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Notch Effects in Tensile Behavior of AM60 Magnesium Alloys

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Abstract. The deformation and failure behavior of an AM60 magnesium alloy was investigated using tensile test on circumferentially notched specimens with different notch radii. The strain and stress triaxiality corresponding to the failure point were evaluated using both analytical and finite element analyses. Combining with systematical observations of the fracture surfaces, it is concluded that deformation and failure of AM60 magnesium alloy are notch (constraint) sensitive. The failure mechanisms change from ductile tearing to quasi cleavage with the increase of constraint.

Introduction

Magnesium (Mg) alloys are attractive for applications in automobile, aerospace, communication and computer industry because of their very low density, high specific strength and good machineability and availability as compared to other structural materials. Mg has a low density of 1.74g/cm^3, which is approximately 35% lighter than Al alloys and 65% lighter than Ti alloys. It also has good conductivity and high damping capacity. However, the disadvantages of magnesium are low elastic modulus and limited toughness due to few slip systems which are available in a hexagonal close-packed structure. Many investigations have shown that failure of metallic materials is highly dependent on the constraint condition ahead of a crack or notch. A high constraint (stress triaxiality) level can prompt brittle fracture and lead to a low fracture toughness. Normally, ductile tearing is controlled by nucleation, growth and coalescence of microvoids. It has been experimentally observed that the crack tip opening displacement (CTOD) or *J*-integral at the initiation of ductile fracture is higher for specimens with low constraint than those with high constraint [1-3]. Yan and Mai [4-6] indicated that ductile crack propagation and ductile-brittle transition are also strongly dependent on constraint level at the crack tip. Unfortunately, very few studies have been conducted to understand the effect of constraint on deformation and failure of magnesium alloys. In this work, the effect of notch (constraint) on deformation and failure of an AM60 magnesium alloy in tension was investigated.

Experimental Procedure

AM60 magnesium alloy (with 6% Al, 0.2% Zn and 0.21% Mn) was used in this work, which is one of the most popular magnesium alloys with great potential for applications in the automotive industry. The microstructure is shown in Fig. 1, which mainly consists of α-Mg matrix and second phases ($Mg_{17}Al_{12}$). In order to vary the constraint condition, tests were carried out on circumferentially notched tensile bars with different notch radii, whose dimensions are shown in Fig. 2.

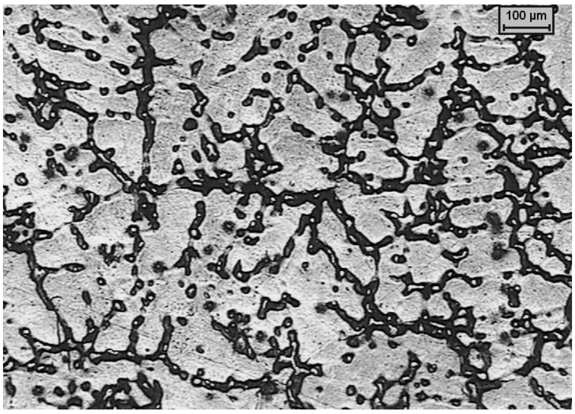


Fig. 1 Microstructure of the Mg alloy.

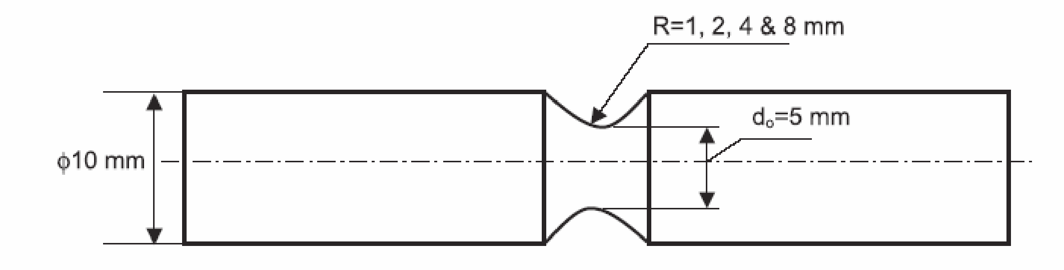


Fig. 2 Schematic of the circumferentially notched tensile specimen.

The specimens were machined from the longitudinal direction in a cast ingot. The tests were carried out in an Instron testing machine at a crosshead speed of 1 mm/min. The axial displacement was recorded using an extensometer mounted on the specimen surface. The continuous changes in the notch profile were monitored using a digital camera connected with a video recorder. The fracture surfaces were examined using scanning electron microscopy (SEM).

Finite Element Analysis

Large deformation finite element analysis was carried out using MSC/MARC. Incremental plasticity theory was used for the material constitutive model. The yield function *f* is related to uniaxial tension by

$$f(\sigma) = \overline{\sigma}(\varepsilon^p), \qquad (1)$$

where ε^p is the plastic strain and $\boldsymbol{\sigma}$ and $\overline{\sigma}$ are the Cauchy (true) stress and equivalent (uniaxial) stress respectively. The form of *f* employed in this study is the von Mises yield function

$$f(\boldsymbol{\sigma}) = \left(\frac{3}{2}(\mathbf{s}_{ij}\mathbf{s}_{ij})\right)^{1/2}, \qquad (2)$$

where $\mathbf{S}_{ij}$ is the deviatoric component of stress. The uniaxial true stress-strain constitutive response was input in the finite element program in a multi-linear form. Because the circumferentially notched specimen is axisymmetric, only a quarter of the specimen was modeled in 2-dimension to reduce the computational cost. The mesh size was optimized by carrying out mesh sensitive test with various element sizes. Small elements (about 10 μm) were placed in the notch root, shown in Fig. 3.

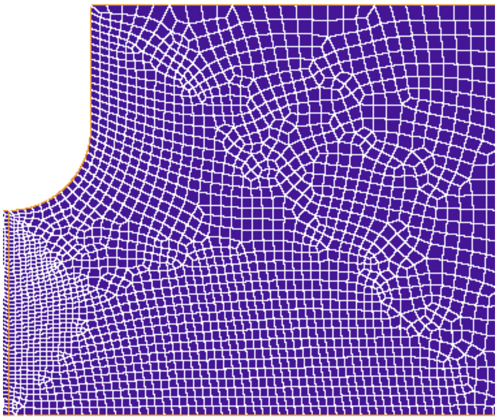


Fig. 3 Finite mesh for the notched bars.

Results and Discussion

Notch Effects on Stress Triaxiality. For a notched bar in tension, it is expected the deformation is not uniform in the axial direction in the notched section. As a result, it is difficult to know the effective gauge length in a notched bar when recording the strain with an extensometer. The strain measured by the extensometer is only the average value within the total gauge length of the extensometer (50 mm). In the stress-strain curves for the smooth tensile specimen (without a notch), it can be observed that after the initial elastic response, the stress rises as a result of strain hardening and then drops. The tensile behavior of the notched specimens, however, differs from that of the smooth bars. There is less degree of strain hardening in the specimens. Also, an apparent increase of break (failure) stress is observed in the notched specimens. To clarify the notch effects in a quantitative way, the distribution of stresses and strains, especially the stress triaxiality need to be estimated.

Firstly, Birdgman's analysis [7] was used to evaluate the stress triaxiality and strain in the minimum cross-section area of the notch. This analysis was originally applied for a smooth tensile bar after necking but it may be used as an approximation to pre-notched specimens. The maximum stress triaxiality (ratio between mean stress and effective stress) is estimated as,

$$(\sigma_m / \sigma_{eff})_{\max} = 1/3 + \ln(d/2R + 1), \tag{3}$$

where R is the profile radius of the cirumferential notch and d is the diameter of the minimum cross-section. The effective plastic strain is

$$\varepsilon_p = 2\ln(d_o / d), \tag{4}$$

where d_0 is the initial value of d. From Eq. 3, high stress triaxiality is associated with the sample with a small radius. Fig. 4 shows the finite element analysis on stress triaxiality along the diameter direction of the notched specimens corresponding to the same load (4.5 kN). Apparently, the specimen with a smaller notch profile radius has a higher level of stress triaxiality, i.e., a higher constraint level. It is interesting to note that the maximum stress triaxiality is located in the centre of the notched specimens. This is consistent with Bridgman's analysis [7]. Fig. 5 gives a comparison between the stress triaxiality corresponding to the failure loads evaluated by Eq. 3 and by the finite element analysis. The agreement is reasonably good, especially for large notch radii (R=4 and 8 mm). Fig. 6 shows the effect of stress triaxiality on the break stress. It is clear that the break stress increases with the stress triaxiality. This is very similar to the investigation of Hancock and

Mackenzie [8] on two low alloy steels where an apparent increase of break strength with stress triaxiality was observed.

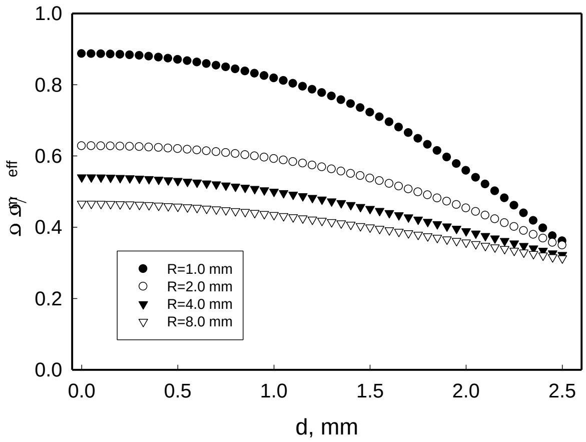


Fig. 4 Stress triaxiality along the diameter direction of the notched bars.

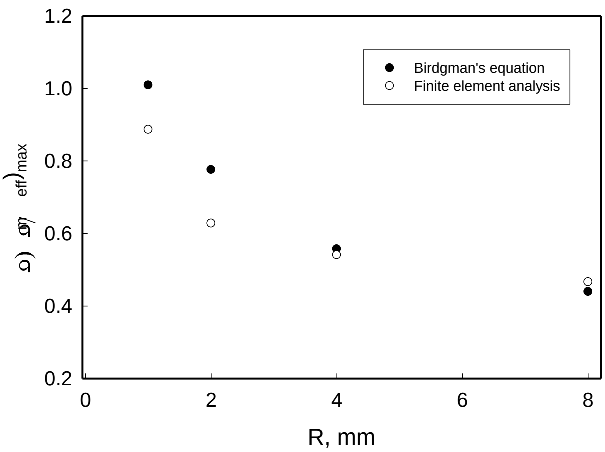


Fig. 5 Variation of the maximum stress triaxiality with notch radii.

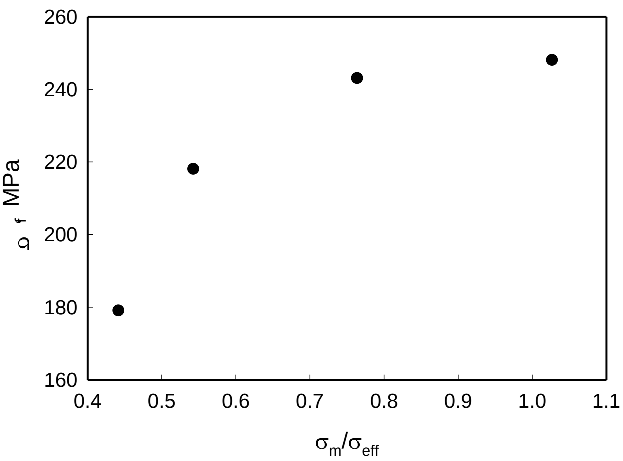
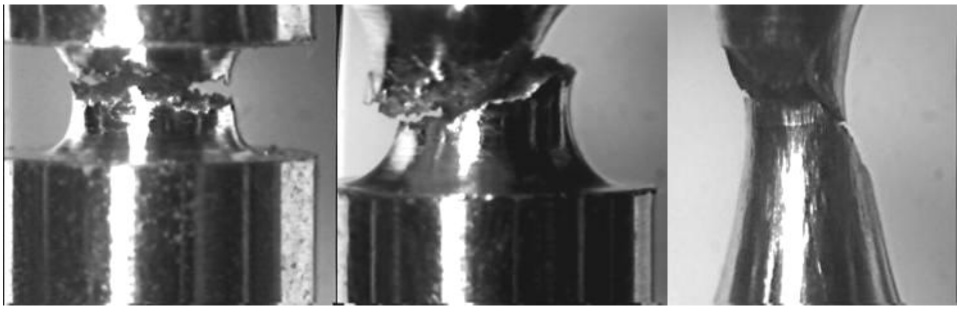


Fig. 6 Variation of failure stress with stress triaxiality.

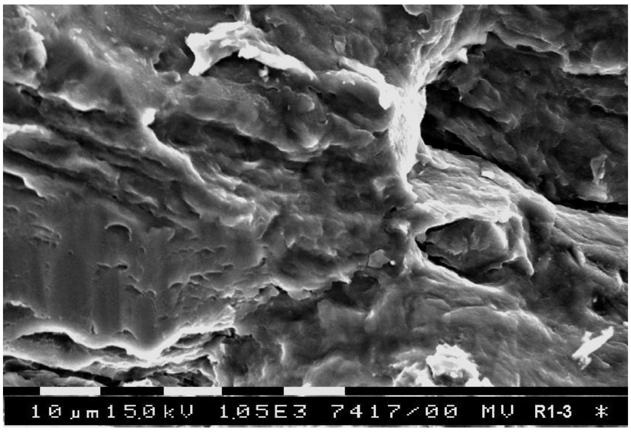
Failure Mechanisms. To gain a better understanding of the fracture mechanisms, the failure process was monitored using a CCD camera connected with a video recorder and the fracture surfaces were examined using SEM. Fig. 7 shows the side views of the notched specimens after the failure.



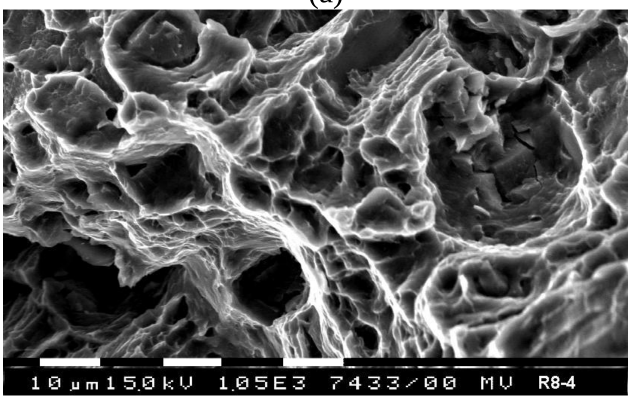
(a) (b) (c)

Fig. 7 Side views of the notched specimen after failure: (a) R=1 mm, (b) R=2 mm, and (c) R=8 mm.

As shown in Fig. 7(a), the upper and lower fracture surfaces of the specimen with R=1mm are perpendicular to the loading direction (specimen axis), indicating the predominant effect of normal stress in the failure. Therefore, brittle fracture is expected in this specimen. Conversely, the fracture surfaces of other specimens, especially those with R=8 mm are tilted to the loading axis due to the effect of shear stress, shown in Fig. 7 (b)~(c).



(a)



(b)

Fig. 8 Typical fracture surfaces of the notched specimens: (a) R=1 mm, and (b) R=8 mm.

The typical fracture surfaces are shown in Fig. 8. For the samples with notch profile radius of 1 mm, the fracture surfaces are typically quasi cleavage, evidenced by the presence of many cleavage facets, Fig. 8 (a). In contrast, the fracture surfaces of the specimens with large notch profile radii (4 and 8 mm) are characterized by ductile fracture. The size and amount of the dimples increase when the notch radius increases from 2 to 8 mm. Therefore, there is an apparent transition from ductile tearing to cleavage with increasing level of constraint. Thus, deformation and failure of magnesium alloy are sensitive to the constraint level.

Summary

Tensile tests on circumferentially notched specimens show that deformation and failure of AM60 magnesium alloy are very sensitive to constraint (stress triaxiality) level. Higher break strength is associated with specimens with higher stress triaxiality. The fracture mechanisms change from typical ductile tearing to quasi cleavage with increasing stress triaxiality. Therefore, apparent embrittlement takes place in this alloy under high constraint conditions.

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