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Experimental fracture characterisation of an anisotropic magnesium alloy sheet in proportional and non-proportional loading conditions

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ABSTRACT

A comprehensive experimental investigation was performed to characterize the fracture behaviour of a rare-earth magnesium alloy sheet, ZEK100-O, under both proportional and non-proportional loading conditions. This material possesses severe plastic anisotropy and tension-compression asymmetry that evolve with plastic deformation and is an excellent candidate to experimentally evaluate phenomenological fracture modelling strategies. Different types of specimen geometries were fabricated in different orientations with respect to the rolling direction of the sheet to reveal the anisotropic fracture response of the alloy. Moreover, three different types of plane-strain tension tests, namely, v-bend, butterfly, and Nakazima dome tests were conducted and compared in terms of their applicability for fracture characterization of sheet materials. To visualize directional dependency of the fracture response of the magnesium alloy, experimental fracture *loci* for different orientations were constructed. Furthermore, non-proportional tests were performed in which abrupt changes in stress state were imposed to study the role of the loading history on fracture behaviour of the alloy. The non-proportional tests entailed pre-straining the material in uniaxial and equi-biaxial tension up to a prescribed plastic work level, followed by extreme strain path changes to plane-strain tension and shear states. Non-proportional deformations with such severe strain path variations have not been reported in the literature for materials with complex anisotropic behaviour such as ZEK100-O. The results of which have enabled the direct experimental evaluation of phenomenological damage models without performing an inverse calibration from finite element simulations. Based on the results of the non-proportional tests, it was shown that simple damage indicators were unable to describe the influence of severe changes in the strain path on fracture.

1. Introduction

Motivated by increasing demand to reduce vehicle weight by incorporating lightweight materials, research on magnesium alloys has been receiving significant attention from the automotive industry. However, despite a high strength-to-weight ratio, applications of wrought magnesium alloys are limited due to insufficient formability at room temperature, pronounced anisotropic response, and poor corrosion resistance (Zarandi and Yue, 2011). To address these issues, the addition of rare-earth elements emerged as a potential solution to increase formability while preserving the low density of magnesium alloys (Imandoust et al., 2017). Nevertheless, severe anisotropy persists in rare-earth magnesium and from the perspective of evolution of anisotropy and complications in plasticity and fracture, behaviour of such materials is even more complex than conventional commercial magnesium alloys such as AZ31B (Kurukuri et al., 2014; Abedini et al., 2017a). Therefore, these alloys require a broad material characterisation to develop and calibrate anisotropic constitutive plasticity and fracture models.

Notable progress has been made over the past two decades in developing and modifying robust experimental methods to characterize the effect of stress state on fracture initiation in sheet metals over a wide range of stress triaxialities. For instance, significant efforts have been made to design shear specimens to evaluate the fracture response under zero hydrostatic stress and stress triaxiality (Mohr and Henn, 2007; Tarigopula et al., 2008; Peirs et al., 2012). In addition, characterisation tests by flat specimens with central holes or notches have been widely used to study the failure behaviour under tensile dominated stress states (Bao, 2004; Luo et al., 2012; Roth and Mohr, 2016). The critical plane-strain tension state has been achieved using specimens featuring wide gauge widths to supresses straining in the width direction (Mohr and Henn, 2007; Flores et al., 2010; Bagheriasl and Worswick, 2015; Cheong et al., 2017). Moreover, Nakazima dome and bulge tests have been utilized as candidate experimental techniques to determine equi-biaxial tension behaviour of sheets

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(Bai and Wierzbicki, 2010; Koc et al., 2011). Using these experimental techniques, fracture strains under a wide range of stress states can be governed leading to a better understanding of the fracture behaviour of sheet metals.

The interest in developing improved characterisation tests for proportional loading conditions has been driven by the adoption of phenomenological fracture models that are stress state dependent such as the modified Mohr–Coulomb (MMC) (Bai and Wierzbicki, 2010), (Lou and Huh, 2013), and Hosford–Coulomb (Mohr and Marcadet, 2015) as notable examples. In this modelling framework, proportional characterisation tests are performed followed by extensive numerical modelling of each characterisation test to obtain local stress and strain histories. The stress history, that can be quite non-linear due to localisation in tensile-based coupons such as in notched tensile tests, is then averaged into an "average stress triaxiality" for model calibration with the failure strains. Alternatively, an optimisation code can be used to integrate the numerical stress path with a damage parameter, *D*, that predicts fracture when $D = 1$. However, Benzerga et al., (2012) correctly pointed out that there are infinite ways to average the stress triaxiality and that the failure strain will be different due to microstructure evolution in non-linear strain paths even if the average triaxiality is constant. For example, a two-stage deformation path of uniaxial tensile loading followed by uniaxial compression back to the initial length would lead to an average stress triaxiality of zero which corresponds to a shear state.

Nevertheless, phenomenological failure models are straightforward to use and perform much better than expected in forming (*e.g.* Malcher et al., 2012; Anderson et al., 2017) and crash simulations (*e.g.* Omer et al., 2017) that is a testament to their widespread adoption. However, there is a clear need to experimentally evaluate the influence of non-proportionality on the fracture behaviour and assess the predictions of a phenomenological damage model, especially for an anisotropic material such as magnesium alloys. In the so-called "hybrid experimental-numerical" approach to fracture characterisation, the failure model is generated from the simulations of the experiments and the procedure is effectively a closed-loop validation which is a prime reason that different phenomenological models can be calibrated to give similar results despite different formulations.

In addition, understanding of the behaviour of materials under non-proportional states is essential since in forming operations and in crash events, materials are subjected to complex stress state changes. The role of non-proportionality on yielding behaviour of materials is well-established with concepts of kinematic hardening (Chaboche, 2008) and distortional hardening in homogeneous anisotropic hardening (HAH) models (Barlat et al., 2011,2017). Moreover, it is well-known that the onset of necking is dependent on the loading history of sheet metals (Volk and Suh, 2013; Jocham et al., 2016). Graf and Hosford (1993) showed that pre-straining an AA2008-T4 alloy remarkably influenced its forming limit diagram (FLD). A similar observation on path-dependency of FLDs was made by Korkolis and Kyriakides (2009) for AA6260-T4 tubes under combined internal pressure and axial loading. To overcome this issue, Stoughton (2000) proposed a stress-based FLD that significantly reduced path-dependency of forming limit curves (see also Stoughton and Yoon, 2012); however, it was discussed by Yoshida and Kuwabara (2007) that the idea of stress-based FLDs is strictly valid for isotropic hardening models while non-isotropic hardening effects are only manifested in non-proportional loading.

In contrast to the published research on the role of non-proportionality on yielding response and FLDs, there are limited studies on fracture characterisation of materials under non-proportional conditions. Bao and Treitler (2004) performed notch compression tests on axisymmetric AA2024-T351 bars followed by tension tests to fracture where a substantial increase in ductility was reported due to the pre-straining in compression. Basu and Benzerga (2015) studied a conventional medium-carbon steel alloy by uniaxial tension with axisymmetric bars followed by machining notches on the specimen to increase the stress triaxiality. In addition, the influence of the loading direction reversal on the onset of fracture of DP780 steel sheet was investigated by Marcadet and Mohr (2015) through compression–tension experiments where it was reported that the strain to fracture was increased with pre-straining in compression. A similar study was also performed by Papasidero et al. (2015) on AA2024-T351 tubes by pre-straining the material in tension, compression, and torsion where it was observed that applying pre-compression and pre-torsion increased the ductility while applying pre-tension reduced the ductility of the material. More recently, ten Kortenaar (2016) studied the influence of non-proportional loadings on fracture behaviour of boron steel under different loading conditions after imposing an initial biaxial pre-straining.

The objective of the present work is to experimentally characterize fracture behaviour of a rare-earth magnesium alloy, ZEK100-O, under proportional and non-proportional loading conditions. The fracture response of ZEK100-O has not been thoroughly studied in the literature, even under proportional loading, the notable exception being the microstructural study of Ray and Wilkinson (2016) in which the failure behaviour of ZEK100-O was analyzed with notched tensile specimens where the role of grain boundaries and twin boundaries on fracture initiation was revealed. The formability of this material has been studied by Boba et al. (2017) for a range of temperatures, who reported significant anisotropy in the forming limit strains, particularly at room temperature. However, formability is typically controlled by the onset of necking whereas the current paper focuses on strain at final fracture. To the authors' knowledge, magnesium alloys have not been investigated in terms of their fracture behaviour under non-proportional loading conditions. Unlike most of the studies cited above in which only a uniaxial state is applied for pre-straining (of steel and aluminum sheets), the present study will consider both uniaxial and equi-biaxial tension states with dogbone and Marciniak tests, respectively, for the initial stages of deformation of the magnesium alloy, followed by simple shear and plane-strain tension conditions up to fracture.

To these ends, a novel test program was undertaken to experimentally obtain the fracture strains in proportional plane-stress loading conditions and to calibrate a phenomenological damage model. Secondly, a series of severely non-proportional loading conditions were achieved where the pre-straining tests enable experimental assessments of non-proportional stress states as shear and tight-radius bending samples were extracted from the deformed region where homogeneous plane-stress conditions apply. Furthermore, the magnitude of pre-straining in the various tests was performed up to the same level of plastic work to enable an appropriate comparison between stress states; such an approach has not been considered in prior non-proportional experimental studies. Therefore, it is expected that the present study would shed some light into the understanding of fracture in magnesium alloys under various proportional and non-proportional loading conditions.

2. Material

The material used in the present study was a commercial rare-earth magnesium alloy, ZEK100 (O-temper) rolled sheet with a nominal thickness of 1.55 mm. Recently, Abedini et al. (2017a) performed X-Ray Diffraction (XRD) analysis on this same lot of material and reported that the texture of ZEK100-O exhibits a spread of the basal poles along the transverse direction which is typical of rare-earth magnesium rolled sheets (Fig. 1). The engineering stress-strain response of the material in uniaxial tension was

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