Fracture Toughness in an Extruded ZK60 Magnesium Alloy

Hidetoshi Somekawa* and Toshiji Mukai

Ecomaterials Center, National Institute for Materials Science, Tsukuba 305-0047, Japan

Examination of fracture toughness has been performed a commercial Mg-Zn-Zr alloy, ZK60, with fine strengthening particles. The commercial alloy was extruded at 633 K, and then heat treated at specific conditions. The microstructures were equi-axed grains, and average grain size and precipitate size were 11.6 μm and 50–150 nm, respectively. The yield strength and elongation-to-failure were 225 MPa and 17.0%. The plane-strain fracture toughness, $K_{IC}$, was estimated to be 20.6 MPa m$^{1/2}$ in stretched zone analysis. From ductile fracture model, all the finer particles did not affect the void formation. The precipitates having a large diameter, more than 100 nm, were supposed to be the origin of void formation.

(Received December 1, 2005; Accepted February 24, 2006; Published April 15, 2006)

Keywords: toughness, magnesium alloy, extrusion, particle, ductile fracture model

1. Introduction

Magnesium alloys have great potential to be used as structural materials because of being the lightest of all structural alloys in use. In order to use magnesium alloys in structural applications, it is important to ensure that their mechanical properties satisfy both reliability and safety requirements. One of the methods of ensuring that is to investigate the fracture toughness. There are some reports on the fracture toughness in magnesium alloys$^{1–5}$ and magnesium.$^{6}$ However, the value of fracture toughness in magnesium alloys has been generally reported to be much lower than that in aluminum alloys. Therefore, methods for improving the fracture toughness have been investigated in magnesium alloy.

To date, it has been reported that the fracture toughness of magnesium alloys is affected by the basal texture.$^{5}$ The samples of magnesium alloys having a pre-crack normal to the basal texture exhibited higher fracture toughness in comparison with the samples having a pre-crack parallel to the basal texture. In addition, grain refinement improves the fracture toughness in magnesium$^{6}$ and magnesium alloys$^{7,8}$ This is a result of a large plastic zone created ahead of the fracture pre-crack. The plastic zone influences the mechanical properties of yield strength, elongation-to-failure and strain hardening exponent. These sensitive factors in magnesium and magnesium alloys, the yield strength, strain hardening exponent, and the elongation-to-failure$^{12,13}$ increased with refining the grain structures. Therefore, controlling of the basal texture and/or grain refinement is one of the effective methods of improving the fracture toughness in magnesium and magnesium alloy.

In general, it has been reported that the creation of fine particle is also one of the effective methods of enhancement for the fracture toughness in metallic materials.$^{14–16}$ In magnesium alloys, inclusions composed of Mn- or Fe-bearing intermetallics are the origin of fracture.$^{17}$ However, the effect of particle, which enhances the fracture toughness, has not been investigated yet. Mg-Zn-Zr alloy is a popular alloy in which fine precipitates are created during heat treatment easily. Therefore, in this study, a wrought ZK60 magnesium alloy has been used to examine the effect of particles on the fracture toughness.

2. Experimental Procedure

The material used in the present study was a commercial Mg-Zn-Zr alloy, ZK60. The as-received alloy was solutionized at a temperature of 773 K for 7.2 ks, and then the solutionized alloy was extruded at 633 K with a reduction ratio of 18. The extruded alloy was annealed at 618 K for 24 h, and then aged at 423 K for 24 h in accordance with a previous report.$^{18}$ The microstructure of the material was examined by laser three-dimensional (3D) microscopy and transmission electron microscopy (TEM) with a JEOL 2000FX-II.

Tensile test was performed at an initial strain rate of $1 \times 10^{-3}$ s$^{-1}$ at room temperature. The tensile specimen with a gauge length of 10 mm and a gauge diameter of 2.5 mm was machined from the material to make the tensile axis parallel to the extrusion direction.

Plane-strain fracture toughness test was carried out according to ASTM-E399.$^{19}$ The fracture toughness specimen was a three point bending sample with a width and a thickness of 10 and 5 mm, respectively. The fracture toughness specimen was directly machined from the material. The V-notch was normal to the extrusion direction. Before plane-strain fracture toughness test, fatigue crack test was performed to insert a fatigue pre-crack in the specimen. The pre-crack length was between 0.45 and 0.55 W, where W is the width of 10 mm. The plane-strain fracture toughness test was carried out at a cross head speed of 1 mm/min. The fractured surface after plane-strain fracture toughness test was examined by scanning electron microscopy (SEM) with a HITACHI S-4800 and by laser 3D profile microscopy.

3. Results and Discussion

3.1 Microstructures

Typical microstructures of ZK60 alloy are shown in Fig. 1; (a) laser 3D microscopy and (b) TEM bright-field image, respectively. The average grain size, $d (= 1.74L$: L is the
linear intercept size), was 11.6 μm. Each grain was equi-axed (without bimodal grain structures), because the present heat treatment temperature was lower than the extrusion temperature. It is also observed in Fig. 1(b) that many fine precipitates having a diameter of 10–150 nm (average size; ~50 nm) and spacing of 50–200 nm (average spacing; ~200 nm) exist in the alloy. The composition of the precipitates is MgZn according to previous reports.20,21)

3.2 Mechanical properties

Typical nominal stress and nominal strain tensile curve at room temperature is shown in Fig. 2. The yield strength (σ_y), ultimate tensile strength (σ_UTS) and elongation-to-failure (δ) were 225 MPa, 266 MPa and 17.0%, respectively. From Fig. 2, it is noted that strain hardening occurred in ZK60 alloy and the strain hardening exponent, n, is estimated to be 0.140.

Stretched Zone (SZ) analysis has been frequently used to estimate the plane-strain fracture toughness, K_{IC}, for a sample of small thickness.4-8) A typical SEM micrograph of the fracture surface after plane-strain fracture toughness test is shown in Fig. 3. The pre-crack propagated direction and SZ are marked in this figure. It is found that the SZ exists between the fatigue pre-crack and the fracture surface. A void like feature, which indicates typical ductile fracture, was also observed on the fracture surface. When the load was applied to the specimen having a sharp pre-crack, the pre-crack itself blunted and the crack-tip moved forward normal to the tensile axis, producing the SZ. The SZ is closely related to the value of K_{IC} as follows equation:22)

$$K_{IC} = \frac{2 \times SZH \times \lambda \times E \times \sigma_y/(1 - \nu)^2}{\pi}^{1/2}$$  \hspace{1cm} (1)

where SZH is the stretched zone height, λ is a constant (≈ 2), E is Young’s modulus and ν is the Poisson ratio (44.8 GPa and 0.35, respectively, for a wrought ZK60 alloy). From eq. (1), it is seen that the value of K_{IC} depends on the height of SZ, SZH. The SZH measured by laser 3D profile microscopy and the calculated value of fracture toughness, K, by eq. (1) are 4.5 μm and 20.6 MPam^{1/2}, respectively. The method to measure the SZH by laser 3D profile microscopy was reported in detail elsewhere.5) The value of fracture toughness, K_{O}, which is obtained according to ASTM-E399, was 24.8 MPam^{1/2} in the present study. It is found that the calculated value of the fracture toughness, K, by using eq. (1) for ZK60 alloy is smaller than the values of K_{O}. In general, the plane-stain fracture toughness, K_{IC}, is the smallest value; the value of K, which is estimated from SZ
3.3 Ductile failure model

In ductile fracture, there have been a number of attempts to establish the relation between the fracture toughness and (i) the mechanical properties, which are obtained from tensile test at room temperature\(^{24-26}\) or (ii) other microstructural parameters such as size, spacing and volume fraction of inclusions and/or particles\(^{27,28}\). In the present material, there are traces of void formation, -typical ductile fracture-, on the fracture surface after the fracture toughness test in Fig. 3. For the initiation of the ductile fracture by void coalescence, Ritchie et al.\(^{28}\) have indicated that the ductile fracture occurs when the local effective plastic strain, \(\varepsilon_{ep}\), at a crack tip have exceeded the value of \(\varepsilon_1 \times (\sigma_m/\sigma)\). The local effective plastic strain, \(\varepsilon_{ep}\), is defined the strain field adjacent to the crack tip along y-axis and given by:\(^{29,30}\)

\[
\varepsilon_{ep} \approx C \times \varepsilon_{ys} \times [J_{IC}/(\sigma_{ys} \times \varepsilon_{ys} \times \ln(n) \times X)]^{1/(\alpha+1)}
\]

where \(C\) is a material constant (\(=0.74\))\(^{30}\), \(J_{IC}\) is the J-integral (\(= (1 - v^2) \times K_{IC}^2/E\)), \(\varepsilon_{ys}\) is the uniaxial fracture strain at tensile test (\(=0.174\)), \(X\) is the distance from the origin of fracture, \(n\) is the strain hardening exponent and \(\ln(n)\) is the function of \(n\) (\(=10.3 \times (0.13 + n)^{1/2} - 4.8n\))\(^{31}\). The value of \(\varepsilon_1 \times (\sigma_m/\sigma)\) is the product of limitative fracture strain, \(\varepsilon_1\), and stress triaxially, \((\sigma_m/\sigma)\), which are respectively given by:\(^{32,33}\)

\[
\varepsilon_1 = 1/3 \times \ln(M^2/3f)
\]

and

\[
(\sigma_m/\sigma) = 1/3 \times [1 + 2 \ln(1 + 2X/\delta)]
\]

where \(M\) is the fracture surface micro roughness (\(=h/w; h\) is the micro void depth and \(w\) is the width\(^{32}\)), \(f\) is the volume fraction of particle (\(=\pi d_p^2/2/(3^{1/2} \lambda_p + 2^{1/2} d_p)\); \(d_p\) is the diameter of particle and \(\lambda_p\) is the spacing of particle\(^{34}\) respectively) and \(\delta\) is the critical crack tip opening displacement (\(=2 \times SZH\)). The value of \(M\) has been experimentally evaluated to be \(\sim 0.6\) in the previous article,\(^{35}\) and the previous experimental value was substituted to eq. (3). Combined with eq. (1) and J-integral, eq. (2) is rewritten as follows:

\[
\varepsilon_{ep} \approx C \times \varepsilon_{ys} \times [2 \times \delta/(\varepsilon_{ys} \times \ln(n) \times X)]^{1/(\alpha+1)}
\]

By using eqs. (3)–(5), the variation in \(\varepsilon_{ep}\) and \(\varepsilon_1 \times (\sigma_m/\sigma)\) as a function of \(X/\delta\) is shown in Fig. 4. In Fig. 4(a), the average precipitate size of 50 nm and average spacing of 200 nm were assumed for analysis. A simple illustration of the present analysis of ductile fracture is shown in Fig. 5. From Fig. 4(a), the value of intersection between \(\varepsilon_{ep}\) and \(\varepsilon_1 \times (\sigma_m/\sigma)\) at x-axis is estimated to be 1.25. Since the value of SZH was 4.5 \(\mu m\), the interaction distance from the crack tip is calculated to be \(\sim 10 \mu m\). Therefore, from the present analysis, it is suggested that the void formation occurs at the particle, which exists \(\sim 10 \mu m\) ahead of the fatigue pre-crack (Fig. 5). However, the average spacing of fine precipitates [Fig. 1(b)] was \(\sim 200 \mu m\). The estimated distance, \(X\), by using \(d_p = 50 \mu m\) and \(\lambda_p = 200 \mu m\) [Fig. 4(a)], is not in agreement with the present result of the TEM observation.

4. Summary

The fracture toughness of an extruded ZK60 alloy was investigated. The following results were obtained.

(1) From microstructure observation, the average grain size and precipitate size were 11.6 \(\mu m\) and 50–150 \(\mu m\),
respectively. The yield strength, elongation-to-failure and plane-strain fracture toughness were 225 MPa, 17% and 20.6 MPam$^{1/2}$, respectively.

(2) It was possible to apply the ductile fracture model to the magnesium alloy. From the ductile fracture model, a precipitate having a large diameter of more than 100 nm was affectively the origin of void formation in the ZK60 alloy.

REFERENCES