Axisymmetric V-Bending of Sheet Metal: Determining the Fracture Strain and the Weakest Material Direction for Plane Strain Tension in One Test

T Beerli1*, V Grolleau1,2, D Mohr1, C C Roth1

1 Department of Mechanical and Process Engineering, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland
2Univ. Bretagne Sud, Laboratoire IRDL UMR CNRS 6027, F-56100 Lorient, France
*beerlit@ethz.ch

Abstract. Plane strain tension is one of the most critical loading conditions leading to ductile failure in forming and crash applications. Hence knowing the fracture strain and weakest orientation for this stress state is crucial for safe design. A novel axisymmetric V-bending experiment is proposed to identify the strain to fracture and the weakest material orientation for plane strain tension under proportional loading. After clamping its inner and outer boundaries, a disc-shaped specimen with an annular gage section is bent over a tubular knife of diameter 54mm. A single camera takes images of the top surface of the specimen throughout the experiment. It allows for timely crack detection and digital image correlation-based strain measurements. Experiments are performed on a range of modern engineering materials comprising two aluminium alloys (AA7075 and AA6014) as well as two steels (DP1180 and CR4). The experiments are complemented by Finite Element simulations to assess the robustness of the novel experimental approach.

1. Introduction

Plane strain tension is one of the most critical loading conditions leading to ductile failure in forming and crash applications. Most fracture models, whether they are phenomenological or micromechanics-based, assume a minimum in failure strain under plane strain tension. For a Levy von Mises solid, a triaxiality of $\eta = 1/\sqrt{3} \approx 0.58$ and a Lode angle parameter of zero characterizes this stress state.

Existing experimental testing techniques for this stress state can be divided into in-plane and out of plane experiments. One of the most common in-plane experiment uses symmetrical notched tensile specimens [1-3]. These specimens expose severe limitations in the strain field and thus stress state homogeneity, which is partially due to through thickness necking [4, 5]. In addition, early onset of fracture might occur from the free edges in a tensile stress state, thereby leading to an underestimation of the fracture strain for plane strain tension.

Out of plane experiments on the other hand are usually performed on flat specimens, for example in Keeler or Nakazima experiments [6]. The most common out of plane testing technique is V-bending of a flat sheet strip coupon over a knife [7, 8], which has also been included in several norms, e.g. VDA 238-100, DIN 50111, ASTM E290, ISO 7438, and JIS Z2248. The major limitation of the V-bending experiment is the maximum strain that can be obtained, once full fold over is reached. Dihedral Mini-Nakazima experiments [9] can be used to overcome this shortcoming by taking advantage of a stretch-bending type of mechanism.
The present paper is an extension of [10], in which a novel experimental technique is presented which allows to determine the weakest material orientation from a single test. A wide range of material thicknesses between 0.5 to 2.5mm can be assessed, allowing for fracture strains of at least 0.8. The main idea revolves around a disk shaped sheet specimen clamped on the inside and outside being bent over an axisymmetric knife. To validate the novel experimental setup, four new sheet metals are tested with up to five repeats: 1.2mm thick aluminium alloy AA6014, 2mm thick aluminium alloy AA7075, 1mm thick dual phase steel DP1180 and a 0.6mm thick deep drawing steel CR4. The results are compared to Dihedral Mini-Nakazima experiments as well as to numerical simulations.

2. Design

In most plane strain tension fracture experiments the material is tested in one orientation at a time, hence several experiments with different orientations have to be performed per material. The idea of the novel axisymmetric V-bending technique is to test all material orientations at the same time and determine the orientation with the lowest fracture strain under plane strain tension. Figure 1a shows the setup used for the test. It consists of an inner shaft which clamps the disk shaped sample on the inside (Figure 1d) with a single fine pitch M16-12.9 screw. The outside of the specimen is clamped by a top and bottom ring connected with eight M10 screws. The outer clamping of the specimen is connected to the lower fixture with the help of four rods. The upper part (light gray) is connected to the load cell and the moving crosshead of the testing machine as well as to the tubular knife (Figure 1c). The camera with attached ring light is connected to the upper part to maintain a constant focal distance from the specimen surface. The clamping solution chosen for this setup allows an unobstructed view on the whole specimen surface (Figure 3c) enabling planar Digital Image Correlation.

Figure 2 exemplarily shows the mechanism of the experiment with a 1.5mm thick generic material (DP 780 hardening from [11] with von Mises constitutive framework). The ring shaped knife moves upwards and thereby deforms the disk specimen. From the beginning of the experiment, the strain concentrates in a toroidal prism above the knife with the highest strains on the top surface. To assess the quality of the stress state, the evolution of the stress triaxiality in the element with maximum equivalent plastic is evaluated (Figure 2b). For the whole experiment, the stress triaxiality of the element stays between 0.568 and 0.575, which is well within ±1.5% of the ideal value of $\eta = \frac{1}{\sqrt{3}}$ for plane strain tension for a Levy-von Mises material. To quantify the amount of deformation we introduce the effective strain based on the principal strains as

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_i^2 + \varepsilon_{ii}^2 + \varepsilon_{III}^2}.$$  

(1)
Figure 1. Experimental Setup: (a) axisymmetric V-bending device and (b) picture of setup with
1 specimen (red), 2 inner clamping with center screw, 3 outer clamping, 4 knife-like circular punch (green), 5 lower fixture (dark grey), 6 camera with ring light and upper fixture (light grey). (c) Technical drawing of the central part and (d) of the specimen. A notch is introduced to mark the rolling direction.

To determine the optimal specimen dimension a parametric study is performed. The diameter of the disk is limited by the maximum force of the machine. To be able to test sheets up to 2.5mm on a 250kN electro-mechanical testing machine (Instron 5985), the outer diameter is fixed to 92mm (Figure 1d) and the hole diameter to 16.2mm allowing a M16 screw to fit. The single screw allows for a maximum clamping force of 145kN in the centre, which is matched by eight M10 screws on the outside. With the constraint of keeping the clamping width and the distance from the knife on the inside and outside equal, the remaining dimensions of the specimen are selected. Numerical studies show that a sharper knife leads to lower forces at fracture, thus a tip radius of 0.5mm is chosen (Figure 1c). To compensate any misalignment in the setup, the circular knife is set on a spherical joint.
3. Computational models
For the design and validation of the testing technique, finite element simulations are performed. For the steels, a rate independent non-associated quadratic plasticity model as proposed in [12] is used, whereas for the aluminium alloy a 3D extension of the YLD2000-2D proposed in [13, 14] is implemented. A self-similar hardening law is used to define the relationship between the equivalent plastic strain and the deformation resistance [13]. All simulations are carried out with the commercial FE solver Abaqus/Explicit (6.13-2) and the respective material models are implemented in VUMAT user subroutines. A model of the full disk is created, with 14 elements over the thickness and an element size in the critical area of 0.1mm (Figure 2a), resulting in more than 600'000 reduced integration solid brick elements (C3D8R). The clamping area as well as the knife are modelled as analytical rigid bodies and a penalty contact friction coefficient of 0.1 is used. Uniform mass scaling is applied to the model so that a simulation is completed within 500'000 explicit time steps, ensuring that inertia effects can be neglected.

4. Experiments
The performance of the new experimental setup is assessed on four engineering materials each with at least 3 repeats:
- 1.2mm thick aluminium alloy AA6014
- 2mm thick aluminium alloy AA7075
- 1mm thick dual phase steel DP1180
- 0.6mm thick deep drawing steel CR4
The samples for the experiments are waterjet cut as shown in Figure 1d. To allow for Digital Image Correlation (DIC), a random speckle pattern with a white background and black speckles of a size of around 50μm is applied. The axisymmetric V-bending setup is mounted in the testing machine and all tests are carried out with a crosshead speed of 2mm/min. A SVS-Vistek hr25CCX (5120 x 5120 pixels) camera with a 55mm f2.0 lens is used to take images of the test at 2fps and with spatial resolution of 14 μm/pixel. A LED ring light is mounted on the lens, evenly lighting the whole specimen surface during the experiment. Images from the experiments are post processed with the commercial DIC software Vic 2D (Correlated Solutions). A subset size of 25 and a step size of 6 are selected and the strain fields are computed using a Gaussian filter of size 5.

| Table 1. Yld2000-3D model parameters for aluminium AA6014 and AA7075 |
|---|
| A [MPa] | ε0 [-] | η [-] | k0 [MPa] | Q [MPa] | β [-] | α [-] | E [GPa] | ν [-] | ρ [kg/m³] |
| AA6014 | 513 | 1.041 | 0.768 | 1.003 | 0.9626 | 0.7501 | 0.9305 | 1.276 | 2780 |
| AA7075 | 0.8991 | 1.039 | 0.9980 | 1.008 | 1.017 | 0.9519 | 1.0298 | 1.052 | 2780 |
| A | 469.3 | 0.00295 | 0.259 | 135.5 | 179.2 | 12.169 | 0.008 | 73 | 0.33 |
| AA7075 | 855.4 | 0.00262 | 0.151 | 502.4 | 194.1 | 10.08 | 0.5 | 69 | 0.33 |

| Table 2. Non-associated Hill’48 model parameters for MP980 and CR4 steels |
|---|
| P12 [-] | P22 [-] | P44 [-] | G12 [-] | G22 [-] | G44 [-] | A [MPa] | ε0 [-] |
| CR4 | -0.5923 | 1.021 | 3.139 | -0.6558 | 0.9081 | 3.033 | 553 | 0.00417 |
| DP1180 | -0.4948 | 0.9896 | 3.095 | -0.4573 | 0.9023 | 2.946 | 1917 | 0 |
| η [-] | k0 [MPa] | Q [MPa] | β [-] | α [-] | E [GPa] | ν [-] | ρ [kg/m³] |
| CR4 | 0.2704 | 158.3 | 236.3 | 9.427 | 0.99 | 200 | 0.3 | 7850 |
| DP1180 | 0.1168 | 717.1 | 484.9 | 169.3 | 0.4485 | 202 | 0.3 | 7850 |

4.1. Results for the 2mm thick aluminum alloy AA7075

The results from the three experiments on the 2mm thick aluminum AA7075 are shown in figure 3. Excellent repeatability is obtained on the force displacement curves (black solid lines). All tests expose an initial elastic response (up to 0.7mm and 37kN), followed by a plastic regime that is indicated by a change in slope from 52kN/mm to 14kN/mm before a force maximum is reached (Figure 3a). As the slope of the force-displacement response flattens after transition to plastic deformation, the slope of the average effective strain around the sample (blue solid line) increases. A first crack occurs on the specimen surface at an effective strain between 0.18 and 0.2.

Figure 3b shows the strain evolution along the specimen circumference. A uniform evolution is observed exposing only minor deviations which are attributed to clamping errors. At 90% of the total displacement the first crack appears, which subsequently grows until the sample fails. It is not possible to detect the crack from a change in the evolution of the effective strain or the force displacement curve for this material. Only with optical methods the crack can be detected. To evaluate the quality of the plain strain condition during the experiment, we also introduce the absolute strain ratio

\[
\lambda = \frac{\varepsilon_1}{|\varepsilon_2|}.
\]

In theory, for plane strain tension this ratio would increase to infinity as the limit of the second principal strain approaches zero. For the selected experiments (Figure 3d) the absolute strain ratio increases with the effective strain. Throughout the test it stays well above 20, reaching more than 60 at the location of fracture.
4.2. Results for the 1mm thick dual phase steel DP1180

The force-displacement and average effective strain curves of the four repeats of the DP1180 experiments are shown in figure 4a. Very good repeatability is observed for both measurements. An initially elastic response (28kN/mm) is followed by a plastic regime (22kN/mm). After reaching a force maximum at about 80kN, a slight decrease in the force level is observed for all specimen before complete loss of load carrying capacity occurs.

![Image](image-url)

**Figure 3.** Results for Aluminium AA7075 experiments. (a) Force-displacement curves (solid grey lines) and average effective strain curves (solid blue lines) of the experiments, the corresponding simulation (dashed red line) and the fracture strain for the weakest material orientation of the dihedral mini Nakazima experiment (green dot). The chosen reference experiment is plotted darker and used in (b-d) (b) Evolution of the effective strain around the specimen. (c) Plot of the effective strain at the last instant before failure. (d) Circumferential average effective strain (black) and strain ratio (blue) along a radial path shown in green in figure 1c at the time points denoted in (a).

However, the initial onset of fracture (determined from visual inspection) occurs much earlier at a force level of about 72 kN and an effective strain of 0.26±0.01. The evolution of the crack is shown in figure 4b-d on a two quarter painted sample to better observe the crack. At step I (figure 4b) with \( U = 0.86U_{\text{max}} \) and only 75% of the strain at force maximum, the first two cracks develop in the negative 90°-orientation. These initial cracks continue to grow and at step II additional cracks start to appear in
the 90°-orientation (Figure 4c). At step III, the instant before complete fracture, i.e. full specimen separation, the cracks in 90° and -90°-orientation have grown to ±22.5° each. This underlines the importance of evaluating crack initiation with optical methods – force maximum criteria or slope change criteria might lead to significantly overestimating the fracture strain; in this case by 36%.

![Figure 4. Results for the dual phase steel DP1180.](image)

(a) Experimental force-displacement curves (solid grey lines) and average effective strain curves (solid blue lines), the corresponding simulation (dashed red line) and the fracture strain for the weakest material orientation of the dihedral mini Nakazima experiment (green dot). (b-d) evolution of the crack.

4.3. Results for the 1.2mm thick aluminum alloy AA6014
For the 1.2mm aluminum AA6014 alloy, three repeats were performed. The force displacement curves as well as the average effective strain lie perfectly on top of each other (figure 5a). After yielding around 4kN, the force displacement curve transitions into a plastic region with a slope of 8kN/mm. Fracture is reached at 27.25±0.25kN, a displacement of 3.65±0.05mm and an effective strain of 0.485±0.015. In this case the first crack coincides with the force maximum.
4.4. Results for the 0.6mm thick deep drawing steel CR4
As a fourth material a 0.6mm thick deep drawing steel CR4 is tested. Excellent repeatability is obtained for the three repeats (figure 5b), all of which expose only a small elastic region before the transition to the plastic region occurs. The first crack appears in all experiments at the force maximum of 31.6±0.3kN, a displacement of 4.8±0.08mm and an average effective strain of 0.65±0.03. After force maximum the effective strain continues to rise up to 0.8 before the force abruptly drops upon final fracture.

Figure 5. Results for the (a) aluminium alloy AA6014 and (b) the deep drawing steel CR4. Experimental force-displacement curves (solid grey line) and average effective strain curves (solid blue lines), the corresponding simulation (dashed red line) and the fracture strain for the weakest material orientation of the dihedral mini Nakazima experiment (green dot).

5. Discussion

5.1. Comparison with numerical results
For each of the four materials a simulation of the axisymmetric V-bending experiment is carried out using a full finite element model as described in section 2. For each material the calibration is done as described in [9], the model parameters are given in tables 1 and 2. For all but the CR4 the force displacement response from the simulations (red dashed curves in Figures 3a, 4a and 5) show excellent agreement with the experiment, assuming a machine stiffness of 100kN/mm. For the CR4 the simulation underestimates the force at fracture by 15%. This is tentatively attributed to an underestimation of the friction coefficient for the thin sheet. The estimation of the effective strain from the numerical simulations also works well for all materials, matching the fracture strain within less than 5% error.

5.2. Comparison with other plane strain tension experiment
All axisymmetric V-bending experiments are compared to the fracture strains obtained from Dihedral Mini-Nakazima (DMN) experiments in the weakest direction (green dots in Figures 3a, 4a and 5) performed as in [9]. For all experiments the fracture strain from the V-bending is slightly lower than in the DMN experiment with the biggest difference in the DP1180 with a difference of 0.08 and the aluminum AA7075 alloy with a difference of 0.05, while the other two materials have less than 5% difference. This is attributed to the challenging crack detection in DMN experiments which might lead to a late identification of a cracked specimen. Another possible reason might be the difference in measurement technique, as for the axisymmetric V-bending the average effective strain is taken, which might be slightly lower than the strain at the location where the first crack occurs.
6. Conclusion

A novel axisymmetric V-bending experiment is develop that allows characterizing the fracture strain in the weakest direction of sheet metal under proportional plane strain tension loading. The sample has a disk shape which is bent over a tubular knife of 54mm diameter. The design of the device allows to monitor the whole specimen surface with a single camera used to determine the surface strains with the help of planar DIC. The setup allows to probe all material directions in one single experiment and determine the least ductile material orientation for low strain as well as strains up to 0.8. Due to the axisymmetric shape of the specimen, early fracture from free (i.e. machined) edges is not possible.

References

[1] Wagoner R H 1980 Measurement and Analysis of Plane-Strain Work-Hardening Metall Trans A 11 165-75
[2] Gruben G, Hopperstad O S and Børvik T 2013 Simulation of ductile crack propagation in dual-phase steel Int J Fracture 180 1-22
[3] Lou Y and Yoon J W 2017 Anisotropic ductile fracture criterion based on linear transformation Int J Plasticity 93 3-25
[4] Dournaux J, Bouvier S, Aouafi A and Vacher P 2009 Full-field measurement technique and its application to the analysis of materials behaviour under plane strain mode Mat Sci Eng a-Struct 500 47-62
[5] Flores P, Tuninetti V, Gilles G, Gonry P, Duchêne L and Habraken A M 2010 Accurate stress computation in plane strain tensile tests for sheet metal using experimental data Journal of Materials Processing Technology 210 1772-9
[6] Banabic D 2010 Sheet Metal Forming Processes: Constitutive Modelling and Numerical Simulation Sheet Metal Forming Processes: Constitutive Modelling and Numerical Simulation 1-301
[7] Roth C C and Mohr D 2016 Ductile fracture experiments with locally proportional loading histories Int J Plasticity 79 328-54
[8] Noder J, Dykeman J and Butcher C 2021 New Methodologies for Fracture Detection of Automotive Steels in Tight Radius Bending: Application to the VDA 238–100 V-Bend Test Exp Mech 61 367-94
[9] Grolleau V, Roth C C, Lafile V, Galpin B and Mohr D 2019 Loading of mini-Nakazima specimens with a dihedral punch: Determining the strain to fracture for plane strain tension through stretch-bending Int J Mech Sci 152 329-45
[10] Beerli T, Grolleau V, Roth C C and Mohr D (submitted) Axisymmetric V-Bending: a Single Experiment to Determine the Fracture Strain and Weakest Sheet Material Direction for Plane Strain Tension.
[11] Li X, Roth C C, Bonatti C and Mohr D 2022 Counterexample-trained neural network model of rate and temperature dependent hardening with dynamic strain aging Int J Plasticity 151 103218
[12] Mohr D, Dunand M and Kim K H 2010 Evaluation of associated and non-associated quadratic plasticity models for advanced high strength steel sheets under multi-axial loading Int J Plasticity 26 939-56
[13] Roth C C, Fras T and Mohr D 2020 Dynamic perforation of lightweight armor: Temperature-dependent plasticity and fracture of aluminum 7020-T6 Mech Mater 149
[14] Dunand M, Maertens A P, Luo M and Mohr D 2012 Experiments and modeling of anisotropic aluminum extrusions under multi-axial loading - Part I: Plasticity Int J Plasticity 36 34-49