Simplified measurement of the strain to fracture for plane strain tension: On the use of 2D DIC for dual hole plane strain tension mini Nakazima specimens with dihedral punch

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Abstract. A plane-strain-tension stress state leads to a minimum in ductility in most micro-mechanical and phenomenological fracture models as well as Forming Limit Curves. Hence, this stress state plays a crucial role in many applications and a reliable measurement of the strain to fracture under plane strain tension is of particular importance when calibrating modern fracture initiation models. Recently, a new experimental technique has been proposed for measuring the strain to fracture for sheet metal after proportional loading under plane strain conditions. The basic configuration of the novel setup includes a dihedral punch applying out-of-plane loading onto a Nakazima-type disc-shaped specimen with two symmetric circular cut-outs. 3D Digital Image Correlation (DIC) is used to measure the surface strains of the specimen up to fracture. In contrast to the widely used V-Bending test, the maximum obtainable strain is not limited when using this set up, and fracture will always initiate after proportional loading in a plane strain tension stress state. In the present study, a major simplification of the testing methodology is proposed, reducing from 3D DIC to a simple 2D DIC method for measuring the fracture strain. Comparisons are presented on three metals, a 1.5 mm thick DP600 steel, a 0.8 mm thick DP450 steel and a 1.2 mm thick AA2024 aluminum alloy.

1. Introduction

The plane-strain-tension stress state plays a crucial role in many drawing applications as well as in crash events. Under plane stress conditions, most micro-mechanical and phenomenological models predict a minimum in ductility for a plane strain tension stress state. Forming Limit Curves (FLC) or modern stress state dependent fracture initiation models exhibit a “plane strain ductility valley” between uniaxial and equi-biaxial tension. Hence, the reliable measurement of the strain to fracture for plane strain tension is of utmost importance which requires reliable and accurate experimental techniques.

Attempts to classify the wide range of proposed experimental techniques can be found in Cheong et al. [1] or Grolleau et al. [2]. As already observed by Ghosh and Hecker [3], Morales et al. [4], and more recently by Tharrett and Stoughton [5], bending strain has a positive influence on the formability of a metal sheet, effectively delaying localized necking. The main difference amongst the various experimental techniques is the relative amount of in-plane stretching and out-of-plane bending:
- Example with almost pure stretching are the in-plane tension experiment of a flat specimen with lateral notches [6] or the Marciniak experiment [7]. These tests are of primary importance when determining the FLC since through thickness localization is not delayed by any bending. Hence, a conservative value of the strain at the onset of localization can be determined.

- Conversely, the V-bending test, as proposed in the VDA 238–100 [8] standard and used by Roth et al. [9], leads to a bending dominated state. A schematic view is proposed in figure 1a. In this case, through thickness localization is delayed, cracks occur on the free surface, and the strain path to fracture is almost free from any change related to tensile instability.

![Figure 1](image.png)

**Figure 1.** Schematic view of the V-Bending test (a) and the dual hole mini Nakazima with dihedral punch (b)

With a so-called inverse configuration, where the two rollers (component 4 in figure 1a) push the specimen (component 6) against the knife (component 3) with stationary spatial position, the displacement field of the specimen surface can be monitored using 3D DIC. This test leads to high major-to-minor strain ratios (above 20) and a homogenous plane strain tension stress state along 80% of the specimen width. The major drawback of V-bending is its maximum obtainable strain, limited by geometrical constraints [9]. This hinders its use for thin and/or highly ductile materials, see Grolleau et al. [2] and Noder et al. [10], without an initial pre-straining of the specimen. Usually pre-straining of the material is performed under stress states different from PST, which leads to non-proportional loading histories, which may influence the calculated fracture strain.

Alternatively, the dual-hole mini-Nakazima test (figure 1b) with a dihedral punch, creates a constant stress state through a stretch-bending plane strain tension experiment [2]. It is composed of a disc-shaped specimen (component 1) with an outer diameter of 60 mm and two 8 mm diameter circular cut-outs (2) creating a 10 mm long ligament. The cutouts on the face opposite to the punch are chamfered to prevent early fracture from the edge of the holes. The dihedral punch (component 3) has a 90° tip angle and a 1 mm edge radius. The first proposed experimental set-up [2] was used in a universal tension and compression machine.

2. **Automated mini-Nakazima device**

The second generation of mini-Nakazima device is presented in this study. It is a completely self-contained machine allowing for the automation of the test, from loading to unloading, including DIC analysis. The punch can be exchanged within minutes allowing the test of mini-Nakazima specimen with any kind of punch geometry, including hemispherical and dihedral. A sketch of the device is shown in figure 2. In this set-up, the loaded specimen is lying on top of the blank-holder. The blank-holder is supported with four gas-springs, each of them being able to apply a maximum vertical load of 28 kN. The punch lies on a 100 kN load cell, and passes through the blank-holder, via a linear ball bearing. Similar to the inverse configuration of the V-Bending setup [9], the vertical displacement is imposed to

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the die, using two translating screws with trapezoidal threads each of which can apply 100kN. Prior to testing, the die is moved down so that it is in contact with the specimen (figure 2, step 1). Next, the specimen is sandwiched between the blank-holder and the die. During step 2, the die and the blank-holder move together (figure 2, step 2) onto the gas-springs, thereby applying a clamping load on the specimen. Since the inner pressure of the gas-springs can be adjusted, the initial clamping load value applied at the beginning of step 2 can be tuned. After a displacement of about 5 mm, i.e. the clamping stroke, the punch is in contact with the specimen, and the stretch bending process begins. The testing speed is 2 mm/min, leading to a strain rate about 10^{-3}/s.

A pair of 5 MP cameras equipped with 100 mm f2.8 1:1 lenses is used to monitor the free surface of the specimen at an acquisition frequency of 1 Hz, with a pixel size of about 10 μm. The focal distance of about 400 mm between the cameras and the punch edge is almost constant along the test. The first camera (figure 2 “Cam.1”) is positioned vertically along the punch displacement direction, while the second camera is tilted by an angle of approximately 20° (figure 2 “Cam.2”). To determine the surface strain fields, digital image correlation are used (VIC 2D and 3D, Correlated Solutions). With this configuration, pictures from the first camera can be used for 2D DIC, or in combination with the pictures from the second camera for 3D DIC purposes. Logarithmic Hencky strains are calculated from the DIC analysis, using a facet size of 30 px (about 0.3 mm) and a step size of 7 px. In the absence of deformation, i.e. for a rigid body motion, the noise in effective strain ranges from 0 to 0.0022 with a standard deviation about 0.0004.

Figure 2. Description and time sequences of the automated mini-Nakazima device used for testing.

3. Experimental results
Four different materials are tested with three repeats, a 1.2 mm thick AA2024 aluminium alloy as well as three dual phase steels: a 0.8 mm thick DP450, a 1.5 mm thick DP600 and 1.5 mm thick DP980. All subsequent experimental results are given for the case of DP600 steel.

Figure 3 shows the evolution of the load as a function of the displacement of the upper die, which corresponds to the relative displacement of the specimen surface from the punch, if the stiffness of the specimen can be considered as negligible compared to the machine stiffness. For all materials, the load value reaches a maximum, and after a small decrease, the global failure of the specimen is indicated by a rapid drop. Depending on the material, the first cracks can be visible on the free surface before (for all steels), or at force maximum (in the case of aluminum). Figure 3 shows the top view of a DP600 specimen at the time of the very first visible cracks, along with the experimental strain field from the DIC analysis in terms of effective strain, i.e. Mises equivalent strain with plane stress and isochoric strain assumptions. Defining the ligament as the line joining the two chamfered holes, it is clear from figure 3 that the iso-values of strain are almost parallel to the ligament.
Figure 3. Load versus displacement during the plane strain tension test of a DP600 specimen, and views of the free surface and effective strain field at initiation of fracture just before force maximum.

The shape of the outer surface of the DP600 specimen at onset of first cracks is shown in figure 4a. The vertical displacement is plotted as function of the position along and across the ligament and calculated from 3D DIC. Starting from zero at the apex, i.e. highest points of the free surface, isolines at regular steps of 0.1 mm of the vertical ordinate are plotted. Figure 4b shows a through thickness micrograph of a DP600 specimen at ligament center, from an interrupted test at a time just before force maximum, with the ligament direction perpendicular to the figure, and thickness direction along the vertical axis. It is clear from figures 4 that the outer shape is far from a simple cylinder with its radius equaling the sum of the punch radius and sheet thickness. The local thickness strain gradient across the ligament direction leads to a flattened apex surface of the specimen.

Figure 4. Displacement field of the free surface of the specimen at the time of onset of first cracks (a). Through thickness micrography of the specimen from interrupted test, where ligament direction is perpendicular to the figure, thickness direction is vertical.
Major advantages of the dual hole plane strain tension experiment with dihedral punch are illustrated in figure 5a:

- The homogeneity of the strain field along the ligament is visible in figure 5a, where the effective strain is plotted as a function of the normalized position along the ligament, from -1 on the side of the left hand chamfered hole, to +1 at ligament’s end. Here, the amplitude of the variation in effective strain is only about 0.06 [-] along the ligament. The optical observation of the free surface enables a straightforward selection of the position of the very first crack to measure the fracture strain.

- The second advantage of the test is the quality of the plane stress tension state achieved. This quality is measured with the major to minor surface strain ratio, plotted as a function of the normalized position along the ligament in figure 5a. With a value above 5 to 20 recommended in literature, the value of the ratio in the present test significantly exceeds 20 along 80% of the central ligament length.

With the relative position of the cameras, the pictures from camera #1 are used for 2D image correlation, as well as for 3D image correlation along with camera #2 pictures. For 3D DIC, they are used as reference pictures. When using the same facet and step sizes in both DIC analyses, it is then possible to calculate a strain field from 2D and 3D DIC at the same reference positions within the picture frame of camera 1. The two DIC analyses lead to remarkably close strain field values.

The difference in strain value, 3D value minus the 2D DIC value, is plotted in figure 5b as function of the spatial position along and across the ligament, at the time of onset of first cracks. Iso-values of the difference in strain are plotted with a step of 0.02 in strain. The difference in effective strain is in the [0:0.01] range on a 0.5 mm wide strip, and in the [0:0.02] range on a 1.0 mm wide strip along the ligament. These ranges of strain difference can be reduced. Using a smaller facet size of 20 px, the error is reduced by about 50%. However, the drawback of this approach is an increased number of uncorrelated facets, i.e. loss of correlation, and a reduced number of strain values in the strain field as along the ligament (up to 10%). These ranges are found to be almost independent from the three tested materials or the strain level, but mainly depend on the shape of the deformed surface of the specimen.

A decrease in the punch radius from 1 mm down to 0.4 mm reduces the width of the strips by about 25 % in the case of the DP600 steel. The decrease in thickness from 1.5 mm DP600 to 0.8 mm thick DP450 lead to the same strip widths for each range of discrepancy for these two materials which fracture at almost the same strain level (0.8 in effective strain for DP600 and 0.85 for DP450).

![Figure 5](image-url)
4. Conclusion

A new testing device for automated mini Nakazima testing type is presented. This stretch-bending set-up is used on dual hole specimens with a dihedral punch, leading to a high quality plane strain tension stress state experiment as exemplarily shown for four materials. The experimental study shows that it is possible to reduce a standard three dimensional Digital Image Correlation analysis to a simple two dimensional analysis using a single camera positioned along the punch displacement direction. This simplification requires an initial validation of the image acquisition set-up for the given range of materials and thicknesses, but drastically simplifies the fracture strain identification from stretch bending experiments under a plane strain tension stress state.

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References

[1] Cheong, K., Omer, K., Butcher, C., George, R., & Dykeman, J. 2017. Evaluation of the VDA 238-100 Tight Radius Bending Test using Digital Image Correlation Strain Measurement. *Journal of Physics: Conference Series*, 896.

[2] Grolleau, V., Roth, C. C., Lafilé, V., Galpin, B., & Mohr, D. 2019. Loading of mini-Nakazima specimens with a dihedral punch: Determining the strain to fracture for plane strain tension through stretch-bending. *International Journal of Mechanical Sciences*, 152.

[3] Ghosh, A. K., & Hecker, S. S. (1974). Stretching limits in sheet metals: in-plane versus out-of-plane deformation. *Metallurgical Transactions*, 5, 2161-2164.

[4] Morales-Palma, D., Vallellano, C. and García-Lomas, F.J., 2013. Assessment of the effect of the through-thickness strain/stress gradient on the formability of stretch-bend metal sheets. *Materials & Design*, 50, pp.798-809.

[5] Tharrett, M. R., & Stoughton, T. B. (2003). Stretch-bend forming limits of 1008 AK steel (No. 2003-01-1157). SAE Technical Paper.

[6] Wagoner RH. 1980. Measurement and analysis of plane-strain work hardening. *Metall and Mat Trans A*, 11.

[7] Banabic, D. 2010. *Sheet metal forming processes: constitutive modelling and numerical simulation*. Springer Science & Business Media.

[8] VDA 238–100, (2017). *Test Specification: Plate Bending Test for Metallic Materials*

[9] Roth, C. C., & Mohr, D. 2016. Ductile fracture experiments with locally proportional loading histories. *International Journal of Plasticity*, 79.

[10] Noder, J., Abedini, A., & Butcher, C. (2020). Evaluation of the VDA 238–100 tight radius bend test for plane strain fracture characterization of automotive sheet metals. *Experimental Mechanics*, 60, 787–800.