Microstructure and damage evolution during tensile loading in a wrought magnesium alloy

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Damage evolution in a wrought magnesium alloy under uniaxial tensile deformation is investigated. Sectioned specimens subjected to interrupted tensile deformation were examined under optical microscopy to quantify the number density of cracked intermetallic particles as a function of applied strain. Digital image analysis of the optical images was employed to quantify damage by separating cracked from non-cracked particles. Finally, an internal state variable damage model was shown to adequately capture the experimentally observed damage progression due to the intermetallics.

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Magnesium alloys are attracting increasing interest from researchers and industry: their attractive mechanical properties (strength-to-weight ratio) offer the possibility of reducing the weight of components. In addition, the automotive industry has focused on magnesium alloys as a means for reducing cost [1]. Essentially, magnesium alloys may be suitable replacements for aluminum alloys [2], steel alloys [2] and plastics [1].

Despite the fact that magnesium alloys have been incorporated into a wide range of industrial components, their mechanical behavior is still not well known. Some studies [2–8] have reported the tensile and compression properties and the microstructure changes under various temperature conditions. In magnesium alloys, twinning plays a primary role in damage during plastic deformation, and several studies on this subject are available in the literature (e.g. [3,4,9,10]). However, relatively few studies have concentrated on the role of second phases and intermetallics during damage evolution of magnesium alloys. Although there has been some research interest in the mechanical properties of magnesium, damage models that incorporate the microstructure as related to crack initiation sites are rare. Currently, however, it is not known whether or not cracking activity influences the damage process in magnesium alloys.

The objective of this research is to evaluate the microstructural damage evolution for an AZ61 magnesium alloy. A stereological analysis of the alloy microstructure was conducted using interrupted uniaxial tensile tests to determine the evolution of damage via microstructural analysis and statistics. An understanding of the sources of damage in the AZ61 magnesium alloy in this study may provide insight into the plasticity and fracture of other magnesium alloys as well.

The failure process in ductile materials is associated with local failure of second-phase particles, e.g. inclusions, intermetallic particles and precipitates [11]. In aluminum alloys, damage is produced by cracking of intermetallic inclusions/particles, growth of voids at cracked particles, and void coalescence [12]. However, magnesium alloys undergo moderate amounts of plastic deformation at room temperature [9] and show limited ductility [3]. Additionally, slip dislocation and twinning have been identified as the main sources of plastic deformation in magnesium alloys [5,9,13,24–27]. Nonetheless, intermetallics and second phases have been observed in the magnesium alloys [2,5,14–19].

Damage evolution can be divided into three components: (i) void nucleation, (ii) void growth and (iii) void coalescence [20]. Horstemeyer et al. [21] demonstrated that these components develop simultaneously under deformation, and developed a damage evolution model...
that uses finite-element codes to describe void nucleation, growth and coalescence. Using this model, they showed that void nucleation is highly influenced by the stress state of the material.

Damage evolution can be quantified by measuring the evolution of microstructural features with metrics such as the number density, number fraction and volume fraction [21,22]. Horstemeyer and Gokhale [22] proposed a model capable of capturing damage nucleation in ductile materials associated with inclusions or second-phase particles. The void nucleation parameters in this model are two primary microstructural quantities: the length scale parameter, $d$, which often represents the particle size, and the particle volume fraction, $f$. Horstemeyer and Gokhale developed the following equation for the number of voids per area:

$$
\eta = C_{\text{coeff}} \exp \left( \frac{\varepsilon(t) d^2}{K_e f^3} \right) \left[ a \left( \frac{4}{27} - \frac{J_2^2}{J_2^3} \right) + b \frac{J_2}{J_2^3} + c \frac{J_1}{\sqrt{J_2}} \right],
$$

(1)

where $C_{\text{coeff}}$, $a$, $b$ and $c$ are material constants determined of tension, compression and torsion tests. Further details of this damage model can be found in Ref. [22].

The AZ61 magnesium alloy in this study was provided in the form of an extrusion approximately 3.17 mm thick. Flat tensile specimens produced to ASTM standard were prepared with a 50 mm gage length, 12.7 mm width and 3.17 mm thickness. A program of interrupted tensile tests was conducted at 1%, 2%, 4%, 6% and 8% strain. The tests were conducted using an Instron electromechanical load frame under strain control at a strain rate of 0.001 s$^{-1}$. An extensometer was used to measure and control strain. At each interrupted strain, the specimens were removed and sectioned for metallographic analysis.

Figure 1 shows the L–S planes that were cut from the gage section for metallographic analysis. The metallographic specimens contained a vertical plane parallel to the applied load direction (extruded direction). The L–S planes provided a clear picture of cracked particles, while the planes perpendicular to the applied loading did not show these features very readily.

The metallographic sample was polished to obtain a highly reflective surface with no scratches. The samples were then examined in an Axiovert Zeiss optical microscope with magnification of 500× in the unetched condition. Manual methods for identification of features are tedious, susceptible to error and time consuming. Hence, automating microstructural feature characterization via digital image analysis is essential for quantifying the evolution of the microstructure. Digital image processing was used to measure the evolution of features within the microstructure images as a function of deformation. A program was developed to perform the digital image analysis using the Image Processing Toolkit in MATLAB. The code performed the following principal tasks: (i) segmenting all particles based on a threshold parameter, (ii) distinguishing the light-colored particles from the dark particles, (iii) separating the cracked gray particles from the non-cracked gray particles, and (iv) computing the microstructure statistics. An associated stress–strain curve for the AZ61 magnesium alloy is shown in Figure 1 with the strain levels designated based on the optical imaging.

Various types of particles were observed in the metallographic study. Figure 2 shows the intermetallics that exist in the alloy in an image taken with a magnification of 1000× at 8% strain. Three particle shapes were distinguishable: round particles (Fig. 2A), irregular and slender (Fig. 2B and C), and small dark particles (Fig. 2D). Cracks were observed in all the particles except in dark particles.

The microscope used in this study was equipped with an automatic stage capable of creating montages of many adjacent fields. Since the distribution of intermetallic particles is non-uniform and the particle volume fraction is low in this alloy, a reasonable sample size must be taken. Therefore, montages composed of 25 adjacent fields arranged in a $5 \times 5$ grid were captured. In addition, several samples at each strain level were taken to increase the reliability of our analysis.

The evolution of microstructure in a material can be described in terms of quantitative stereological parameters. For instance, the area fraction ($A_A$) and the number of cracked particles (number density) were measured and their evolution is shown in Figure 3. The number density is defined as the number of cracked particles divided by the total area of the field observed. The number density was determined based only on the gray-colored particles, since cracks in dark particles were difficult to observe using optical images. Figure 3 shows the evolution of area fraction, and number density, and its corresponding standard deviation, as a function of strain.

Hort et al. [14] have investigated the intermetallics that exist in magnesium alloys. They found that intermetallics and inclusions can adopt shapes such as blocky, rosette-like, Chinese script, lamellar and needle-like, among others. These types of particles have also been identified by other researchers [2,5,14–19]. Some of these shapes are shown in Figure 2.
In the AZ alloys these intermetallics are based on Mg\textsubscript{17}Al\textsubscript{12}, MnAl, MnAl\textsubscript{14} and MnA\textsubscript{16} compounds [15]. Tartaglia and Grebetz [16] in their studies of intermetallics and inclusions in magnesium alloys found three types of particles: oxide/intermetallics, Mn–Al and Mg–Al phases. The oxide/intermetallics that they found had diverse morphologies ranging from small particles to larger complex shapes. These oxide/intermetallics are typically dark colored.

Regarding the color and shape of particles observed in Figure 2, three types of intermetallics can be distinguished in the AZ61 alloy: oxide/intermetallics (Fig. 2D), Mn–Al and Mg–Al phases (Fig. 2A–C). Energy-dispersive X-ray spectroscopy analysis was conducted to determine the composition of these particles. This analysis showed that the gray-colored particles were based on Mn–Al and Mg–Al phases, and the dark particles were oxide/intermetallics. Since the interest here was on stereological parameters, we deemed it sufficient to quantify the distinguishable cracked particles. Therefore, the particles were classified into two groups (gray-colored and dark particles), and the gray-colored particles were used to quantify cracking as a function of strain while the dark particles were neglected. The area fraction of dark particles was found to be 0.038%.

Figure 4 shows the number of cracked particles per volume vs. applied tensile strain. Damage in this type of alloy is due mainly to slip and twinning occurring in the matrix magnesium adjacent to the particles. However, Figure 4 shows a strong correlation between progression of cracking particles and damage. The constants used in the void nucleation model (Eq. (1)) are the following: \( a = 0 \), \( b = 55,000 \), \( c = 50,000 \), \( C_{\text{coeff}} = 1.9 \), \( f = 0.004 \), \( d = 2.4 \, \mu m \), and \( K_{IC} = 20 \, MPa \, m^{1/2} \). The constants \( C_{\text{coeff}}, a, b \) and \( c \) were determined from the interrupted tension tests using a best correlation method. A good correlation between the predicted nucleation model and experimental results was observed. The nucleation model predicts an exponential increase in the number density with increasing strain. For tensile loading, the number density estimated with a 2-D technique is approximately equal to the number using a 3-D methodology [23].

In summary, the damage evolution of an AZ61 magnesium alloy under uniaxial tension has been investigated. Using stereological methods and digital image analysis, a quantitative microstructural analysis was conducted. With respect to the microstructural proper-

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**Figure 2.** Particles observed in an AZ61 magnesium alloy. Note the cracks are generally orthogonal to the extrusion (uniaxial straining) direction. Note also that the particles are typically less than 10 \( \mu m \).

**Figure 3.** Area fraction and number density of AZ61 magnesium alloy fractured intermetallic particles as a function of strain.

**Figure 4.** Number density vs. strain of an AZ61 magnesium alloy showing a comparison of the Horstemeyer–Gokhale [22] void nucleation model with experimental data.
ties, the following can be concluded: (1) under uniaxial tension the area fraction of cracked particles composed of Mn–Al and Mg–Al varies in an exponential pattern as a function of strain; (2) the number density (mm$^{-2}$) of cracks follows a shallow nonlinear pattern; (3) three types of particles were identified—oxide/intermetallics, Mn–Al and Mg–Al-based particles. In addition, the damage nucleation model of Horstemeyer and Gokhale [22] was in good agreement with the observed damage progression of the AZ61 magnesium alloy.

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