International Journal of Solids and Structures 000 (2018) 1–19

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

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

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ARTICLE INFO

Article history:
Received 24 November 2017
Revised 3 April 2018
Available online xxx

Keywords:
Fracture characterisation
Magnesium alloy
Non-proportional loading
Damage accumulation

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.

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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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https://doi.org/10.1016/j.ijsolstr.2018.04.010
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Please cite this article as: A. Abedini et al., Experimental fracture characterisation of an anisotropic magnesium alloy sheet in proportional and non-proportional loading conditions, International Journal of Solids and Structures (2018), https://doi.org/10.1016/j.ijsolstr.2018.04.010

(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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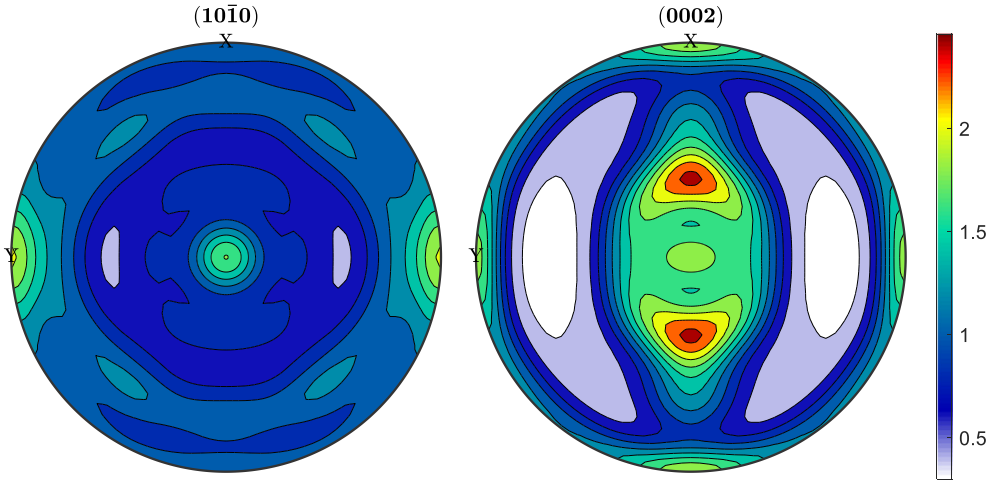


Fig. 1. XRD pole figures for as-received ZEK100-O sheet. *X* and *Y* directions correspond to the TD and RD, respectively.

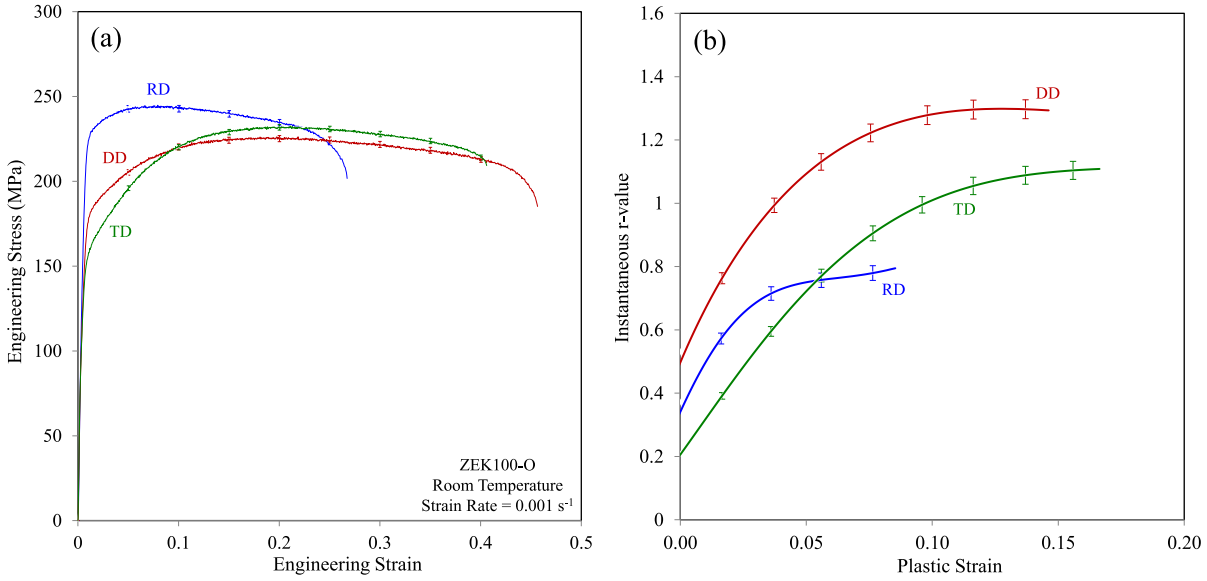


Fig. 2. Uniaxial tensile response obtained with sub-sized ASTM E8 specimens tested at room temperature under a quasi-static strain rate of 0.001 s^{-1} in terms of (a) engineering stress–strain curves and (b) instantaneous *r*-values.

obtained with a sub-sized ASTM E8 specimen under a quasi-static strain rate of 0.001 s^{-1}, with specimens extracted from the rolling (RD), diagonal (DD), and transverse (TD) directions of the sheet. As shown in Fig. 2a, the material demonstrates significant anisotropic behaviour with the rolling direction having the highest ultimate tensile strength (UTS). Furthermore, the variation in the instantaneous *r*-values (Lankford parameters) depicted in Fig. 2(b) suggests evolution of the texture of the material with deformation and highlights the complexities associated with constructing yield *loci* for the material.

The constitutive response of this material under a wide range of stress states was reported by Abedini et al. (2017a). Recently, Abedini et al. (2018d) used this experimental data to calibrate the CPB06 yield criterion of Cazacu et al. (2006) at different levels of plastic deformation and the yield *loci* for two of these plastic deformation levels, *i.e.* the plastic work levels of 2.24 MJ/m^3 and 22.46 MJ/m^3 (associated with equivalent plastic strains of 0.01 and 0.09 for a uniaxial tension test in the RD), are presented in Fig. 3. Note that the specific plastic work, w_p, is defined as:

$$w_p = \int \sigma : d\varepsilon^p \tag{1}$$

where σ and $d\varepsilon^p$ are the stress and plastic strain rate tensors, respectively. It can be seen from Fig. 3 that ZEK100-O displays a significant tension–compression asymmetry. For the lower plastic work level of 2.24 MJ/m^3, which is close to initial yielding, it can be seen from Fig. 3(a) that the tension region (first quadrant) exhibits larger yield stresses than the compression region (third quadrant), however this trend is reversed at the plastic work level of 22.46 MJ/m^3 in Fig. 3(b). Therefore, it is apparent that the shape of the yield *loci* of ZEK100-O evolves with deformation. The experimental results presented in Figs. 2 and 3 show the challenging nature of ZEK100-O in terms of constitutive characterisation.

3. Experiments and methodology

Different types of experimental tests were performed in the present study to evaluate the fracture behaviour of ZEK100-O sheet at room temperature under quasi-static conditions. In terms of the loading histories, these tests can be categorized into two types, corresponding to “proportional” *versus* “non-proportional” conditions. This section describes the experiments along with the strain measurement techniques used to obtain fracture strains under dif-

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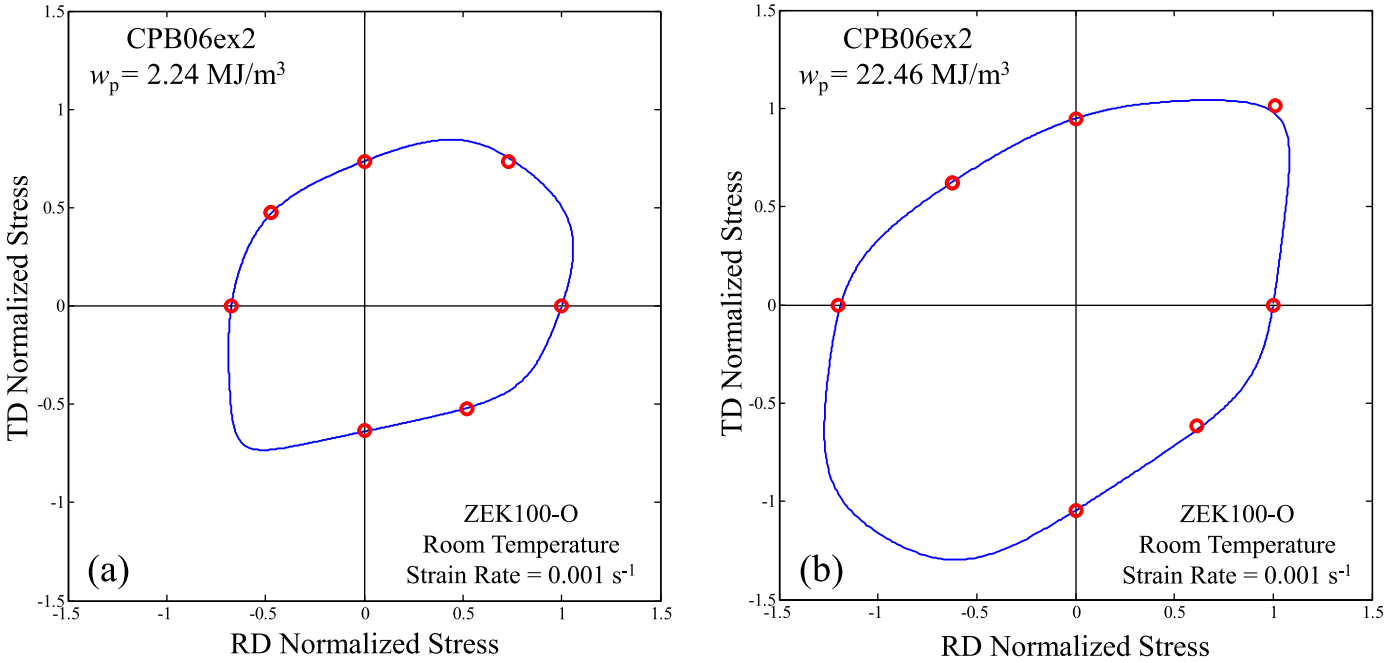


Fig. 3. Yield *loci* of ZEK100-O with CPB06ex2 formulation obtained from Abedini et al. (2017d) calibrated at two plastic work levels of (a) 2.24 MJ/m^3 and (b) 22.46 MJ/m^3. It should be mentioned that the plastic work levels of 2.24 MJ/m^3 and 22.46 MJ/m^3 correspond to equivalent plastic strains of 0.01 and 0.09, respectively, for a uniaxial tension test in the reference direction of the RD.

ferent loading conditions. It is common in the literature to define the stress state in terms of the stress triaxiality and Lode parameter; thus before describing the tests, these concepts in characterisation of loading conditions with stress invariant are reviewed.

3.1. Characterisation of stress state

The first invariant of the stress tensor, I_1, and the second and third invariant of the stress deviator, J_2 and J_3, are defined as:

$$I_1 = tr(\sigma), \quad J_2 = \frac{1}{2}(s:s), \quad J_3 = \det(s) \tag{2, 3, 4}$$

where $\boldsymbol{s}$ is the stress deviator. Note that boldface letters refer to tensor quantities and the symbol ":" denotes the doubled contracted product between two tensors. The hydrostatic pressure σ_{hyd} is defined as:

$$\sigma_{hyd} = -\frac{I_1}{3}. \tag{5}$$

And the stress triaxiality η is written as:

$$\eta = -\frac{\sigma_{hyd}}{\sqrt{3J_2}} \tag{6}$$

The so-called Lode angle θ is related to the second and third invariant of the stress deviator by:

$$\theta = \frac{1}{3}\cos^{-1}\left(\frac{3\sqrt{3}}{2}\frac{J_3}{J_2^{\frac{3}{2}}}\right), \quad 0 \le \theta \le \frac{\pi}{3} \tag{7}$$

The use of the dimensionless Lode parameter, $\bar{\theta}$, is more common in the literature, and is written as:

$$\bar{\theta} = 1 - \frac{6\theta}{\pi}, \quad -1 \le \bar{\theta} \le 1 \tag{8}$$

While the stress triaxiality and Lode parameter are in general independent variables, for plane-stress conditions, the following relation exists between them (Bai and Wierzbicki, 2008):

$$\cos\left[\frac{\pi}{2}(1-\bar{\theta})\right] = -\frac{27}{2}\eta\left(\eta^2 - \frac{1}{3}\right) \tag{9}$$

Using the stress triaxiality and Lode parameter, all forms of loading conditions can be distinguished. For instance, a shear state is characterized by the triaxiality and Lode parameter both equal to zero, uniaxial tension is characterized by stress triaxiality of 1/3 and Lode parameter of unity, plane-strain tension state has a triaxiality of $1/\sqrt{3}$ and Lode parameter of zero, and equi-biaxial tension is characterized by a triaxiality of 2/3 and Lode parameter of -1.

It should be noted that the use of the stress triaxiality and Lode parameter are convenient but has some important limitations. By definition, these measures are invariant and thus cannot account for anisotropy. The failure strains in the rolling and transverse directions of a material from a tensile test might be different but they will have the same stress triaxiality since the principal directions are not considered. Additional calibration parameters have been added into phenomenological fracture surfaces to account for anisotropy (*e.g.* Luo et al., 2012; Jia and Bai, 2016; Lou and Yoon, 2017) to generalize the failure *locus*. The appropriateness of using invariant to describe the stress state of anisotropic materials remains an open question. Furthermore, as discussed by Butcher and Abedini (2017), the stress triaxiality cannot differentiate between coaxial and non-coaxial stress states such as in pure and simple shear deformation. The stress triaxiality is zero for both of these shear loading cases, but the plastic work rates are different. Therefore, the work-conjugate equivalent strain will be different for the same level of major strain as the principal stress and the principal strain directions do not remain aligned in simple shear.

3.2. Proportional fracture characterisation tests

A typical fracture testing program for sheet materials includes the main stress states of shear, uniaxial tension, plane-strain tension, and equi-biaxial tension under proportional conditions. Within this context, a proportional loading condition is defined when the principal stress and strain directions are coaxial and the stress triaxiality and Lode parameter are constant from initial deformation up to fracture. However, as schematically shown in Fig. 4 for a typical tensile specimen, this is not the case when the char-

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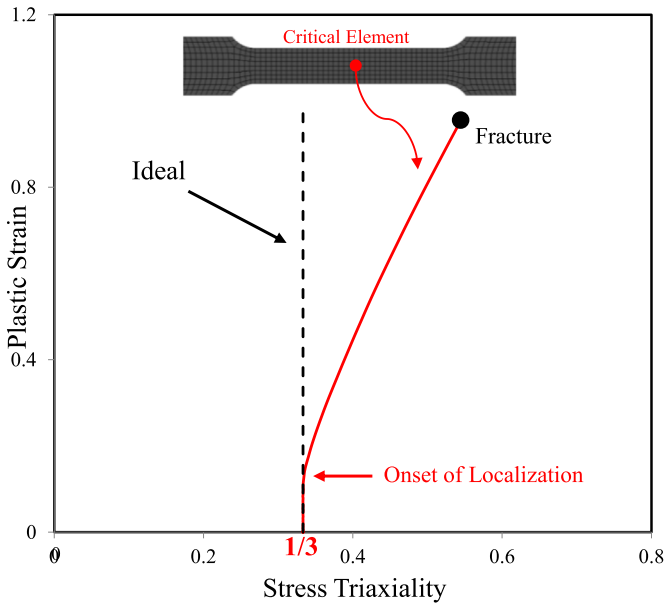


Fig. 4. Schematic of stress state deviations from the initial triaxiality for a tensile dogbone specimen.

acterisation test leads to plastic instabilities, changing the loading conditions from their initial stress triaxialities and Lode parameters. For test geometries based upon in-plane tensile stretching, proportional loading ceases at the onset of strain localisation so it is important to select fracture tests that minimize necking and non-linear effects such as choosing a tight radius bend test for plane strain where necking is mitigated rather than a plane strain notch test. Recognizing that perfectly proportional tests across all stress states of interest is generally not possible from an experimental perspective, the present paper will define the selected fracture tests as "proportional" to differentiate from the non-proportional tests where the stress states are deliberately varied as described in Section 3.3.

Assessing the degree to which the "proportional tests" described in this section are not proportional is important since the deviation of the stress state generally coincides with the stress state becoming triaxial and no longer plane-stress. This deviation of the stress state is most apparent when using uniaxial tensile or notched tensile tests where the onset of necking occurs at comparatively low strains relative to the fracture strains. For the uniaxial test, the strain measurements of the surface will show a transition from uniaxial tension towards plane-strain but at the center of the specimen within the neck where failure initiates, the stress state is strongly triaxial. One could argue that such tests are neither plane-stress nor proportional and FE simulations with solid

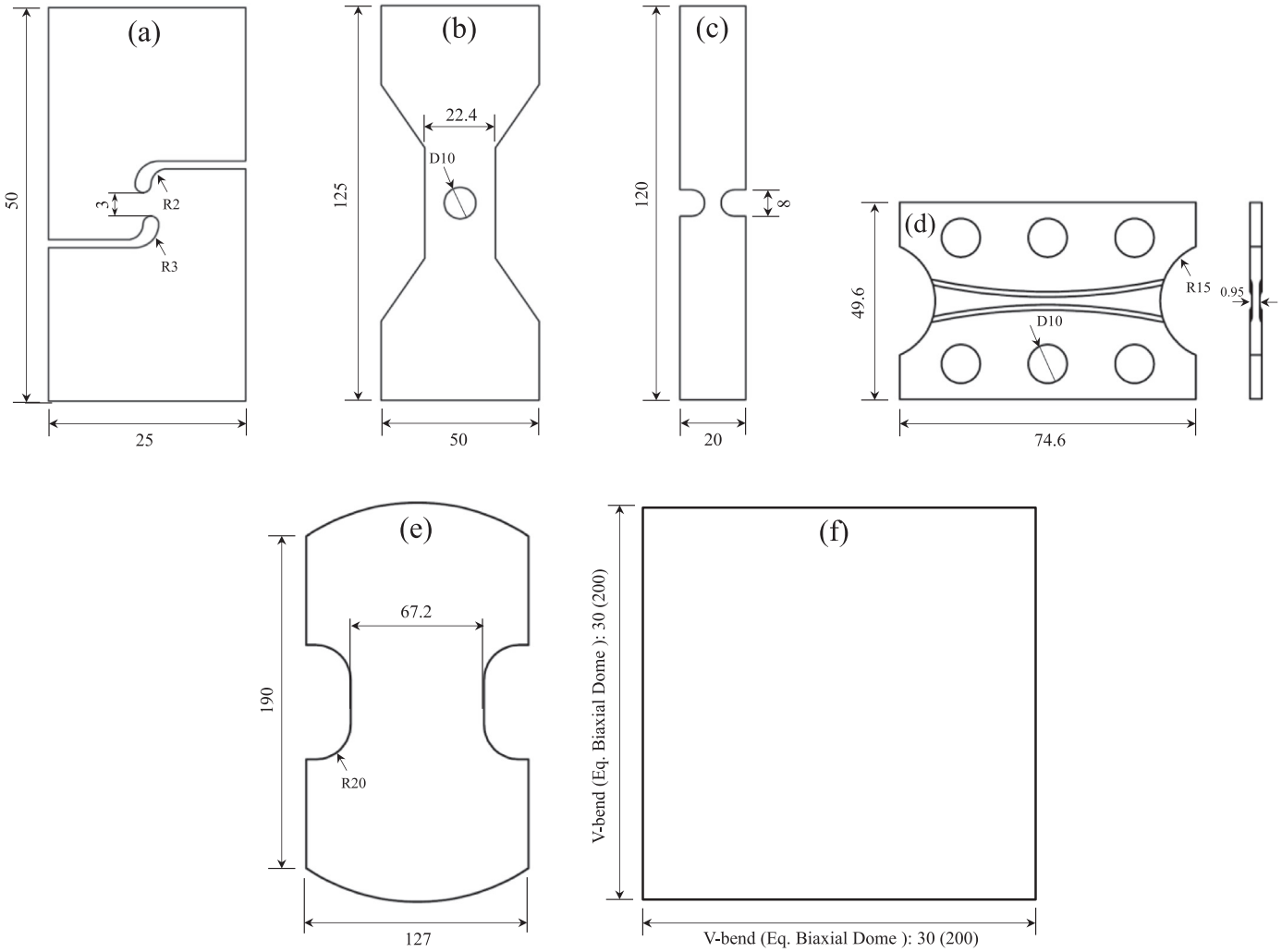


Fig. 5. Specimen geometries of (a) shear (Peirs et al., 2012), (b) hole tension, (c) notch tension, (d) butterfly (Mohr and Henn, 2007; Dunand and Mohr, 2011), (e) plane-strain dome, and (f) equi-biaxial dome and v-bend tests. All dimensions are in millimetres. For the in-plane tests (samples a–d) the load is applied in the vertical direction.

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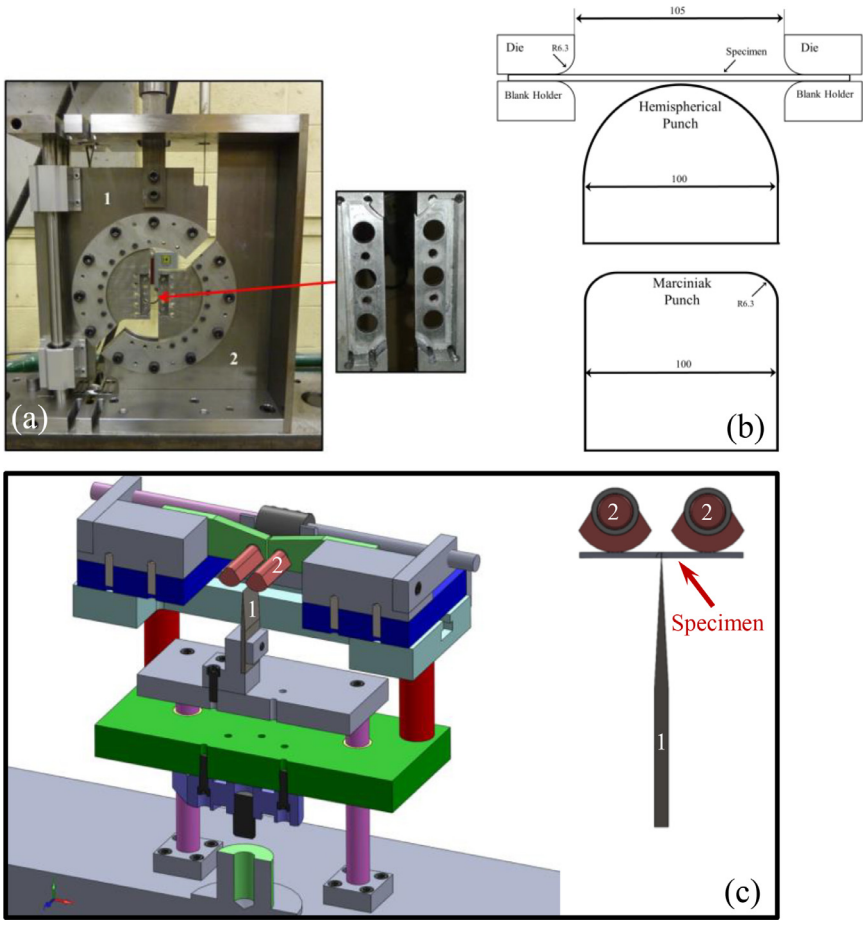


Fig. 6. Equipment used to perform experiments: (a) butterfly apparatus where labels (1) and (2) refer to the moveable and fixed parts, respectively. When the grips are rotated by 90°, plane-strain tension state is achieved, (b) dome test tooling, and (c) v-bend tester where labels (1) and (2) show the knife and rollers, respectively. All dimensions are in millimetres.

element are used in the literature to extract the stress state history (*e.g.* Dunand and Mohr, 2010; Anderson et al., 2014) where the stress triaxiality is generally averaged for these tests (*e.g.* Bao and Wierzbicki, 2004).

The different types of specimen geometries used in the present paper for fracture characterisation of ZEK100-O under proportional conditions are shown in Fig. 5. The shear specimen depicted in Fig. 5(a) was adopted from Peirs et al. (2012), and recently Abedini et al. (2015, 2017b) compared this specimen with the butterfly shear specimen of Dunand and Mohr (2011) (see Fig. 5d) for different sheet materials and it was reported that both specimens performed well for fracture characterisation of materials under a shear state while the shear specimen of Peirs et al. (2012) (Fig. 5a) is marginally superior since it does not need through-thickness machining that may lead to surface micro-cracks. Moreover, this specimen can be loaded with conventional uniaxial frames as opposed to the butterfly specimen that requires a custom-made testing apparatus. Note that although the butterfly specimen will not be used in the present study for fracture characterisation under the shear state, it will be utilized by taking advantage of its wide gauge width to impose a plane-strain tension condition as explained below. The shear tests with the specimen shown in Fig. 5(a) were performed in the three directions of 0° (RD), 45°, and 135° with respect to the rolling direction. Note that in the shear state, the principal stress and strain directions are initially aligned at $\pm$ 45° to the applied loading direction. For instance, a shear test in the RD direction leads to the principal components in the $\pm$ 45° orientations. More information regarding shear tests for anisotropic and asymmetric materials and the choice of the test orientations can be found in Abedini et al. (2017a).

Typically, uniaxial tensile tests are performed with dogbone specimens; however, necking at low deformation levels limits their utility for studying large strains and for fracture characterisation. Compared to regular dogbone specimens, the hole tension specimen shown in Fig. 5(b) can delay the onset of necking and is a more representative test for fracture behaviour of materials under a uniaxial tension condition (Dunand and Mohr, 2010; Luo et al., 2012; Kofiani et al., 2013; Roth and Mohr, 2016; Pathak et al., 2017). Therefore, in the present study, the fracture response of the material under uniaxial tension is determined using the hole tension specimen shown in Fig. 5(b). In addition, classical notch tensile tests provide means to control the stress triaxiality in tensile specimens and are commonly used in the literature (*e.g.* Dunand and Mohr, 2010; Lou and Yoon, 2017). It was mentioned earlier that these tests lead to early localisation that makes interpretation of their results difficult; nevertheless, it is of interest in the present paper to perform these tests for the magnesium alloy, thus the notch specimen depicted in Fig. 5(c) was utilized to obtain the response of the material with surface strain paths lying between uniaxial and plane-strain tension. The hole tension and notch tension tests were conducted in three orientations corresponding to the RD, DD, and TD.

In addition, the plane-strain tension condition is a critical state for formability and fracture characterisation of sheet metals that corresponds to the lowest ductility under plane-stress states (Mahmudi, 1999). Therefore, three different types of plane-strain

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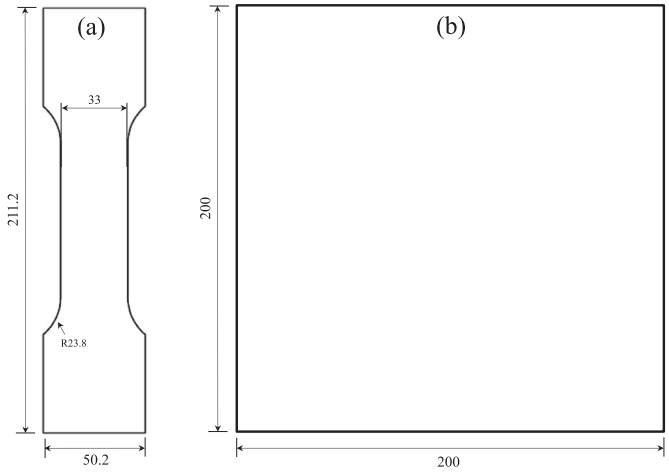


Fig. 7. Specimen geometries of (a) scaled JIS and (b) Marciniak tests. All dimensions are in millimetres.

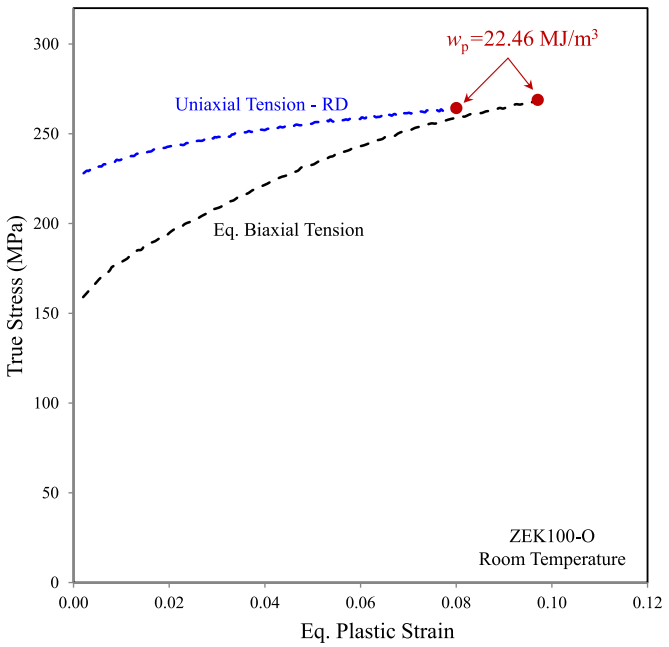


Fig. 8. Uniaxial and equi-biaxial tensile response of ZEK100-O at room temperature under a quasi-static strain rate of 0.001 s^{-1}. For the non-proportional tests, the first stages of deformation were stopped at the plastic work level of 22.46 MJ/m^3. Note that the equi-biaxial data is from through-thickness compression tests in Abedini et al. (2017a).

tests were considered in the present study, namely, plane-strain butterfly test, hemispherical dome test, and v-bend test shown in Fig. 5(d), (e), and (f), respectively. The v-bend tests were performed with the major axis of strain along either the RD, DD, or TD, while the plane-strain butterfly and dome tests were loaded along the RD and TD directions. All these specimens possess wide gauge widths that facilitate achieving a plane-strain condition with zero minor strain at the center of the gauge area. The plane-strain test results are compared and discussed in detail in Section 4.1.1. Finally, testing under the equi-biaxial tension state was conducted using a Nakazima hemispherical dome test with 200 mm × 200 mm blanks depicted in Fig. 5(f).

The tests described above were performed with different types of equipment. The shear, hole tension, and notch tension tests were performed using an MTS Criterion Model 45 servo-electric apparatus. The plane-strain butterfly test was performed with a displacement-controlled butterfly test frame in Fig. 6(a) (see also Anderson et al., 2017), and the plane-strain and equi-biaxial Nakazima dome tests were conducted with an MTS formability press with tooling shown in Fig. 6(b) that conforms to the ISO12004-2 standard. Furthermore, the v-bend tests were done with a novel inverted v-bend test frame shown in Fig. 6(c) that allows for direct strain measurements (Cheong et al., 2017). The v-bend tests were performed according to the VDA 238–100 specifications utilizing a knife with a tip radius of 0.4 mm and a spacing between roller supports of twice the sheet thickness of 1.55 mm. Note that in all the tests where tooling contact is required to impose deformation (dome and v-bend tests) Teflon® film lubricated with Vaseline® were used to reduce the influence of friction.

It is worth mentioning that fracture characterisation of sheet materials under compressive loading is extremely difficult because of complexities in compression testing due to occurrence of buckling. Therefore, in the present study, the fracture response of the material was only characterized in stress states ranging from shear to biaxial stretching.

3.3. Non-proportional fracture characterisation tests

To study the influence of non-proportional loading on fracture response of the material, two-stage tests were performed to induce significant changes in the stress state. For the first stage of the loading (pre-straining), two types of specimens were used: a scaled-up JIS tensile specimen shown in Fig. 7(a) and an equi-biaxial Marciniak specimen shown in Fig. 7(b). As a standard practice, the Marciniak test employs a carrier blank with a central hole in order to eliminate friction between the flat punch (see Fig. 6b) and the centre of the blank. In the present study, AA5182-O carrier blanks with a central hole diameter of 50.8 mm were utilized. The uniaxial tensile test was performed in the rolling direction of the sheet using the MTS tensile frame. The first stages of deformation with uniaxial and equi-biaxial tension states were stopped at a plastic work level of 22.46 MJ/m^3. This deformation level was chosen since it corresponds to the onset of necking in the uniaxial tension test in the RD, thus the two first stages of deformation were interrupted at the same plastic work level. This plastic work level corresponds to von Mises equivalent strains of approximately 0.09 and 0.10 in the uniaxial and equi-biaxial tension tests, respectively (Fig. 8). The tensile tests were carefully interrupted at the prescribed deformation level and no indication of necking or localized deformation was observed on the deformed specimens based on visual inspection and DIC measurements (see Fig. 9).

It should be mentioned that the biaxial stresses cannot be extracted from the Marciniak tests thus prior to these tests a primary characterisation test was performed with through-thickness compression of stacked sheet specimens (Abedini et al., 2017a) to obtain the approximate stress-strain response of the material in equi-biaxial tension (Fig. 8). The equi-biaxial tension and through-thickness compression tests are considered to be equivalent stress states for plastic characterisation of materials since they possess the same stress deviator (Steglich et al., 2014). Subsequently, the punch movement in the Marciniak tests was terminated at the punch height associated with the von Mises equivalent strain of 0.10 determined with the aid of the DIC measurements. Note that due to the complex anisotropy of the magnesium alloy, the plastic work measure was selected to stop the pre-straining deformation. The definition of the plastic work (Eq. 1) is independent of adopted constitutive plasticity models and can be used to interrupt the first stages of loading at an equivalent level of plastic deformation.

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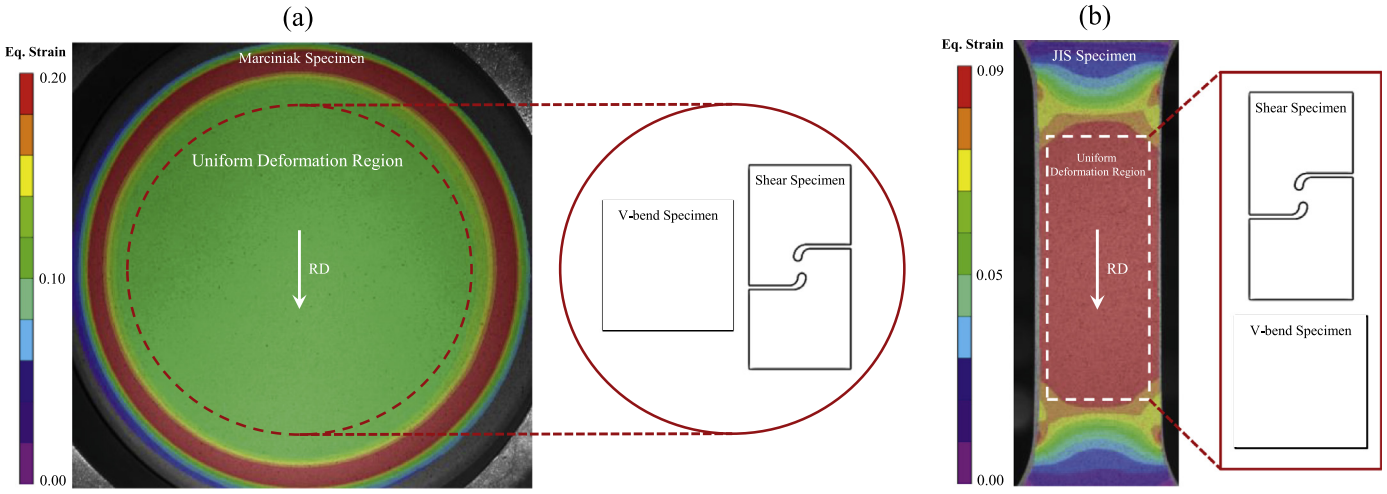
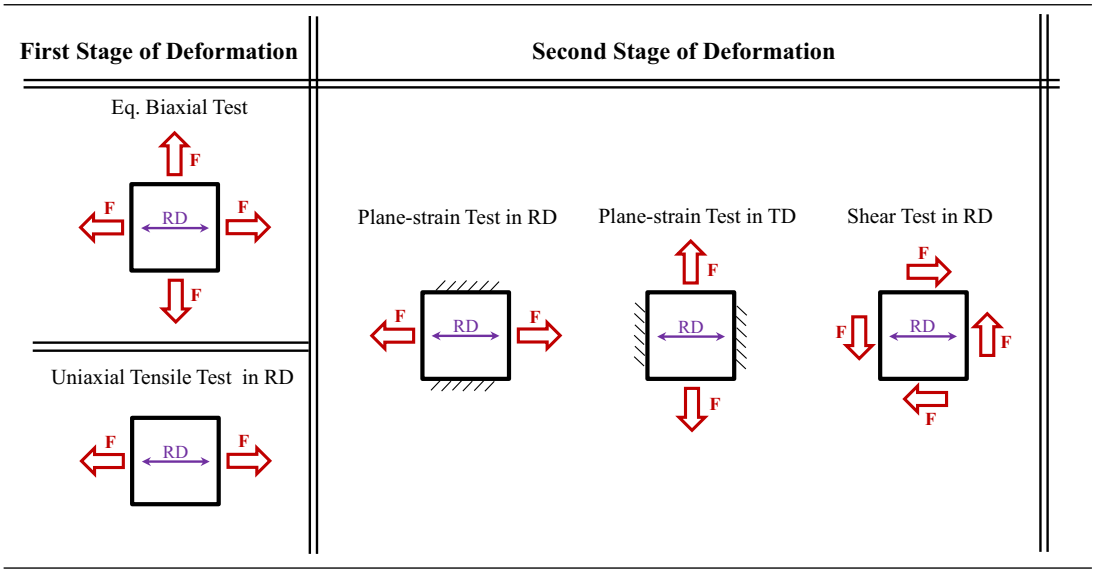


Fig. 9. Specimens extracted at the end of the first stages of the non-proportional tests from the uniformly deformed regions of (a) Marciniak and (b) JIS tensile specimens. The measured DIC contours of equivalent strain are also depicted.

Table 1
Description of stress state change in non-proportional tests.



Subsequently, simple shear and v-bend specimens shown in Fig. 5(a) and (f), respectively, were extracted from the pre-strained specimens to apply the second stages of loading, as presented in Table 1. As shown in Fig. 9, the shear and v-bend specimens were extracted from the uniformly deformed regions of the Marciniak and tensile specimens. Also note that this region of the Marciniak specimen is in the cut-out area where there is no frictional contact and deformation is plane-stress. As mentioned earlier, the tests were interrupted before the onset of plastic localisation; therefore; surface strain measurements are representative of deformation of the sheet since there are no through-thickness strain gradients. The two-stage nature of stress histories in the non-proportional tests is also shown schematically along with theoretical stress triaxialities in Fig. 10 where it can be seen that the initial stress states are abruptly switched to plane-strain tension and shear states. The v-bend specimens were fabricated in the RD and TD directions while the shear samples were extracted in the RD direction only. These specimens were subsequently tested up to fracture using the same procedure explained for proportional tests. Note that all of the specimens used in the present study were fabricated by CNC machining.

3.4. Strain measurements

The experiments described above were recorded using digital cameras to obtain full-field logarithmic strain measurements using digital image correlation (DIC) techniques. The commercial VIC3D DIC software from Correlated Solutions, Inc. was used for the DIC analysis. The images were recorded using two Point Grey 4.1 MP cameras for stereoscopic DIC measurements. Depending upon the size of the specimens, different types of lenses were utilized, resulting in various image resolutions; however, a virtual strain gauge length (VSGL = resolution [mm/pixel] × step size [pixel] × filter size) of 0.3 mm was used for all the tests. It was shown by Rahmaan et al. (2017) that a VSGL of 0.3 mm is sufficiently small for fracture characterisation of the shear specimen which is the smallest specimen used in this study. For consistency, the DIC analyses of rest of the (larger) specimens were also performed with the same VSGL size. More information regarding the VSGL size and its influence on the DIC strain measurements can be found in Reu (2015) and Rahmaan et al. (2017). The DIC images in each experiment were recorded with a prescribed frequency to provide at least 300 images from the initial deformation up to frac-

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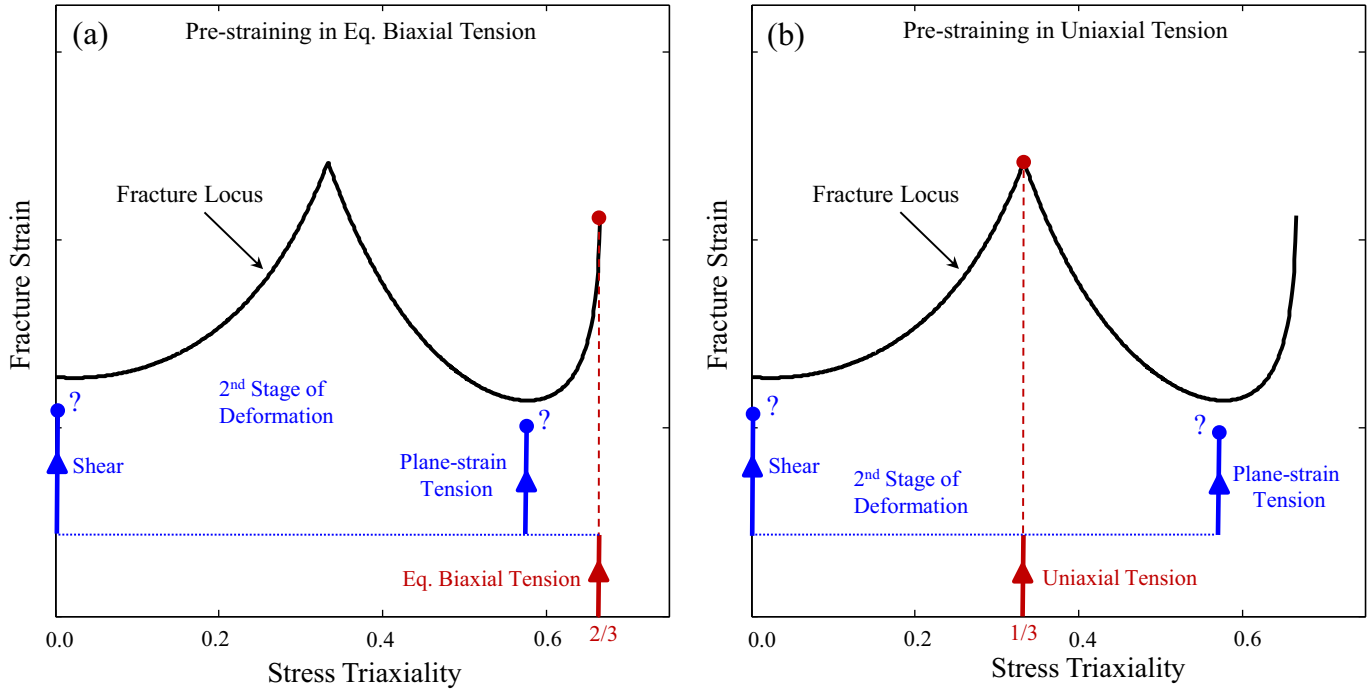


Fig. 10. Schematic illustration of first and second stages of deformation shown on a fracture *locus* for (a) equi-biaxial and (b) uniaxial tension pre-straining. Note that the initial uniaxial pre-straining was performed in the RD only. Also subsequent tests for the second stages of deformation were performed in the RD for the shear tests and in the RD and TD for the v-bend tests. Question marks show the unknown fracture strains in non-proportional tests.

Table 2
DIC parameters for full-field stereoscopic strain measurements.

Test	Image resolution (mm/pixel)	Step size (pixel)	Filter size	VSGL (mm)
Shear	0.023	2	7	~0.3
Hole tension	0.021	2	7	~0.3
Scaled JIS	0.060	1	5	~0.3
Notch tension	0.021	2	7	~0.3
V-bend	0.021	2	7	~0.3
Plane-strain butterfly	0.039	1	7	~0.3
Plane-strain dome	0.056	1	5	~0.3
Eq. biaxial dome	0.056	1	5	~0.3
Eq. biaxial Marciniak	0.056	1	5	~0.3

ture. The DIC parameters associated with each test are presented in Table 2.

When it comes to reporting fracture strains, it is common in the literature to provide equivalent strain measurements. However, equivalent strain measures are a function of the adopted constitutive plasticity model (Butcher and Abedini, 2017), so they require knowledge of appropriate yield functions and their coefficients. Given the complex evolving anisotropy of ZEK100-O, this is a challenging task and will not be considered in the present study. Instead, the von Mises equivalent fracture strains are reported along with the components of the strain tensor so that the interested reader can re-cast them in terms of the adopted constitutive models. The von Mises equivalent strain rate, $\dot{\varepsilon}_{VM}$, is written as:

$$\dot{\varepsilon}_{VM} = \frac{2}{\sqrt{3}}\sqrt{\dot{\varepsilon}_1^2 + \dot{\varepsilon}_2^2 + \dot{\varepsilon}_1\dot{\varepsilon}_2} \tag{10}$$

where $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are the measured principal strain rate components. The von Mises equivalent strain, ε_{VM}, is calculated by integrating the equivalent strain rate using the measured DIC time increments:

$$\varepsilon_{VM} = \int \dot{\varepsilon}_{VM} dt. \tag{11}$$

Note that as discussed in Butcher and Abedini (2017), Eq. (10) is strictly valid for coaxial loading conditions. Non-coaxiality may develop specifically for shear tests since the stress state is close to the simple shear definition in which the principal stress and strain components rotate during deformation with different rates; however, for the current magnesium alloy with relatively low ductility (major principal strain at fracture of about 0.2 under shear state) the difference between the coaxial formulation of Eq. (10) and the work-conjugate definition remain negligibly small and the principal stress and strain directions remain closely coaxial. Therefore, Eq. (10) was used to determine the equivalent fracture strains in shear loading.

All of the tests described above were conducted at room temperature, under a quasi-static von Mises equivalent strain rate of approximately 0.001 s^{-1}. To assess the repeatability of the results, at least four specimens per loading condition and orientation were tested which resulted in approximately 100 tests in total to reveal the constitutive fracture behaviour of ZEK100-O magnesium alloy under different proportional and non-proportional stress states.

3.4.1. Fracture initiation location

Fig. 11 shows the DIC images at the time of appearance of the first detectable discontinuity on the specimen surface which is defined as the onset of fracture. Consequently, DIC measurements were performed up to the last image before the onset of fracture. The fracture strains were reported by averaging strains

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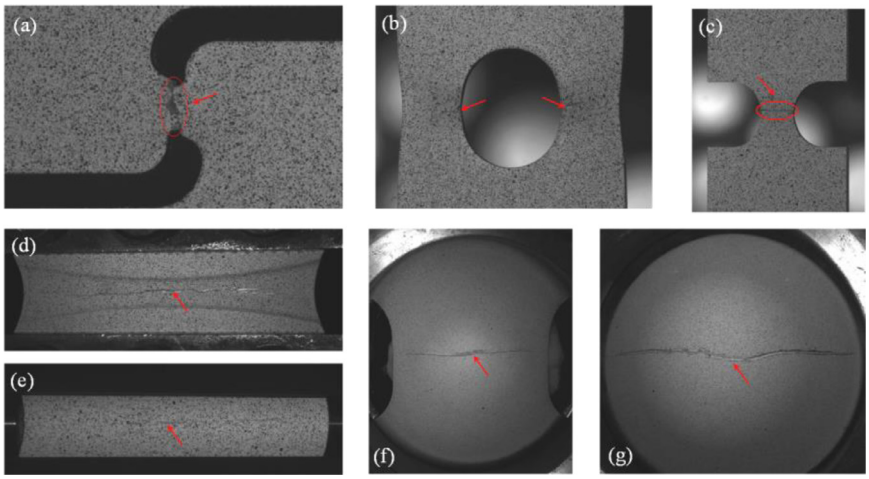


Fig. 11. The DIC images captured at the time of first appearance of visible crack on the surface of (a) shear, (b) hole tension, (c) notch tension, (d) plane-strain butterfly, (e) v-bend, (f) plane-strain dome, and (g) equi-biaxial dome specimens. Images (a–f) correspond to tests in the RD. Arrows show the crack locations.

of all points within a circle inspector with a diameter of 0.3 mm at the fracture initiation locations. This circle size was chosen for consistency with the VSGL size. The locations where fracture initiates were identifiable for all specimens except for the shear and notch specimens. However, it was shown in Peirs et al. (2012) and Abedini et al. (2015) that fracture initiated from the center of the shear specimen for Ti6Al4V and DP600 sheets, respectively. For the current shear and notch tension specimens, the fracture strains were measured at the center of the gauge area where the highest strains occur. It is worth mentioning that, recently, Rahmaan et al. (2017) showed that using microscopic strain measurements based upon the grain rotation within the shear band can resolve even larger shear fracture stains than reported by the DIC, specifically for elevated strain rates. This difference was due to the collapse of the shear band into a severe micro shear-band where failure initiates and the gauge length imposed by the VSGL inherent in the DIC calculations. Thus, the shear failure strain obtained using the DIC in the present work must be recognized to be very sensitive to the length scale.

Concerning the hole tension specimen, Pathak et al. (2017) showed that fracture strains obtained from this specimen are comparable to that of a hole expansion test (an alternate test for uniaxial tension fracture characterisation) for CP800 and DP780 steels. It should be noted that fracture in the hole tension specimen may initiate away from the edge where the stress state is not uniaxial tension (Anderson et al., 2017). The hole tension specimen geometry used in the present study is the same as used by Pathak et al. (2017) for a DP780 sheet with the same nominal thickness as the ZEK100-O (1.55 mm). It is emphasized that fracture initiated from the edges of the hole in the ZEK100-O tests. A more detailed study on the geometry of the hole tension specimen can also be found in Roth and Mohr (2016).

3.5. Phenomenological fracture model

Numerous uncoupled phenomenological fracture models have been developed in the literature which ignore the effects of damage on plastic behaviour of materials prior to fracture; therefore, one can utilize any standard metal plasticity model along with a separate phenomenological fracture model (*e.g.* Oyane et al., 1980; Clift et al., 1990; Bai and Wierzbicki, 2008; 2010; Lou and Huh, 2013; Mohr and Marcadet, 2015). Bai and Wierzbicki's (2010) model has received considerable attention in the literature and it has been reported that the model is capable of predicting fracture with a good accuracy for various alloys (*e.g.* Malcher et al., 2012; Gurben et al., 2012; Cao et al., 2013; Lian et al., 2013; Kofiani et al., 2013; Rousselier and Luo, 2014; Wang et al., 2015). Therefore, this model was adopted in the present study to construct the fracture *locus* for ZEK100-O. The Mohr–Coulomb criterion postulates that fracture takes place in a body on a plane on which the combination of the normal and shear stresses reaches a critical value. Bai and Wierzbicki (2010) adopted the Mohr–Coulomb model and transformed it into a stress triaxiality and Lode parameter dependent formulation. They showed that the equivalent strain at fracture, ε^f, in the Mohr–Coulomb criterion can be written in the space of the stress triaxiality and Lode parameter. This formulation has been re-cast into the form of:

$$\varepsilon^f = \left\{ c_1 \left[\sqrt{\frac{1+c_2^2}{3}} \cos\left(\frac{\bar{\theta}\pi}{6}\right) + c_2\left(\eta + \frac{1}{3}\left(\frac{\bar{\theta}\pi}{6}\right)\right)\right]\right\}^{c_3} \tag{12}$$

where the parameters $c_{1\text{-}3}$ are obtained from experimental tests. The equivalent failure strain can be calibrated from the experiments and is implicitly coupled to the constitutive model which is used to convert the equivalent failure strain to a stress depending on the hardening function and stress state. As explained in Section 3.1, for the case of plane-stress conditions, stress triaxiality and Lode parameter are not independent (Eq. 9); therefore, Eq. (12) reduces to a single variable function.

Note that the phenomenological fracture model in Eq. (12) has been proposed for isotropic materials; however, ZEK100-O is anisotropic, thus the model will be calibrated to individual material orientations to evaluate the degree of direction-dependency in the fracture behaviour of the material. It was assumed that the stress triaxialities in each test are constant and are equal to the theoretical values given in Section 3.1. Experimentally, strain paths can be converted to the stress triaxiality but this requires knowledge of the plasticity model and for magnesium it is extremely complex with evolving anisotropy. To enable the development and assessment of an analytical damage model, these constant stress states are required to side-step employing a finite element model. The non-proportional tests have been carefully designed to ensure homogeneous plane-stress deformation to support the analytical framework. Therefore, the results of the phenomenological fracture surface can provide a simple representation of stress state dependency and anisotropy of ZEK100-O under different orientations.

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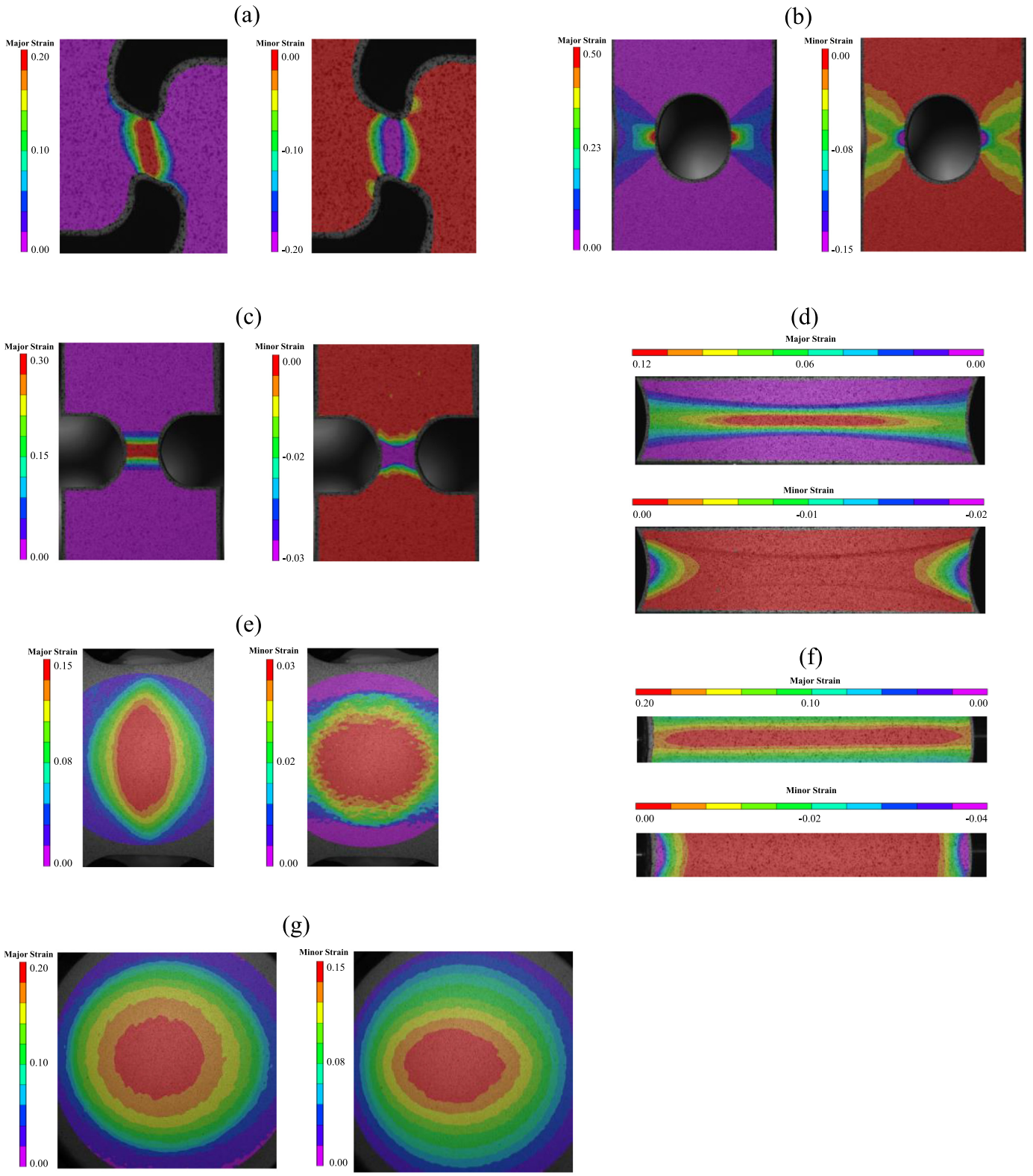


Fig. 12. Contours of DIC strains obtained at the last image before the appearance of visible crack on the surface of specimens of (a) shear, (b) hole tension, (c) notch tension, (d) plane-strain butterfly, (e) plane-strain dome, (f) v-bend, and (g) equi-biaxial dome specimens. Figures (a–f) correspond to tests in the rolling direction.

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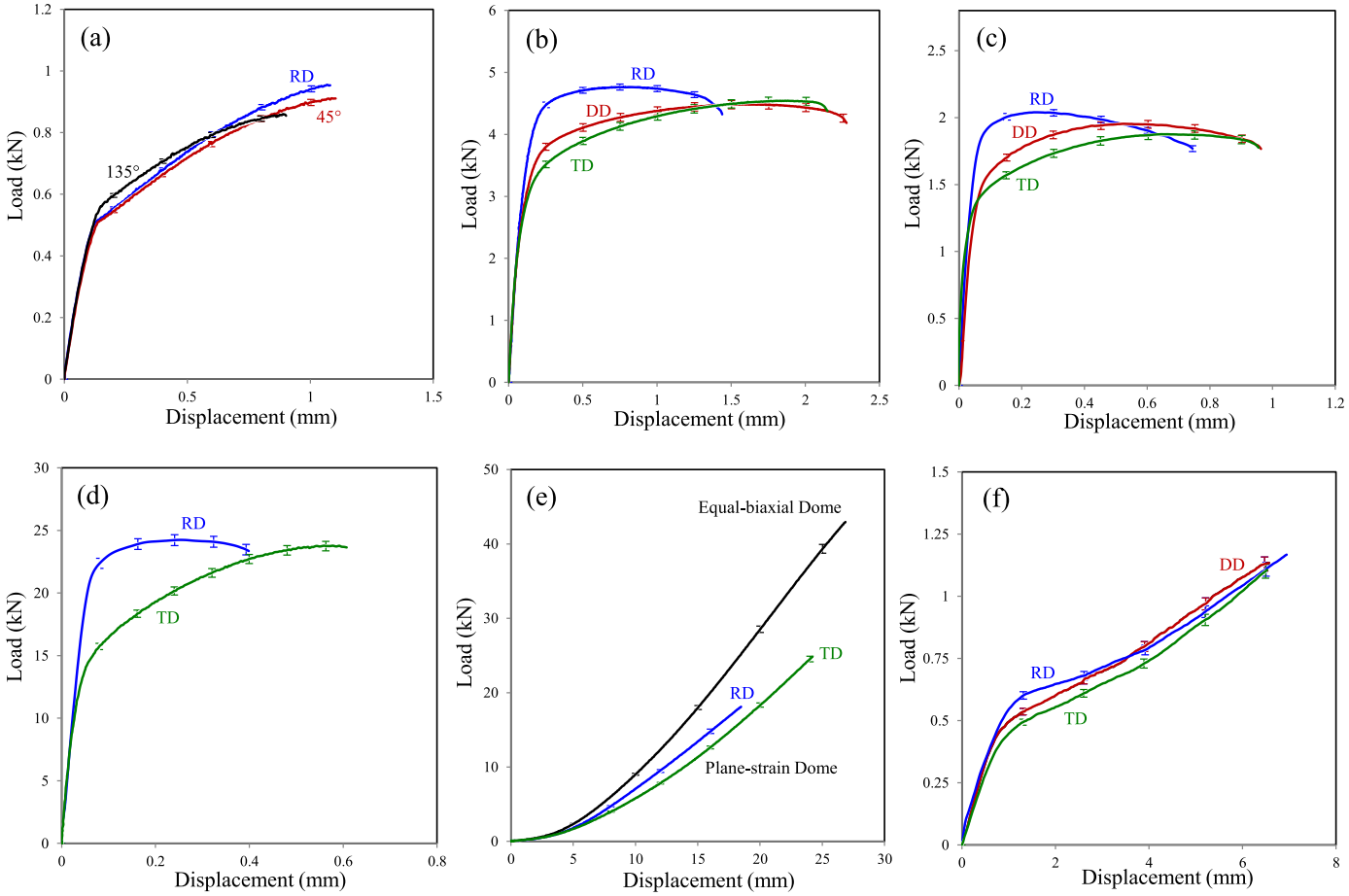


Fig. 13. Load-displacement responses of different specimens of (a) shear, (b) hole tension, (c) notch tension, (d) plane-strain butterfly, (e) Nakaziam dome, and (f) v-bend tests. Note that the sigmoidal shape of the v-bend test is due to compressive components in the inner layers of the bend. In-plane compressive stresses are known to activate twinning mechanisms to accommodate plastic straining.

4. Results and discussion

4.1. Proportional tests

Fig. 12 displays the DIC strain contours of major and minor strains corresponding to the last image before the onset of fracture, while their associated load-displacement responses are shown in Fig. 13. For brevity, only the results of the tests in the RD are shown in Fig. 12 while the strain paths of tests with different orientations are shown in Fig. 14 in terms of major *versus* minor strains. Note that for the plane-strain cases, only the results of the v-bend tests are shown in Fig. 14 since the response of the material exhibits an almost perfectly plane-strain condition with zero minor strains. Also note that all of the plane-strain tests are discussed and compared in detail in Section 4.1.1. Components of the fracture strains are presented in Table 3 along with the von Mises equivalent fracture strains. As mentioned earlier, at least four tests were performed for each stress state and orientation and the standard deviations (SD) are included in Table 3.

It can be seen from Fig. 14 that the material exhibits orientation-dependent strain paths and fracture behaviour. Anisotropy in the strain paths is more pronounced for the hole tension and notch tension tests. Furthermore, the equi-biaxial tension test shows a strain path which is initially close to equal principal strains while it deviates from this condition for larger deformation due to the onset of localisation leading to fracture occurring in the RD direction.

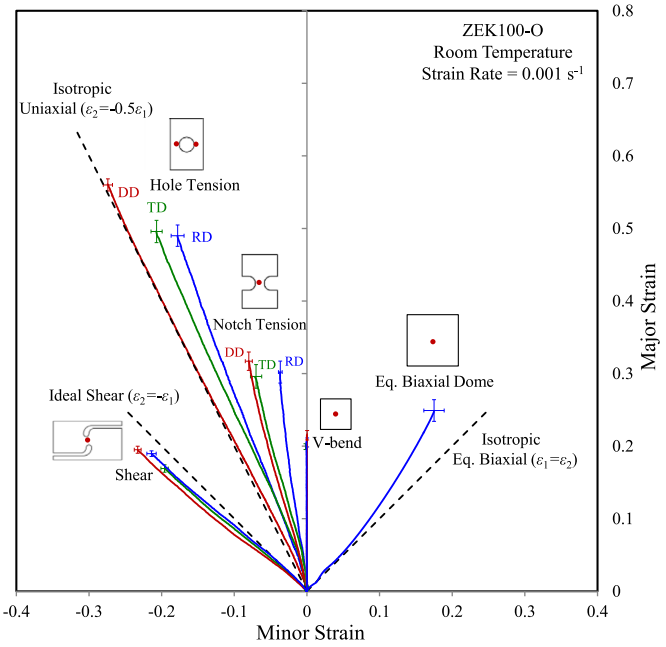


Fig. 14. Strain paths to fracture for different proportional tests. The ideal strain paths for proportional loading of isotropic materials are also shown for comparison.

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Table 3
Fracture strains obtained from characterizing proportional tests performed in different orientations. SD stands for standard deviations. Note that due to the nearly zero minor strains in the plane-strain v-bend and butterfly tests, zero values appear for minor strains and their SD when these are reported with two decimal places.

Tests	Orientation	ε_1 (SD)	ε_2 (SD)	von Mises Eq. strain (SD)
Shear	RD	0.19 (0.01)	−0.22 (0.01)	0.24 (0.01)
	45°	0.20 (0.01)	−0.24 (0.01)	0.25 (0.01)
	135°	0.17 (0.01)	−0.20 (0.01)	0.21 (0.01)
Hole tension	RD	0.48 (0.01)	−0.17 (0.01)	0.48 (0.01)
	DD	0.60 (0.01)	−0.28 (0.01)	0.60 (0.01)
	TD	0.50 (0.02)	−0.22 (0.01)	0.50 (0.02)
Notch tension	RD	0.31 (0.03)	−0.04 (0.00)	0.34 (0.04)
	DD	0.34 (0.03)	−0.08 (0.01)	0.35 (0.03)
	TD	0.29 (0.03)	−0.07 (0.01)	0.31 (0.04)
V-bend	RD	0.20 (0.01)	0.00 (0.00)	0.23 (0.01)
	DD	0.21 (0.01)	0.00 (0.00)	0.25 (0.01)
	TD	0.20 (0.01)	0.00 (0.00)	0.23 (0.01)
Plane-strain butterfly	RD	0.14 (0.02)	0.00 (0.00)	0.17 (0.02)
	TD	0.15 (0.01)	0.00 (0.00)	0.17 (0.01)
Plane-strain dome	RD	0.20 (0.01)	0.03 (0.00)	0.25 (0.01)
	TD	0.20 (0.01)	0.01 (0.00)	0.24 (0.01)
Eq. biaxial dome	–	0.25 (0.02)	0.18 (0.02)	0.43 (0.04)

Table 4
Coefficients of the phenomenological fracture model (Eq. 12).

Orientation	c_1	c_2	c_3
RD	0.8307	0.0547	−5.1814
DD	1.9767	−0.0040	−6.2539
TD	1.9541	−0.0160	−5.4289

Of particular interests are the strain paths corresponding to the shear tests that deviate from the ideal principal strain path of equal and opposite strains $\left(\frac{\varepsilon_2}{\varepsilon_1} = -1\right)$. As discussed by Abedini et al. (2017c), this strain path for simple shear tests is a direct consequence of the kinematics of simple shear from the imposed deformation gradient and is thus independent of the material. The strain path for ZEK100-O initially follows the simple shear strain path near yielding but then deviates towards a more compressive strain path. Assuming volume conservation for deformation of the magnesium alloy, the results of Fig. 14 suggest that the thickness of an element subjected to shear state increases with deformation. The Swift phenomenon, defined as the occurrence of axial plastic deformation during monotonic free-end torsion of solid rods or tubes (Swift, 1947), might be responsible for this behaviour. Recently, Guo et al. (2013) related the Swift phenomenon to twinning mechanisms activated during plastic deformation of hcp alloys, a description which is in line with the twinning activities reported by Abedini et al. (2017a) for shear tests of ZEK100-O using electron backscattered diffraction (EBSD) analysis. It should be noted that this observation in the shear tests is not due to the selection of the shear geometry since ideal strain paths with equal and opposite principal strains have been previously reported for shear tests on different fcc and bcc materials with the same specimen geometry (Abedini et al., 2017b,c; Rahmaan et al., 2017).

The fracture strains depend on the imposed stress states and orientations. To visualize this better, the phenomenological fracture curve described in Section 3.5 was calibrated to the experimental data in three directions corresponding to the RD, DD, and TD, with the associated coefficients given in Table 4 and the results shown in Fig. 15. Note that the notch tension tests were not considered for the calibration since these tests are known to exhibit a pronounced increase in the stress triaxiality from the onset of plastic deformation (Dunand and Mohr, 2010; Beese et al., 2010). Furthermore, due to the significant strain localisation, the stress state is no longer plane-stress with severe through-thickness stress gradients. Due to these reasons, the notch tensile tests were excluded from calibration of the phenomenological fracture curve.

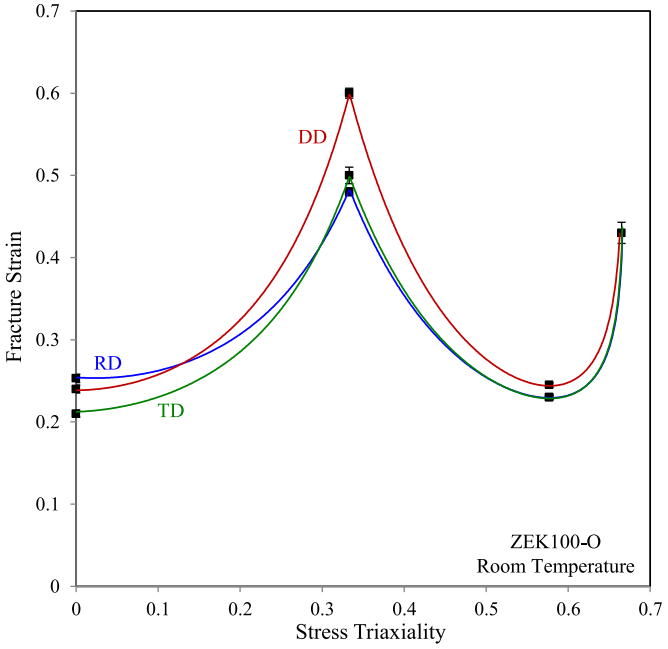


Fig. 15. Fracture *locus* under proportional conditions. Symbols show the average experimental data.

When it comes to stress state dependency, it can be seen from Fig. 15 that the plane-strain tension condition has the lowest fracture strain closely followed by the shear state while the material shows the highest ductility under the uniaxial tension condition for all orientations. In terms of anisotropy, it can be seen from Fig. 15 that the DD direction possesses the highest ductility while the fracture strains in the RD and TD directions are comparable. Anisotropy in fracture is most significant under the uniaxial tension condition in which the DD direction displays approximately 20% higher ductility than the RD and TD directions while the plane-strain condition exhibits a negligible directional sensitivity. It should be mentioned that the equi-biaxial state is direction independent, in other words, all the directions on the plane of the

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sheet experience an equal magnitude of stress which is the underlying reason why all the fracture curves converged at the equi-biaxial point in Fig. 15, and the same fracture strain was used to calibrate the curves at this point. However, the material eventually fails from a limiting direction that was observed to be the RD for equi-biaxial dome tests on ZEK100-O.

It is important to note the general shape of the fracture *loci* in Fig. 15 where the failure strain in shear is markedly lower than in uniaxial tension and is very similar to that of plane-strain tension. Whether the shear failure strains should be lower than uniaxial tensile loading is a current source of controversy in the literature and potentially might be related to the choice of the shear test specimen. For instance, Scales et al. (2016) conducted torsion tests on AA6061-T6 tubes and observed that the shear fracture strain of the material is significantly (about 300%) higher than that of reported by Beese et al. (2010) for AA6061-T6 sheets with an in-plane shear specimen. However, conducting torsion tests is not experimentally feasible for sheet metals. In-plane shear specimens are highly susceptible to fracture initiation from free boundaries where deformation is close to uniaxial states. In such cases, the strain at the center of the gauge area (shear zone) can only be considered as a lower-bound estimate of the fracture strain under the shear state. It should be mentioned that, for the magnesium alloy considered in the present study, Abedini et al. (2017b) conducted shear tests with the butterfly specimen where fracture was detected to clearly initiate from the center of the gauge section and not the specimen edges and the fracture strains were comparable to the values obtained with the shear specimen used in the present study. It is worth mentioning that, recently, Rahmaan et al. (2017) have shown that gauge lengths are critical for shear tests and that local shear strains measured microscopically near the fracture surface resolved from grain rotations can be much higher than the strains reported from DIC measurements that average the strains over a larger area.

4.1.1. Selection of appropriate test geometry for plane-strain tension

The plane-strain condition is critical for sheet metal forming operations since most materials exhibit their lowest ductility under this state of deformation. During an automotive crash event, structural components such as crush rails fold and tight-radius bends are commonly formed within which the state of stress is plane-strain tension at the outer radius of the bend. Due to the importance of this loading condition, this section is devoted to comparing the results of all the three plane-strain tension tests performed in the present study. Fig. 16 shows the strain paths to fracture from the three tests, namely the plane-strain dome, butterfly, and v-bend, in the RD direction. It can be seen that all of the tests lead to strain paths close to the desired plane-strain condition with small minor strains. The strain path of the v-bend test lies almost perfectly on the zero minor strain axis and the strain path of the plane-strain butterfly test is also close to the perfect condition. However, the plane-strain dome test shows some deviations from an ideal plane-strain path for small deformation which is due to biaxial bending associated with the dome radius (Hotz and Timm, 2008).

Furthermore, in terms of the fracture strains in Fig. 16 and Table 3, it can be observed that the v-bend test results in higher fracture strains than the other two tests, specifically, the fracture strains are significantly higher than those of the plane-strain butterfly test. The reason for the generally higher fracture strains in the v-bend test can be correlated to the location where the maximum strain occurs in the specimen. As opposed to the plane-strain dome and butterfly specimens in which the maximum strains occur through the thickness on the mid-plane (Dunand and Mohr, 2010), the maximum strains in the v-bend test happen on the surface of the specimen with strong strain and

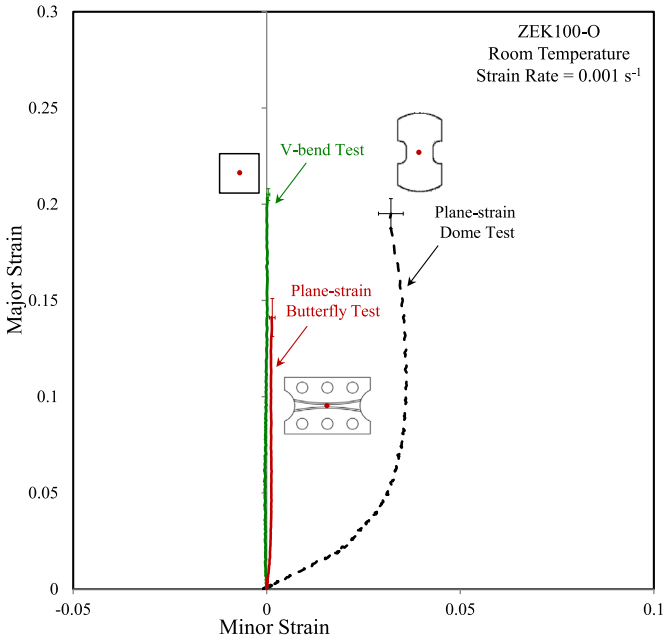


Fig. 16. Strain paths to fracture for different plane-strain tests. All the tests were performed in the RD.

stress gradients through the thickness. It is argued by Morales-Palma et al. (2013) that such gradients help with suppressing the onset of plastic localisation in tight-radius bending resulting in a proportional test to fracture. Moreover, the DIC method is only capable of capturing strains on the surface; therefore, strains at the center of the butterfly and dome specimens at the time of fracture are expected to be closer to the fracture strain on the surface of the v-bend specimen. It should be noted that through-thickness strain gradients with maximum values on the mid-plane exist more or less for all of the tensile specimens used in this study so that the fracture strains on the surfaces are lower-bound estimates for the ductility of the material. This highlights the advantage of the v-bend test for fracture characterisation of sheet under plane-strain conditions, with fracture strains that can be more representative of the failure strains observed in tight-radius bends in crashworthiness experiments of crush rails (Omer et al., 2017).

In addition, as discussed by Abedini et al. (2017b), using through-thickness machining for fabricating specimens, increases the likelihood of initiating fracture at a local discontinuity as a result of machining-induced defects. In general, specimens that do not require through-thickness machining are more suitable for fracture characterisation. The butterfly specimen features a large through-thickness machined section that represents a potential reason for lower fracture strains compared to the other two specimens. Despite this drawback, it should be mentioned that the butterfly is a versatile specimen that can be used to characterize fracture over a range of stress states (Mohr and Henn, 2007; Anderson et al., 2017) although only the plane-strain state was utilized in the present study.

4.2. Non-proportional tests

The load-displacement responses and the strains at the time of fracture for the non-proportional tests are given in Fig. 17 and Table 5, respectively. Note that for the results presented in Fig. 17 and Table 5, the pre-strained material was treated as a new material thus the deformation corresponds only to the second stages of the loading without considering the initial strains existing in the material from the first stages of the deformation. Based on

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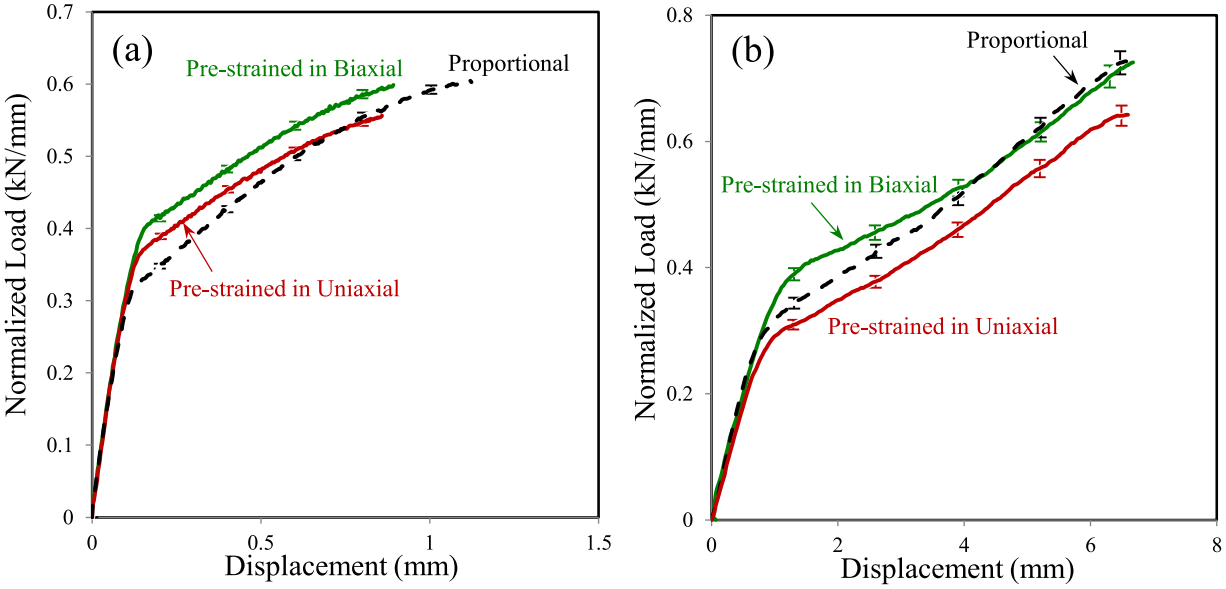


Fig. 17. Representative load-displacement responses in the RD direction of the specimens of (a) shear and (b) v-bend after pre-straining. Results of the proportional tests are also shown for comparison. Note that due to the different initial sheet thicknesses caused by pre-straining, the loads are normalized by the initial sheet thicknesses to provide a better comparison between different tests.

Table 5
Fracture strains obtained from non-proportional tests performed with different orientations. SD stands for standard deviations.

First stage deformation	Second stage deformation	Orientation	ε_1 (SD)	ε_2 (SD)	von Mises Eq. strain (SD)
Uniaxial tension	Shear	RD	0.20 (0.01)	−0.23 (0.01)	0.25 (0.01)
	Plane-strain	RD	0.19 (0.01)	0.00 (0.00)	0.22 (0.01)
	Plane-strain	TD	0.18 (0.01)	0.00 (0.00)	0.21 (0.02)
Eq. biaxial tension	Shear	RD	0.18 (0.01)	−0.23 (0.01)	0.24 (0.01)
	Plane-strain	RD	0.15 (0.01)	0.00 (0.00)	0.17 (0.01)
	Plane-strain	TD	0.14 (0.01)	0.00 (0.00)	0.16 (0.01)

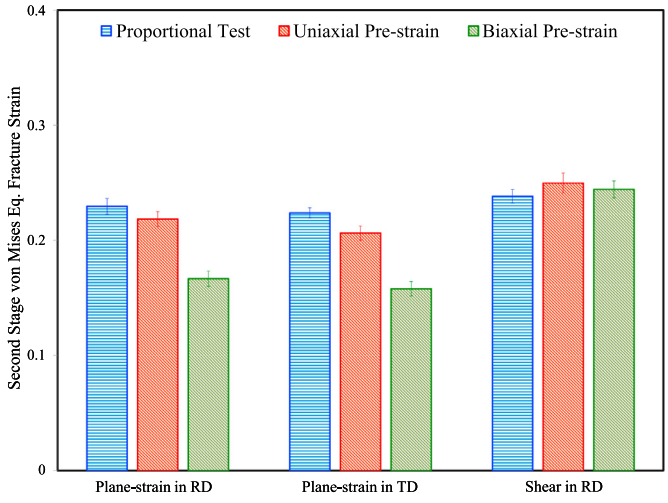


Fig. 18. Fracture strains under proportional and non-proportional tests. The pre-strains are not considered in this figure.

this assumption, the fracture strains in the proportional and non-proportional tests are compared in Fig. 18. It can be seen that the fracture strains under the shear state are not significantly influenced by pre-straining; however, the fracture strains for the plane-strain tension condition are reduced by the pre-straining deformation. The decrease of the fracture strains in the plane-strain v-bend tests is similar for both orientations of the RD and TD. Furthermore, it can be seen from Fig. 18 that the reductions in fracture strain in the plane-strain condition are more remarkable after biaxial pre-straining.

Moreover, the strains can be considered in a cumulative manner such as shown in Fig. 19 where the strain paths of non-proportional tests from the initial deformation (pre-straining) up to fracture are compared where the abrupt changes of the stress states are apparent. In addition, the cumulative fracture strains in the non-proportional tests are compared with that of the proportional tests in Fig. 20. It can be seen that the ductility under all loading conditions has increased, specifically the fracture strains of the shear tests are significantly higher due to pre-straining. The implications of the results of the non-proportional tests can be further evaluated in light of the "damage indicator" approach, as described below.

4.2.1. Damage accumulation

Generally speaking, the entire class of phenomenological fracture models are built upon a failure *locus* and a damage accumulation function. Commonly, the equivalent plastic strain is taken as the failure metric and the stress state is characterized in terms of the stress triaxiality. Most of the reported work presented the results of fracture simulations in terms of averaged stress triaxiality (*e.g.* Bao and Wierzbicki, 2004) or the stress triaxiality at the onset of fracture (*e.g.* Barsoum and Faleskog, 2007). However, a more recent investigation into non-proportionality by Benzerga et al. (2012) raised doubts about utilizing averaged or final stress triaxialities for fracture characterisation. Moreover, another common practice in the literature to consider non-proportionality is utiliz-

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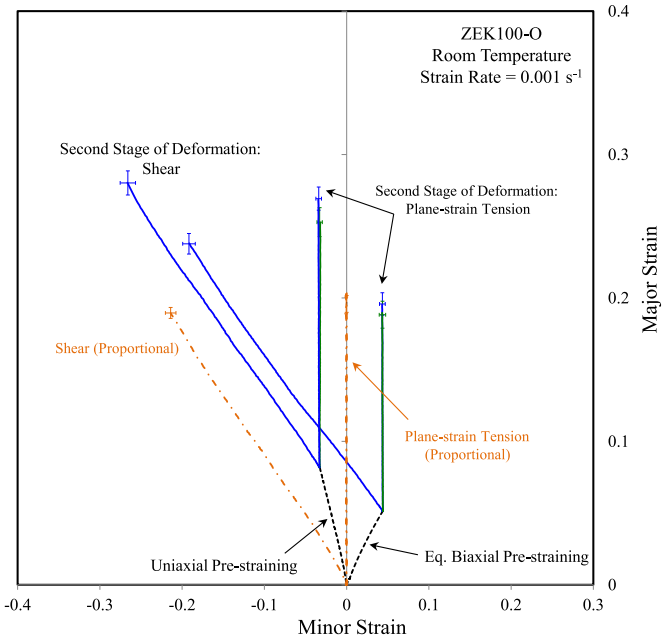


Fig. 19. Strain paths to fracture for non-proportional tests. The strain paths of the proportional tests are also shown for comparison.

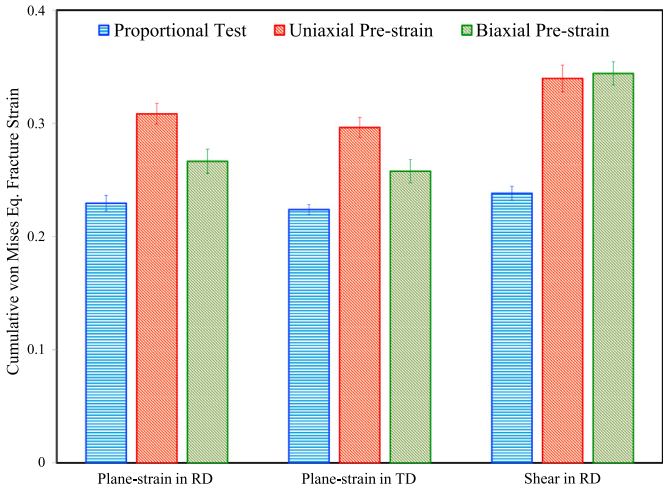


Fig. 20. Fracture strains under proportional and non-proportional tests. Here, the strains of the non-proportional tests are cumulative, *i.e.* the vertical axis plots the sum of the pre-strains plus the strains to fracture in the second stages of deformation.

ing a damage parameter, D, in the form of:

$$D = \left[\frac{\varepsilon^p}{\varepsilon^f(\eta,\bar{\theta})}\right]^m \tag{13}$$

where ε^p is the equivalent plastic strain and m is the damage exponent. It is important to emphasize that the formulation in Eq. (13) is purely phenomenological and only strictly valid for proportional loading. For the case of non-constant stress triaxiality and Lode parameter, Eq. (13) can be written in the incremental form of:

$$dD = \frac{m}{\varepsilon^f(\eta,\bar{\theta})}\left[\frac{\varepsilon^p}{\varepsilon^f(\eta,\bar{\theta})}\right]^{m-1} d\varepsilon^p. \tag{14}$$

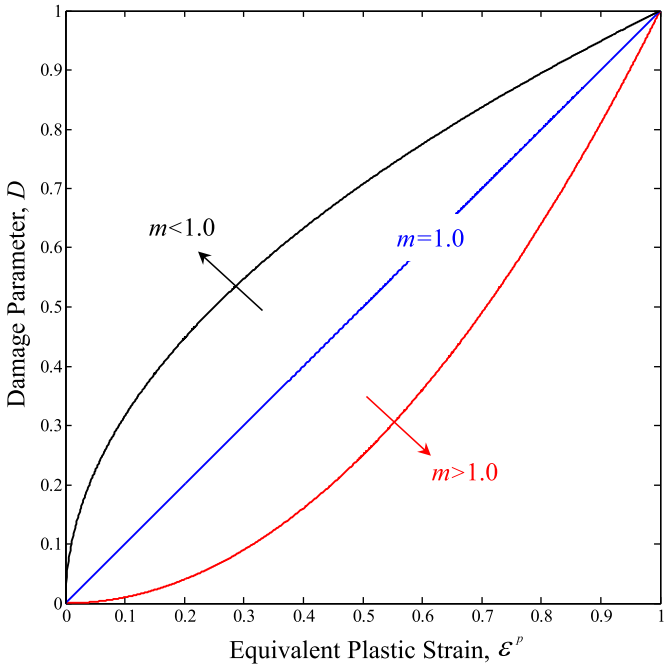


Fig. 21. Accumulation of the damage parameter, D, with plastic deformation for different ranges of the damage exponent.

Such that the cumulative D can be obtained with the following integration:

$$D = \int \frac{m}{\varepsilon^f(\eta,\bar{\theta})}\left[\frac{\varepsilon^p}{\varepsilon^f(\eta,\bar{\theta})}\right]^{m-1} d\varepsilon^p. \tag{15}$$

For the case of a linear damage accumulation with $m = 1.0$, Eq. (15) reduces to:

$$D = \int \frac{d\varepsilon^p}{\varepsilon^f(\eta,\bar{\theta})}. \tag{16}$$

Linear damage in Eq. (16) was first utilized by Johnson and Cook (1985) and is also identical to definition of the so-called "damage indicator" utilized in Marcadet and Mohr (2016). Eqs. (13)–(16) suggest that the damage starts to accumulate from the onset of plastic deformation up to fracture when the damage parameter D reaches unity. As shown in Fig. 21, the rate of increasing D is determined by the exponent m in which slow ($m > 1.0$) to fast ($m < 1.0$) rates of damage (with respect to ε^p) can be obtained, and $m = 1.0$ results in a linear damage accumulation; thus, based on Eqs. (13)–(16) damage accumulation is never zero with plastic deformation.

To demonstrate the evolution of damage for the non-proportional tests performed in the present study, values of the damage parameter for some typical damage exponents used in the literature are shown in Table 6. It is evident from the results in Fig. 18 that pre-straining under uniaxial or biaxial tension did not have any impact on the subsequent fracture strain under the shear state. In fact, when considering the cumulative values in Fig. 20, the cumulative fracture strains are increased by the initial pre-straining. This observation is in contradiction with the approach of Eqs. (13)–(16) since based on Table 6, the value of D before the second stages of deformation is a positive value indicating the existence of an initial damage in the material before commencing the second stage of deformation. To show this discrepancy, Fig. 22 compares the predicted fracture strains using different values of m along with the experimental data for different pre-straining conditions. The predicted fracture strains are also presented in Table 6. It can be seen from Fig. 22 and Table 6 that increasing the value of the damage

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Table 6
Damage parameter D for different pre-straining conditions with various damage exponents and their predictions for the fracture under the second stages of deformation.

	Pre-straining type	$m = 0.5$	$m = 1.0$	$m = 1.5$
Damage parameter D	Uniaxial	43%	19%	8%
Damage parameter D	Biaxial	48%	23%	11%
Predicted shear fracture strain (%Error)	Uniaxial	0.08 (69%)	0.19 (23%)	0.23 (10%)
Predicted shear fracture strain (%Error)	Biaxial	0.06 (74%)	0.18 (25%)	0.22 (10%)
Predicted plane-strain fracture strain in RD (%Error)	Uniaxial	0.08 (66%)	0.19 (15%)	0.22 (1%)
Predicted plane-strain fracture strain in RD (%Error)	Biaxial	0.06 (65%)	0.18 (6%)	0.21 (27%)
Predicted plane-strain fracture strain in TD (%Error)	Uniaxial	0.08 (62%)	0.19 (10%)	0.22 (5%)
Predicted plane-strain fracture strain in TD (%Error)	Biaxial	0.06 (63%)	0.18 (11%)	0.21 (31%)

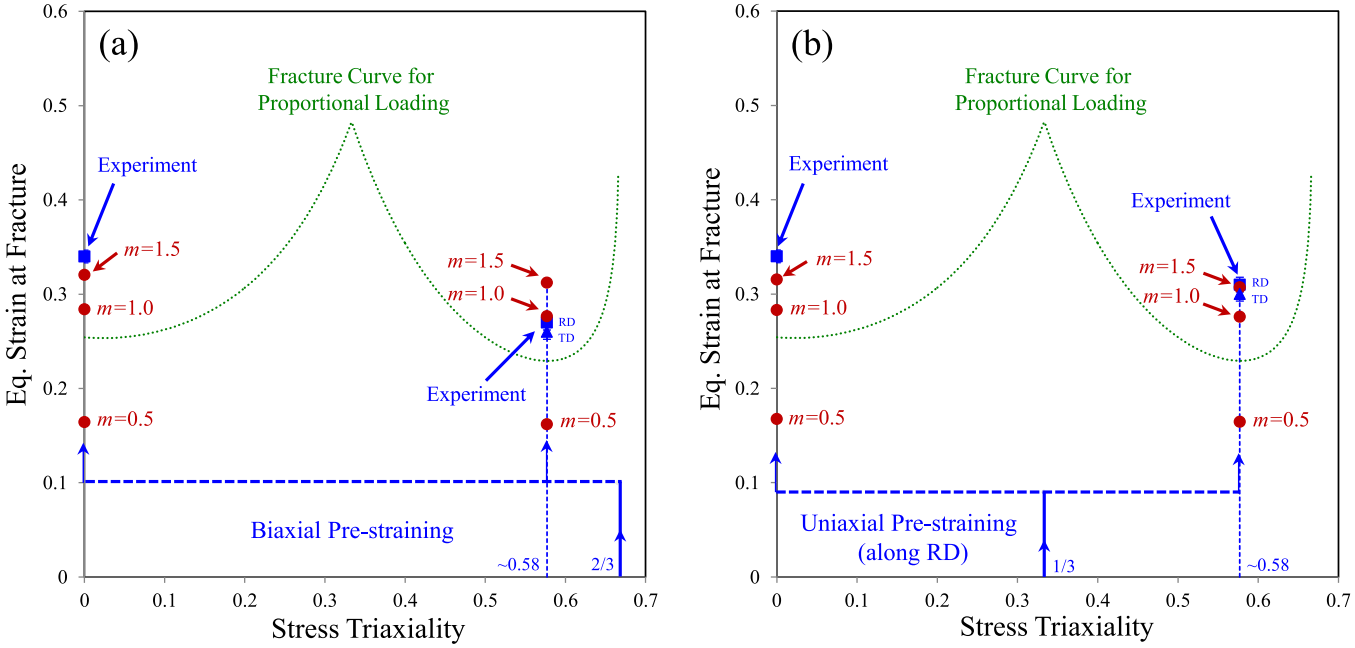


Fig. 22. Influence of the damage exponent, m, on non-proportional fracture predictions with (a) biaxial pre-straining and (b) uniaxial pre-straining (along RD). Load path histories are shown as blue curves. Predictions of fracture strain using the damage indicator approach for a range of damage exponents (m = 0.5, 1.0, 1.5) are plotted as red symbols and corresponding values of m are indicated. For reference, the proportional fracture *locus* in the RD is also plotted (green curve). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

exponent leads to better fracture predictions for the shear state for both pre-straining conditions; however, the damage exponent of unity provides the best prediction for the plane-strain tension test after biaxial pre-straining. It is evident from the comparison between the phenomenological model predictions and measured fracture strains that no single value of damage exponent can capture the measured trends.

The results of the non-proportional tests suggest that the damage mechanisms responsible for fracture in the shear and plane-strain tension states are different such that only the damage mechanisms in the plane-strain condition were affected by pre-straining. In other words, the shear fracture response of the material after uniaxial or biaxial pre-straining is similar to the behaviour of undeformed material, at least for the pre-straining levels considered. In addition, pre-straining prior to the plane-strain tension tests results in different impacts on the fracture strains if the initial deformation is uniaxial or biaxial tension (also note the higher damage parameters for biaxial tension in Table 6). Further investigation in this area requires the evaluation of additional stress states for both the first stage (pre-straining) and second stage of deformation to provide a more complete picture of the influence of non-proportional loading on the fracture response of the alloy. The present results highlight that phenomenological damage indicator models may not be appropriate for severe changes in strain paths. Microstructural evolutions will certainly play a role with respect to fracture in non-linear strain paths. Future work is required to connect the macroscopic fracture behavior to the underlying microscopic damage mechanisms.

5. Conclusions

Fracture experiments were performed with different types of specimens extracted from a rare-earth magnesium alloy sheet to reveal the behaviour of the material at room temperature, under quasi-static conditions. The results of proportional loading under stress states of shear, uniaxial tension, plane-strain tension, and equi-biaxial tension showed that a moderate anisotropic trend exits in the fracture response of the magnesium alloy. The plane-strain tension condition was obtained with three different types of specimens for which it was shown that the v-bend test can lead to a desired condition of almost perfectly zero minor strains. In addition, the fracture strains obtained with the v-bend test are higher than its counterparts since the maximum strains happen on the surface of the specimen with suppressed necking. Non-proportional tests were performed with uniaxial or biaxial pre-straining to the same plastic work level followed by abrupt changes of the stress state to plane-strain tension or shear. The measure of the plastic work was chosen to stop the pre-straining under different stress states to achieve an equivalent plasticity

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level before commencing the second stages of deformation. It was observed that fracture strains under the shear state did not show any significant sensitivity to uniaxial or biaxial pre-straining histories, *i.e.* the shear fracture strains were similar in both the undeformed and pre-strained sheets. Furthermore, when considering cumulative strains from the initial deformation to fracture, the ductility of the material increased under both pre-straining conditions. The novel experimental design of non-proportional experiments facilitated an analytical evaluation of using a so-called damage indicator approach where it was shown that the damage indicator approach commonly used in phenomenological fracture modelling of materials is not applicable to all stress states, at least for the material under investigation.

Acknowledgements

Financial support for this work provided by Cosma International, Automotive Partnership Canada, the Ontario Research Fund, the Natural Sciences and Engineering Research Council of Canada, the Canada Research Chairs Secretariat, and the Canada Foundation for Innovation is gratefully acknowledged. Also the authors would like to thank Dr. Michael Nemcko for helpful discussions on deformation mechanisms of magnesium alloys.

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Please cite this article as: A. Abedini et al., Experimental fracture characterisation of an anisotropic magnesium alloy sheet in proportional and non-proportional loading conditions, International Journal of Solids and Structures (2018), https://doi.org/10.1016/j.ijsolstr.2018.04.010