufficient composition in order to obtain good properties of magnesium alloys.
2.2.1 Classification of Magnesium Alloys

The American Society for Testing and Materials (ASTM) has listed the abbreviation letters of alloying elements generally designated for magnesium alloys (see Table 2.1). Each alloying element represented by letters for the alloy indicating the main element content in magnesium. This is followed by the weight percentage (wt%) of these elements. The last letter refers to the specific compositions as summarised in Table 2.2. For example, in the AZ series magnesium alloy of AZ91C (Mg-9%Al-1%Zn), A and Z represent the element content of aluminium and zinc. The following numbers 9 and 1 are the rounded numbers for the weight percentages of aluminium and zinc. Lastly, C indicates the third specific compositions of alloy (Kainer 2003; Gupta & Sharon 2011).

Table 2.1 ASTM designation system of magnesium alloys

<table>
<thead>
<tr>
<th>Alloying element</th>
<th>Abbreviation letter</th>
<th>Alloying element</th>
<th>Abbreviation letter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>A</td>
<td>Nickel</td>
<td>N</td>
</tr>
<tr>
<td>Bismuth</td>
<td>B</td>
<td>Lead</td>
<td>P</td>
</tr>
<tr>
<td>Copper</td>
<td>C</td>
<td>Silver</td>
<td>Q</td>
</tr>
<tr>
<td>Cadmium</td>
<td>D</td>
<td>Chromium</td>
<td>R</td>
</tr>
<tr>
<td>Rare earth metals</td>
<td>E</td>
<td>Silicon</td>
<td>S</td>
</tr>
<tr>
<td>Iron</td>
<td>F</td>
<td>Tin</td>
<td>T</td>
</tr>
<tr>
<td>Thorium</td>
<td>H</td>
<td>Yttrium</td>
<td>W</td>
</tr>
<tr>
<td>Zirconium</td>
<td>K</td>
<td>Antimony</td>
<td>Y</td>
</tr>
<tr>
<td>Lithium</td>
<td>L</td>
<td>Zinc</td>
<td>Z</td>
</tr>
<tr>
<td>Manganese</td>
<td>M</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Kainer 2003, Gupta & Sharon 2011
Table 2.2 Specific compositions

<table>
<thead>
<tr>
<th>Abbreviation letter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>First compositions, registered with ASTM</td>
</tr>
<tr>
<td>B</td>
<td>Second compositions, registered with ASTM</td>
</tr>
<tr>
<td>C</td>
<td>Third compositions, registered with ASTM</td>
</tr>
<tr>
<td>D</td>
<td>High purity, registered with ASTM</td>
</tr>
<tr>
<td>E</td>
<td>High corrosion resistance, registered with ASTM</td>
</tr>
<tr>
<td>X</td>
<td>Experimental alloy, not registered with ASTM</td>
</tr>
</tbody>
</table>

Source: Gupta & Sharon 2011

2.2.2 Alloving Element Composition

One commercial magnesium alloy is the AZ (Mg-Al-Zn) series. The main element contents of this alloy are aluminium and zinc. These alloying elements are used to modify the significant microstructure for producing better properties of magnesium alloys. The best combination of aluminium and zinc is to improve the mechanical properties, ductility, corrosion resistance and castability of magnesium based alloy. The mechanisms that improve these properties are solid-solution strengthening and precipitation hardening (Kainer 2003). Solid solution strengthening refers to alloying with impurity atoms while, precipitation hardening refers to second phase strengthening in materials to restrict the dislocation mobility for material strengthening and hardening (Callister 2007).

Aluminium (Al) is a common alloying element used in magnesium. The addition of aluminium with sufficient composition corresponds to improved strength, hardness and corrosion resistance. The addition of aluminium between 3 wt% and 9 wt% produces good mechanical properties and high corrosion resistance of magnesium based alloys. Aluminium content increases the tensile strength and hardness of magnesium alloys due to the formation of $\beta$-$Mg_{17}Al_{12}$ precipitation. However, high aluminium content tends to form a high $\beta$-$Mg_{12}Al_{17}$ precipitation to
give low strength and low ductility (Kainer 2003; Friedrich & Mordike 2006). Beck (1940) reported increased tensile strength and elongation with the addition of aluminium content up to the 6 wt%, whereas the tensile strength and elongation decreased with aluminium content up to the 12 wt% in magnesium. Apart from that, aluminium content corresponds to reduce grain size (StJohn et al. 2005; Dargusch et al. 2006; Sillekens & Bormann 2012) to improve the tensile strength of magnesium. In previous studies, Sajuri (2005) reported the tensile strength of extruded and as-cast billet AZ91D was higher than the tensile strength of extruded and as-cast billet AZ61. Meanwhile, Chamos et al. (2008) reported that the tensile strength of rolled AZ61 was higher compared to the tensile strength of rolled AZ31 due to the high aluminium content in magnesium alloys.

Other than aluminium, zinc (Zn), manganese (Mn), zirconium (Zr), yttrium (Y) and rare earth (RE) elements are also common alloying elements used in magnesium. Zinc is similar to aluminium element that corresponds to strengthening. However, increasing zinc content corresponds to microporosity and reduced ductility (Kainer 2003). Zinc content above 3 wt% has a tendency to undergo hot cracking (Baghni et al. 2003). Manganese is beneficial to improve the strength, ductility, corrosion resistance and creep resistance of magnesium. Rare earth elements enhance the high temperature strength, creep resistance, and corrosion resistance. Yttrium is usually incorporated with rare earth elements to increase high temperature strength and creep performance. Zirconium improves strength, ductility and high-temperature strength (Gupta & Sharon 2011; Sillekens & Bormann 2012). The best combination of these alloying elements would be promoted to other commercial magnesium alloys systems such as AM (Mg-Al-Mn), ZK (Mg-Zn-Zr) and WE (Mg-Y-RE) series. Due to the good properties, these commercial magnesium alloys are widely used in automotive application. Table 2.3 summarises the example of the chemical compositions for AZ, AM, ZK and WE magnesium alloys.
Table 2.3 Chemical composition of AZ, AM, ZK and WE magnesium alloys series

<table>
<thead>
<tr>
<th>Alloy designation</th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Zr</th>
<th>RE</th>
<th>Y</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31B, C, D</td>
<td>3</td>
<td>1</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>AZ61A</td>
<td>6</td>
<td>1</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>AZ63A, B, C, D</td>
<td>6</td>
<td>3</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>AZ80A</td>
<td>8</td>
<td>0.5</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>AZ91B, C, D, E</td>
<td>9</td>
<td>1</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>AM50A</td>
<td>5</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>AM60A, B</td>
<td>6</td>
<td>-</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>ZK40A</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>ZK60A</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>WE43A, B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
<td>3</td>
<td>4</td>
<td>Balance</td>
</tr>
<tr>
<td>WE54A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
<td>4</td>
<td>5</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Source: Friedrich & Mordike 2006

2.2.3 Plastic Deformation and Slip Systems of Magnesium Alloys

Plastic deformation is permanent deformation after applying shear stress and relates to the slips involved with the movement of a large number of dislocations. The motion of dislocation corresponds to the slip plane and slip direction. The combination of slip plane and slip direction is called the slip system. Motion of dislocation begins when there is large shear stress on the slip system and is referred to as critical resolved shear stress (CRSS) (Roesler et al. 2006; Callister 2007).

The slip systems for the HCP structure for magnesium are shown in Figure 2.1. According to the von Mises criteria, more than five independent slip systems must be operated in polycrystalline materials for high plastic deformation. The reduced plastic deformation of magnesium in the HCP structure means slip system is fewer. Moreover, the number of independent basal slip systems is fewer than required. Thus, activation of prismatic or pyramidal slip planes (non-basal slip planes) and twinning
are necessary for material to deform. At low temperatures, magnesium is hard to deform due to restricted independence causing the slip system to occur easily. In this regard, high deformation of magnesium is relying on the activation energy of the non-basal slip system (Friedrich & Mordike 2006; Faramarz & Stephen 2011).

Magnesium alloys is difficult to deform at room temperature because the activation of slip planes at room temperature is limited and only involved the basal planes. However, CRSS of non-basal slip systems at room temperature is 100 times greater than CRSS of the basal slip system. When temperature increases, the formability of magnesium is increased due to the activation of non-basal slip system, while the CRSS of non-basal slip planes tends to decrease rapidly. However, CRSS of the basal is temperature independent. Other than that, twinning is also considered a deformation mechanism. Twinning is commonly generated at room temperature. Figure 2.2 shows the example of twinning for extruded AZ31 at room temperature. However, it decreased at increasing temperature due to the activation of non-basal slip systems (Friedrich & Mordike 2006; Faramarz & Stephen 2011). Ulacia et al. (2010) reported the tensile yield stress decreased with temperature at high strain rates and low strain rates for AZ31 magnesium alloy because the CRSS of the non-basal slip decreased with increasing temperatures.

![Formation of twinning in extruded AZ31 at room temperature](image)

**Figure 2.2** Formation of twinning in extruded AZ31 at room temperature

*Source: Barnet 2007*
2.2.4 Strengthening Mechanisms of Magnesium Alloys

Plastic deformation is mainly related to the dislocation movement. If motion of dislocation is piled up and blocked at the grain boundary, this will harden and strengthen the material. In this regard, strengthening mechanisms can possibly impede the dislocation movement. Strengthening mechanisms in metals are commonly divided into grain size reduction, solid-solution alloying, work hardening and precipitation hardening.

a. Grain size reduction

Strengthening by grain size reduction refers to when the greater total grain boundaries area act as an obstacle to dislocation motion. In this regard, many slip planes are stopped and require changing the slip directions to move to the next grains due to the different orientations of grains. This indicates that the fine grain size is harder and stronger than the coarse grain size which, due to the greater total grain boundaries area, impedes dislocation motion. Grain size reduction not only improves the strength and hardness, but also improves the toughness of the material (Callister 2007).

Somekawa and Mukai (2005) reported yield stress, tensile strength, elongation to fracture and fracture toughness of extruded pure magnesium increased with grain refinement. The grain size of the extruded pure magnesium decreased due to decreasing the extrusion temperature. Similarly, Somekawa and Mukai (2006) reported the fracture toughness of AZ31 improved by grain refinement. The grain size of AZ31 was reduced due to the equal-channel-angular extrusion. As seen in Figure 2.3, Khan et al. (2006) reported that tensile strength and hardness of AZ31 and AZ10 increased by decreasing the grain size. In this finding, the reduction in grain size was due to increasing the manganese content up to 0.4 wt%, as shown in Figure 2.4.

Subsequently, twinning formation also decreases in smaller grain size. Barnett (2007) and Li et al. (2009) mentioned the twinning formation decreases at finer grain structure of magnesium alloys. Li et al. (2009) reported the minor twinning formation
Figure 2.3     Effect of grain size on (a) tensile strength and (b) average hardness for Mg-Al-Zn alloys

Source: Khan et al. 2006
in small grain size of ZK60 where the grain size of alloy is only ~0.8 µm. The strength and ductility of magnesium alloys are improved by reducing twinning in finer grain structure.

Figure 2.4  Effect of manganese content on average grain size for Mg-Al-Zn alloys

Source: Khan et al. 2006

b.  Solid solution alloying

In general, pure metals are softer and weaker than alloys composed by same base metal. Thus, alloying with impurity atoms into a solid is a technique to strengthen and harden the material by restricting the dislocation movement. In this case, resistance to slip is increased with the presence of impurity atom in the material. These factors increase the strength and hardness of solid solution alloys (Callister 2007).

As referred to in Figure 2.5(a), Chino et al. (2002) reported that the tensile strength of magnesium-calcium (Mg-Ca) alloy was higher compared to the tensile strength of pure magnesium at increasing temperatures. However, the tensile strength of Mg-Ca alloy at room temperature was almost the same to the tensile strength of
pure magnesium. A 0.2% proof stress of Mg-Ca alloy was found higher than that of pure magnesium at all tested temperatures, as seen in Figure 2.5(b). Increasing tensile strength and yield stress of this alloy was due to the addition of calcium in magnesium. The addition of calcium element is beneficial to grain size refining and increases creep resistance (Kainer 2003). In such a way, alloying is one common
effective method to improve the mechanical properties and microstructure of materials, as discussed in section 2.2.4(a).

c. **Work hardening**

Work hardening refers to the ductile material that becomes harder and stronger due to plastic deformation at low temperature. Dislocation density is generally increased during plastic deformation where the yield stress and tensile strength of material are increased. This is caused by higher resistance to dislocation motion. However, high dislocation density decreases the ductility of the material (Callister 2007). Figure 2.6 shows the stress-strain curve of different hardening behaviours. Figure 2.6(b) indicates the stress is increased after yielding for strain hardens, while Figure 2.6(a) indicates material is perfectly plastic with no hardening after yielding (Roesler et al. 2006). Apart from that, work hardening tends to decrease at increasing temperatures (Callister 2007).

![Stress-strain curves for different hardening behaviours](image)

Figure 2.6 Stress-strain curves for different hardening behaviours

Source: Roesler et al. 2006

Noda et al. (2011) reported the maximum stress and work hardening level of extruded AZ31 magnesium alloy decreased when increasing the temperature from 250 °C to 350 °C. They also reported strain hardening exponent of extruded AZ31 decreased at increasing temperatures, probably due to the dynamic recovery and recrystallization. In this thesis, further explanation of work hardening related to flow
equation was discussed in section 2.4.3. Hence, the findings of work hardening properties such as strain hardening exponent \((n)\) and strength coefficient \((K_s)\) are discussed in detail in terms of plastic characteristics for several materials.

### d. Precipitation hardening

Precipitation hardening is the development of second phase fine particles in the material through heat treatment. It mostly develops at grain boundaries, as seen in Figure 2.7. The presence of precipitation hardening impedes the dislocation motion thus increasing the hardness and strength of the alloy (Roesler et al. 2006). In magnesium, most alloying elements tend to form precipitation hardening. For instance, aluminium content forms \(\beta-Mg_{17}Al_{12}\) precipitation in magnesium. An increase of aluminium content tends to increase the \(\beta\)-phase to enhance the strength of magnesium alloys (Kainer 2003).

Sajuri (2005) reported the distribution and volume fraction of \(\beta-Mg_{17}Al_{12}\) precipitation was higher in AZ91D than that of AZ61 due to the high aluminium content in AZ91D compared to that of AZ61. Thus, tensile strength of AZ91D was slightly higher than that of AZ61. Other than strength, Somekawa et al. (2007) mentioned that the precipitate dispersion is an effective means to enhance the fracture toughness of magnesium alloy. They found that the fracture toughness of ZK60 was higher than that of pure magnesium and AZ31 due to lower volume fraction of precipitates in pure magnesium and AZ31 compared to ZK60.
2.3 APPLICATIONS OF MAGNESIUM ALLOYS IN AUTOMOTIVE INDUSTRY

In the early 1930s, magnesium was used in the Volkswagen (VW) Beetle. Over the past decade, magnesium-based materials have been increasingly used in commercial vehicles by automobile manufacturers such as Volkswagen, Audi, DaimlerChrysler (Mercedes-Benz), Toyota, Ford, BMW, Jaguar, Fiat, Hyundai, and Kia Motors Corporation. To date, magnesium alloys have been used as structural components in automotive applications due to the combination of low density, high specific strength properties, machinability, castability, excellent damping capacity and high recycling potential of magnesium based alloys. These good properties of magnesium alloys attract automobile manufacturer to choose these materials for replacing conventional materials such as steel and aluminium (Gupta & Sharon 2011).

2.3.1 Major Application of Magnesium Alloys in Vehicle

Figure 2.8 shows the use of several materials for vehicles in 2000. Steel is the major material applied in vehicles (Luo 2002). The main interest in applying lightweight magnesium alloys in automotive applications pertain to energy saving, increased engine efficiency and reduced fuel consumption. Indirectly, it also helps in lowering harmful emissions. In the case of high specific strength magnesium alloys, these
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Material Safety Data Sheet
http://www.sciencelab.com [8 April 2013]


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