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MICROSTRUCTURAL RELATIONSHIP IN THE DAMAGE EVOLUTION PROCESS OF AN AZ61 MAGNESIUM ALLOY

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Abstract

The damage evolution process of magnesium AZ61 alloy under monotonic tensile loading conditions is investigated. Specimens that have been subjected to interrupted tensile loading 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 automatically quantify damage by separating cracked from non-cracked particles. Lastly, an internal state variable damage model was shown to adequately capture the experimentally-observed damage of intermetallic particles in the magnesium AZ61 alloy.

Introduction

A marked interest has been placed on magnesium alloys in recent years by both researchers and industry because of the attractive mechanical properties that these alloys have regarding design applications. The automotive industry sees magnesium alloys as a solution for reducing weight and cost [1]. Magnesium alloys are candidates to replace aluminum and steel alloys [2], and plastics also [1].

Despite that magnesium alloys have been incorporated in various industrial components, their mechanical behavior is still not well known. A complete characterization of magnesium alloys is available for only a few alloys. Some studies [2-8] have reported the tensile and compression properties and the microstructure changes under various temperature conditions for magnesium alloys. AZ31 alloy is a commercial alloy that has been investigated more frequently than other magnesium alloys. Although much interest in mechanical properties of magnesium alloys has been shown by researchers, damage models that incorporate the microstructure deterioration are scarce.

In magnesium alloys, twinning plays a primarily role in damage during plastic deformation, and numerous studies are found in the literature [3-4, 9-10]. However, studies regarding the role of second phases and intermetallics on damage evolution of magnesium alloys are lacking. As in other types of metals, cracking and/or debonding of particles could play a significant role in damage evolution in magnesium alloys. Currently it is not known how the cracking activity influences the damage process in these alloys. An understanding of the sources of damage in this alloy will provide insight on the plasticity and fracture in the AZ61 magnesium alloy.

The objective of this paper is to evaluate the microstructural damage evolution for the AZ61 magnesium alloy. A stereological analysis of the material microstructure was conducted on interrupted monotonic tensile loading tests to determine the damage evolution via microstructural statistics.

Damage of Magnesium Alloy

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 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]. Nonetheless, intermetallics and second phases have been observed in the magnesium alloys [2, 5, 14-19].

Damage evolution process leading to fracture is typically divided into three stages: void nucleation, growth, and coalescence [20]. Horstemeyer et al. [21] showed that these components develop simultaneously and have developed a model for damage evolution that includes void nucleation, growth, and coalescence implemented within the finite element method. Using this model, they showed that void nucleation is highly influenced by the stress state of the material. The model framework is represented in Figure 1 by a fictitious material with increasing nucleation density and void growth as a function of increasing strain over domain R.

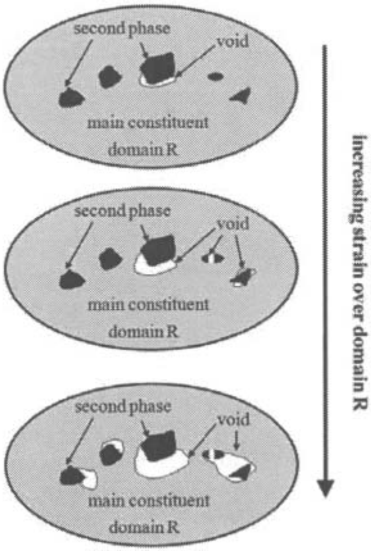

Figure 1. Conceptual Framework showing a fictitious material with increasing nucleation density and void growth.

Damage evolution can be quantified by measuring the evolution of microstructural features with metrics such as the number density, number fraction, and volume fraction [1-2]. Horstemeyer and Gokhale [22] proposed a model capable of capturing damage in ductile materials. This model was defined in terms of void nucleation and void growth. The void nucleation parameters in this model are length scale *d*, and particle volume fraction, *f*. They developed the following equation for the number voids per area.

$$\eta(t) = C \cdot \exp\left(\frac{\varepsilon(t) d^{1/2}}{K_{IC} f^{1/3}} \left\{ a\left[\frac{4}{27} - \frac{J_3^2}{J_2^3} \right] + b\frac{J_3}{J_2^{3/2}} + c\left| \frac{I_1}{\sqrt{J_2}} \right| \right\} \right) \tag{1}$$

where *C*, *a*, *b* and *c* are material constants determined of tension, compression and torsion tests. Further details of this damage model can be found in [22].

Test and Procedures

The material employed in this research was an extruded AZ61 magnesium alloy. The material was provided in the form of an automotive crash rail profile with a thickness of approximately 3 mm.

Tension Test

A flat tensile specimen in conformity with ASTM standard E8 was prepared with a 50.8 mm gage length, 12.7 mm width, and 3mm in thickness. A program of interrupted tensile tests was conducted at strain levels of 1, 2, 4, 6, and 8 percent. The tests were conducted using an INSTRON electromechanical load frame under strain control at a strain rate of 0.001/s at ambient temperature and relative humidity. An extensometer was used to measure and control strain. At each interrupted strain level, the specimens were removed and sectioned for metallographic analysis.

Metallographic Analysis

Figure 2 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 loading direction (extruded direction). The (L-S) planes provide a clear picture of cracked particles, while the planes perpendicular to the applied loading do not show these features very readily [23].

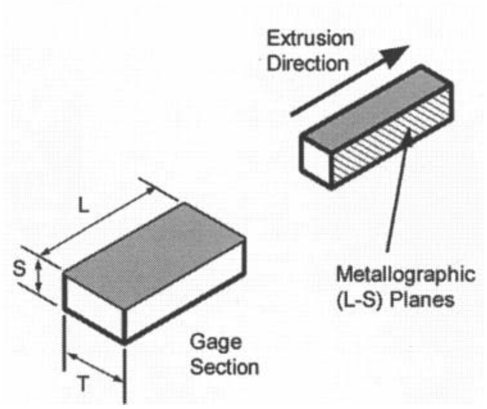

Figure 2. Location of the metallographic samples.

The metallographic samples were polished to obtain a highly reflective surface with no scratches. Further information on preparing magnesium specimens can be found in [24]. The samples were then imaged in an Axiovert Zeiss optical microscope with magnification of 500X in the unetched condition. Manual methods for identification are tedious, susceptible to error, and time-consuming. Hence, automating microstructural feature characterization via digital image analysis is essential for quantifying the evolution of 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 main tasks: a) segmented all particles based on a threshold parameter, b) distinguished the light-colored particles from the dark particles, c) separated the cracked gray particles from the non-cracked gray particles, and d) computed the microstructure statistics.

Results

Tension Tests

A typical true stress-true strain curve for magnesium alloy AZ61 is shown in Figure 3. The following average mechanical properties were determined from the tensile tests: yield strength= 177 MPa; ultimate tensile strength= 285 MPa; elongation at failure =10%.

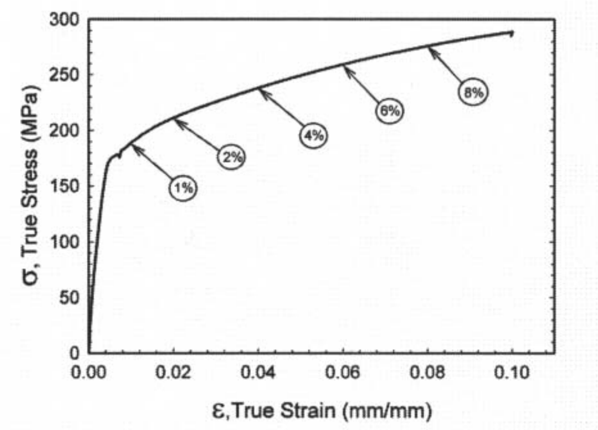

Figure 3. True stress-true strain curve for magnesium alloy AZ61.

Microstructure of AZ61

Various types of particles were observed in the metallographic study. Figure 3 shows the intermetallics that subsist in the alloy in an image taken with a 1000X of magnification at 8% of strain. Three shapes of particles are distinguished, round particles (A), slender particles (B), irregular particles (C), and small dark particles (D). Cracks were observed in all the particles except in dark particles.

Stereology Results

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 no 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 x 5 grid were defined. In addition, we observed several samples at each strain level to increase the reliability of our analysis. Using the equation developed by DeHoff [25] and setting (the relative accuracy) %RA to 10%, it was determined that three samples were required for a statistically accurate analysis. However, in this metallographic analysis five samples were analyzed.

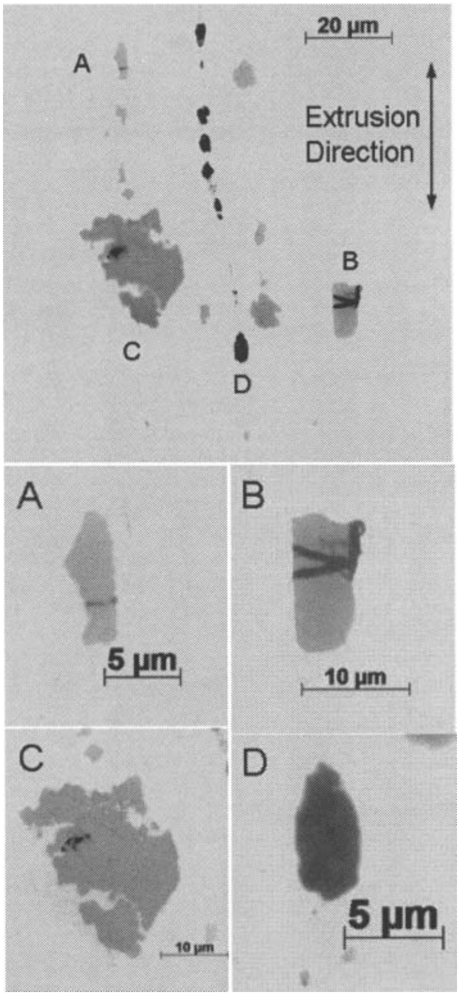

Figure 4. Particles observed at 1000X in an AZ61 magnesium alloy.

The evolution of microstructure in a material can be described by the stereological parameters. For instance; the area fraction and the number of cracked particles (number density) were measured and their evolution is shown in Figures 5 and 6. 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 on the gray-colored particles only, since cracks in dark particles were difficult to observe using optical images. Figures 5 and 6 show the evolution of number density and number fraction, respectively, and their corresponding standard deviation as a function of strain.

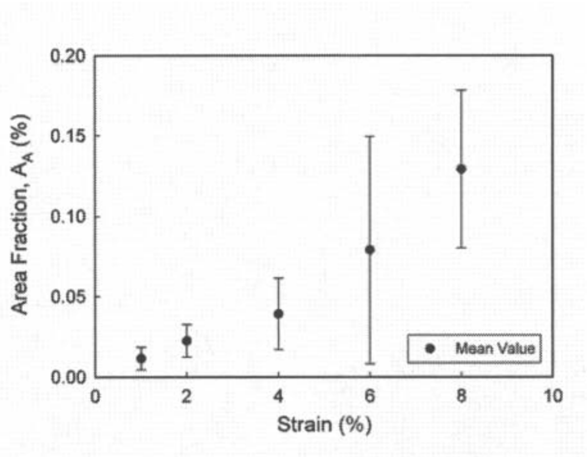

Figure 5. Area fraction for AZ61 magnesium alloy.

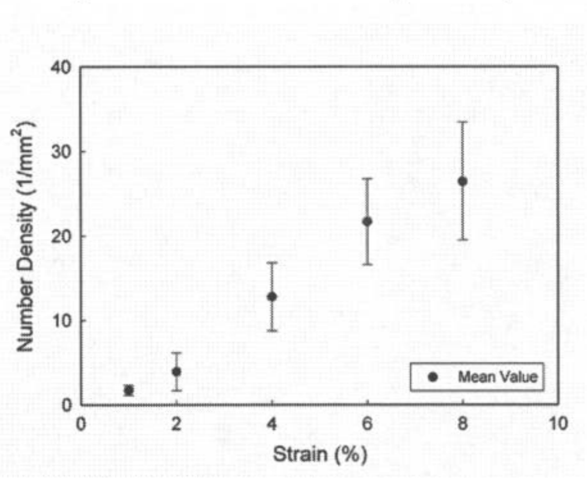

Figure 6. Number density for AZ61 magnesium alloy.

Discussion

Intermetallics in the AZ61 Magnesium Alloy

Hort et al. [14] have investigated the intermetallics that exist in magnesium alloys. They found that intermetallics and inclusions can adopt shapes like blocky, rosette-like, Chinese script, lamellar and needle-like among others. Other researchers have also identified these types of particles [2, 5, 14-19]. Some of these shapes were observed in this alloy, as shown in Figure 4.

In the AZ series alloys, these intermetallics are based on $Mg_{17}Al_{12}$, MnAl, $MnAl_{14}$, and $MnAl_{16}$ compounds [15]. Tartaglia and Grebetz [16] in their studies of intermetallic and inclusions in magnesium alloys found three types of particles. They found oxide/intermetallic, and Mn-Al, and Mg-Al phases. The oxide/intermetallic that they found had diverse morphologies ranging from small particles to a larger complex shapes. These oxide/intermetallics are dark colored.

Regarding the color and shape of particles observed in Figure 4, three type of intermetallics can be distinguished in the AZ61 alloy: oxide/intermetallic (D), Mn-Al, and Mg-Al phases (A, B, and C). Chemical 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 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. In addition, the area fraction of dark particles was found to be 0.038 %.

Damage Evolution

Figure 7 shows the number of cracked particles per volume against applied tensile strain. Damage in this type of alloy is due mainly to slip and twinning as mentioned previously. However, Figure 7 shows a strong correlation between progression of cracking particles and damage. The constants used in the void nucleation model (Equation 1) are: $a=0$, $b=55000$, $c=50000$, $C=1.9$, f=0.004, d=2.4 µm, and K_{IC}=20 MPa·m$^{1/2}$. Constants C, a, b, and c were determined from the interrupted tension tests using a best fit 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 2D technique is approximately equal to the number using a 3D methodology [26].

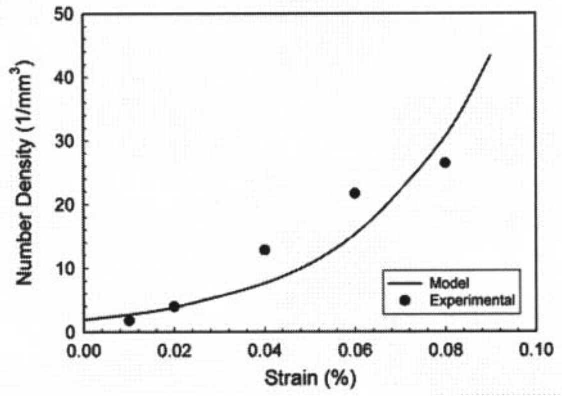

Figure 7. Number density against strain in AZ61 magnesium alloy.

Conclusions

The damage evolution process of magnesium AZ61 alloy under monotonic tensile loading conditions has been investigated. Using stereological methods and digital image analysis, a quantitative microstructural analysis was conducted. With regards to the microstructural properties relating to damage, the following conclusions can be made:

a) Under tensile loading conditions the area fraction of cracked particles composed of (Mn-Al) and (Mg-Al) varies in an exponential pattern as function of strain.
b) The number density (1/mm^2) of cracked particle follows a near linear pattern.
c) Three types of particles were identified: Oxide/intermetallic and Mn-Al, and Mg-Al phases.
d) Cracks were seen on the (Mn-Al) and (Mg-Al) particles.
e) The evolution of damage was modeled using the Horstemeyer and Gokhale nucleation model and good agreement were seen between experimental results and the model.

References

[1] T. Ruden, “Replacing Plastics with Magnesium for Structural Automotive Components”, Light Metals Age, pp. 36-41, April 2005.

[2] S. Müeller, K. Müeller, H. Tao, and W. Reimers, “Microstructure and Mechanical Properties of the Extruded Mg-Alloys AZ31, AZ61, AZ80”, International Journal of Materials Research, Volume 97, Issue 10, pp. 1384-1391, 2006.

[3] Y. Lu, M. Gharghouri, and F. Taheri, “Effect of Texture on Acoustic Emission Produced by Slip and Twinning in AZ31B Magnesium Alloy-Part I: Experimental”, Nondestructive Testing and Evaluation, Volume 23, No. 2, pp. 141-161, June 2008.

[4] Y. Lu, M. Gharghouri, and F. Taheri, “Effect of Texture on Acoustic Emission Produced by Slip and Twinning in AZ31B Magnesium Alloy-Part II: Clustering and Neural Network Analysis”, Nondestructive Testing and Evaluation, Volume 23, No. 3, pp. 211-228, September 2008.

[5] A. N. Chamos, Sp. G. Pantelakis, G.N. Haidemenopolud, and Kamoutsi, “Tensile and Fatigue Behaviour of Wrought Magnesium alloys AZ31 and AZ61”, *Fatigue and Fracture of Engineering Materials and Structures*, Volume 31, pp. 812-821, 2008.

[6] T. Sasaki, H. Somekawa, A. Takara, Y. Nishikawa, and K. Higashi, “Influence of Second Phase Particles on Fracture Toughness in AZ31 Magnesium Alloys”, Key Engineering Materials, Volume 261-263-, pp. 369-374, 2004.

[7] H. T. Zhou, X. Q. Zeng, L. L. Liu, J. Dong, Q. D. Wang, W. J. Ding, and Y. P. Zhu, “Microstructural Evolution of AZ61 Magnesium Alloy During Hot Deformation”, *Materials Science and Technology, Institute of Materials, Minerals and Mining*, Volume 20, pp. 1397-1402, 2004.

[8] H. Yang, S. Yin, C. Huang, Z. Zhang, S. Wu, and S. Li, “EBSD Study on Deformation Twining in AZ31 Magnesium Alloy During Quasi-in-Situ Compression”, *Advanced Engineering materials*, Volume 10, No. 10, pp. 955-960.

[9] M. R. Barnett, “Twinning and the Ductility of Magnesium Alloys Part I: Tension Twins”, *Materials Science and Engineering A*, Volume 464, pp. 1-7, 2007.

[10] M. R. Barnett, “Twinning and the Ductility of Magnesium Alloys Part II: Contraction Twins”, *Materials Science and Engineering A*, Volume 464, pp. 8-16, 2007.

[11] Y. Yeh, and W. Liu, “The Cracking Mechanism of Silicon Particles in an A537 Aluminum Alloy”, *Metallurgical and*

Materials Transactions A, Volume 27A, Issue 11, pp. 3558-3568, 1996.

[12] A. Balasundaram, A. M. Gokhale, S. Graham, and M. F. Horstemeyer, "Three-dimensional Particle Cracking Damage Development in an Al-Mg-base Wrought Alloy", *Materials Science and Engineering A*, Volume 355, pp. 368-383, 2003J.

[13] I. J. Beyerlein, L. Capolungo, P. E. Marshall, R. J. McCabe, and C. N. Tome, "Statistical Analyses of Deformation Twinning in Magnesium", *Philosophical Magazine*, Volume 90, No. 16, pp. 2161-2190, 2010.

[14] N. Hort, Y. Huang, and K. U. Kainer, "Intermetallics in Magnesium Alloys", *Advanced Engineering Materials*, Volume 8, No. 4, 2006.

[15] ASM Speciality Hand book, "Magnesium and Magnesium Alloys", The Materials Information Society, 1999.

[16] J. M. Tartaglia, and J. C. Grebetz "Observations of Intermetallic Particle and Inclusion Distributions in Magnesium Alloys", *Magnesium Technology 2000, The Minerals, Metals and Materials Science Society*, pp 113-121, 2000.

[17] M. Marya, L. G. Hector, R. Verma, and W. Tong, "Microstructural Effects of AZ31 Magnesium Alloy on its Tensile Deformation and Failure Behaviors", *Materials Science and Engineering A*, Volume 418, pp. 341-356, 2006.

[18] R. Zeng, E. Han, W. Ke, W. Dietzel, K. U. Kainer, and A. Atrens, "Influence of the Microstructure on Tensile Properties and Fatigue Crack Growth in Extruded Magnesium Alloy AM60", *International Journal of Fatigue*, Volume 32, pp. 411-419, 2010.

[19] A. Srinivasan, J. Swaminathan, M. K. Gunjan, U. T. S. Pillai, and B. C. Pai, "Effect of Intermetallic Phases on the Creep Behavior of AZ61 Magnesium Alloy", *Materials Science and Engineering A*, Volume 527, pp. 1395-1403, 2010.

[20] W. M. Garrison and N. R. Moody, "Ductile Fracture", *The Journal of Physics and Chemistry of Solids*, Volume 48, No. 11, pp. 1035-1074, 1987.

[21] M. F. Horstemeyer, J. Lathrop, A.M. Gokhale, M. Dighe, "Modeling Stress State Dependent Damage Evolution in a Cast Al-Si-Mg Aluminum Alloy", *Theoretical and Applied Fracture Mechanics*, Volume 33, pp. 31-47, 2000.

[22] M. F. Horstemeyer, and A. M. Gokhale, "A Void-crack Nucleation Model for Ductile Metals", *International Journal of Solids and Structures*, Volume 36, pp. 5029-5055, 1999.

[23] J. Harris, "Particle Cracking Damage Evolution in 7075 Wrought Aluminum Alloy under Monotonic and Cyclic Loading Conditions", Master Thesis, Georgia Institute of Technology, 2005.

[24] G. V. Voort, "Using Microstructural Analaysis to Solve Practical problems", Tech-Notes, Published by Buehler, Volume 4, Issue 2.

[25] ASM International, Practical Guide to Image Analysis, 2000.

[26] H. Agarwal, A. M. Gokhale, M.F. Horstemeyer, and S. Graham, "Quantitative Characterization of Three-dimensional Damage as a Function of Compressive Strains in Al 6061", *Proceedings of the TMS Annual meeting, Aluminum Automotive and Joining Symposia*, Aluminum 2001, pp. 43-50, 2001.