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Effects of void fraction on void growth and linkage in commercially pure magnesium

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ABSTRACT

Void growth and linkage in magnesium is strongly influenced by the local microstructure. An innovative approach is used which allows for a quantitative analysis of the microstructural features that play a significant role in the deformation and fracture processes. Several hole configurations were investigated in order to determine the effects of void fraction on the growth and linkage processes. The samples were pulled in uniaxial tension under both an optical microscope and SEM. The digital image correlation method was used to obtain strain distributions. Furthermore, the experimental results were compared to crystal plasticity finite element simulations in order to determine the role of the various deformation mechanisms on the fracture behavior. It was established that the void fraction did not have a significant impact on the growth and linkage behavior of the holes. Interactions between the holes and the microstructure were observed for all of the configurations analyzed. The strain distributions revealed that twin and grain boundaries produce strain concentrations an order of magnitude larger than the macroscopic strain. Furthermore, the results show that there is likely a critical strain required to initiate fracture in these boundaries.

1. Introduction

Magnesium and its alloys have attracted significant research interest due to their low density and high strength to weight ratio, characteristics which make them candidate materials for lightweight structural applications, particularly in the automotive, aerospace and defense industries. However, the hexagonal closed packed (hcp) crystal structure of Mg introduces significant challenges during metal forming operations. At ambient temperatures there are limited slip systems available and as a result, most magnesium alloys fracture during the forming of complex components. The challenge is to produce magnesium alloys with acceptable strength and formability while developing an economically feasible processing route. The yielding and deformation behavior of magnesium and its alloys is well documented in the literature. However, research focused on the damage and fracture is sparse [1,2].

Ductile fracture occurs by the continuous and overlapping processes of the nucleation, growth and linkage of microvoids. Void nucleation in metallic alloys is typically associated with second phase particles and inclusions [3,4]. However, it has been reported that void nucleation in magnesium alloys is not always associated with particles [5,6]. Microstructural heterogeneities such as grain boundaries [7,8] and twin boundaries [9,10] can serve as nucleation sites in the absence of particle associated damage nucleation [11]. In either case, void nucleation is a stochastic process and typically occurs within the bulk of the material. Therefore, the nucleation process makes it difficult to study ductile fracture in a controllable and non-destructive manner.

Early studies of ductile fracture examined void growth using standard metallographic techniques [12,13]. The experiments allow for a qualitative assessment on the effect of plastic strain and stress state on void growth. However, these techniques are destructive and do not provide information on the growth history of a given void. Weck et al. [14] developed model materials in order to eliminate the stochastic nature of void nucleation and study the growth and linkage of voids on the microstructural scale in a non-destructive manner. Femtosecond laser technology was used to precisely position holes in the gage section of tensile samples. Commercial materials contain voids which are randomly distributed at various separation distances (void fractions) and orientations with respect to one another. These experiments allowed for

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the effects of void fraction and orientation on growth and coalescence to be investigated in a controllable manner. 2D model materials were tailored with void configurations oriented perpendicular to the tensile axis having various void separations. Given the scope of this paper, only the effects of void fraction will be discussed. The experiments were carried out on aluminum and copper, both face-centred cubic (fcc) crystal structures, in which void growth occurs by dislocation slip. A clear trend was observed between the void separation distance (void fraction) and the growth behavior. When voids are more widely separated (i.e. smaller void fractions) more deformation is required before the voids begin to interact with one another [15]. Hosokawa et al. [16] showed that the void growth model proposed by Rice and Tracey [17] provides a good prediction of the void growth behavior in copper during the early stages of deformation, before void interactions occur. However, once the voids begin to interact with one another, void growth is amplified and the Rice and Tracey analysis no longer holds since it does not account for void interactions. Since the pioneering work of Koplik and Needleman [18] more recent void growth modeling studies have used the finite element method to predict the growth behavior in materials which exhibit homogeneous deformation [19–21].

Voids grow in a plastically deforming matrix until they link with one another leading to final fracture. Void linkage is the most important process in ductile fracture as it determines the ductility of a material. However, it is the least understood due to its stochastic nature and the difficulty of observing the process experimentally. When voids are aligned roughly perpendicular to the tensile axis, void linkage generally occurs by the internal necking mechanism. Puttick [12] used a sectioning method to observe the internal necking mechanism in high purity copper. In this case, the voids nucleate and begin to grow in the tensile direction. The lateral dimension initially contracts until a critical point in the deformation is attained whereby lateral expansion of the voids ensues. Hosokawa et al. [16] defined this point as the onset of coalescence. With subsequent deformation, adjacent voids grow towards one another in the lateral direction until the ligament between them necks down to a point. This has been established to occur at low stress triaxiality [22]. In a classical study on ductile damage, Le Roy et al. [23] investigated the effects of the volume fraction of second phase particles on the macroscopic failure strain in spheroidized carbon-steels. They demonstrated that the failure strain decreases with increasing volume fraction of second phase particles. Assuming that voids initiate at second phase particles this work was analogous to analyzing the effects of void fraction on the failure strain. This result was confirmed by Weck and Wilkinson [15] in work dealing with 2D model materials, i.e. with holes drilled through the sheet prior to testing. The results showed that as the void separation distance increased (void fraction decreased) the local tensile strain at failure increased.

In a previous paper [24] we established that the local microstructure has a significant impact on the growth and linkage of voids in magnesium. Interactions between the pre-drilled holes and microstructural features such as twin and grain boundaries were observed. These interactions create a heterogeneous deformation field in which classical isotropic continuum approaches cannot predict. The results pose the question as to the extent that these features contribute to the fracture process. It can be speculated that if two voids are adjacent to one another (i.e. their centre to centre separation distance is comparable to their diameter) the interaction between the voids would be stronger than their interaction with the local microstructure. However, if the voids are spaced further apart the microstructure would play a stronger role in the fracture process. Therefore, the purpose of this work is twofold; to determine the effects of void fraction on the processes of void growth and linkage in commercially pure magnesium and to understand what type of approach can be used to model this behavior.

2. Experimental methods

The material examined in this work is hot rolled commercially pure magnesium with an initial thickness of approximately 0.12 mm. Two different experimental approaches have been used to study deformation and fracture in magnesium model materials [24]. Both consist of in-situ tensile testing, in one case during scanning electron microscopy, in the other case under an optical microscope. The advantage to electron microscopy is that it permits high resolution imaging. This is particularly useful for the precise detection of the void edges; therefore, this approach has been used to obtain geometrical information associated with the holes. The latter approach was adopted because the digital image correlation method is used for strain mapping during these experiments and optical microscopy produces better contrast for strain calculations. One advantage to this method is that it allows for quantitative information to be obtained on the entire surface of the sample. In both cases the sheet was cut into tensile samples containing a reduced gage section with a length of 2 mm and width of 1 mm. The samples were polished with 0.05 μm colloidal silica to produce a smooth surface for characterization and laser machining. On average, the sample thickness was about 100 μm after polishing.

2.1. In-situ tensile testing under SEM

The as-received material was annealed at 250 °C for 1 h with a ceramic block placed on top to flatten the sheet prior to laser drilling. A row of holes was machined into the gage section of the tensile samples using a Ti:sapphire laser system. The holes have a diameter of approximately 12 μm and are aligned perpendicular to the tensile axis. The separation distance λ is related to the local void fraction f, by:

$$f = \frac{2r}{\lambda}$$

where r is the average radius of the holes. Various void separation distances were used to determine the effects of void fraction on the void dimensions at failure. A circular notch was also machined into the sample, with a radius of 0.125 mm, to ensure that fracture occurred within this region. The samples were annealed at 450 °C for 1 h to remove the heat affected zone produced by laser machining. The average grain size, measured using electron backscattered diffraction (EBSD) patterning, was 51 ± 6 μm with a standard deviation of 28 μm. For further details on these samples refer to [24]. Tensile testing was carried out inside the chamber of an Electroscan 2020 environmental SEM (ESEM) at a constant crosshead speed of 10 μm/s. The test was stopped in increments of deformation to acquire images. Geometric parameters associated with the holes, were measured using Image J software [25] to quantify the hole dimensions at failure.

2.2. In-situ tensile testing with optical microscopy using digital image correlation (DIC) strain mapping

A Marciniak notch was machined into these samples to avoid the effect of triaxiality induced by the circular notch described in Section 2.1. The gage section within the notch has a length of 0.5 mm and a width of 0.7 mm. The same void configurations described above were investigated in these samples. However,