A simple device to measure bend limit of sheet metals

A Deole, N Etxebarria, J Mendiguren, A Ilinich, M Weiss

1 Deakin University, Geelong, Australia, Institute for Frontier Materials, Waurn Ponds, Piddons Rd., VIC. 3216
2 Mondragon Unibertsitatea, 4, Loramendi kalea, 20500 Mondragon, Spain
3 Research and Innovation Center, Ford Motor Company, Dearborn, 2101 Village Rd., MI 48121, USA.

*Corresponding author e-mail: adityad@deakin.edu.au, nagore.etxebarria@alumni.mondragon.edu

Abstract. The analysis of bend fracture limits of sheet metals is important for the automotive industry. For high and mid-ductility materials, current methods are often unreliable due to the difficulty of detecting the initiation of a crack on the outer surface of the bend. Sophisticated techniques that rely on the strain evolution in the material are capable to detect the cracks and establish the bend limits using digital image correlation (DIC) strain measurement systems. However, these techniques are complex and sometimes impractical for industrial use. This study uses a simplified bend test technique that uses optical image processing to detect crack initiation to then determine the bend limits of aluminum alloys using a modified angled line method (MALM). The findings of this study indicate that the optical method is inconsistent in detecting the crack initiation and likely to result in a large deviation in detected the bend limits.

1. Introduction

The standard vee bend test [1,2] is commonly used to determine the minimum radius, \( r \), in bending before the sheet fractures. The ratio of this radius, \( r \), and the thickness, \( t \), gives the min bend limit, \( \frac{r}{t} \). A limitation of the standard bend test is that the measurement of the bend limit often relies on the punch radius while the radius of the actual sheet is not considered [3]. This leads to inaccurate estimates of the minimum radius in bending since the sheet is likely to deform to a smaller radius than that of the punch [3,4]. The VDA238-100 standard [2] has been developed to identify fracture in tight radius bending of sheet materials. It is a 3-point bend test with a sharp punch radius and two rolls which act as the bend supports. Fracture is determined using a predefined force threshold. Newly developed setups combine the 3-point bend test with digital image correlation (DIC) systems [2, 3]; this enables analyzing bending radius and strain during testing.

Mattei et al., showed that the fracture in bending is mainly controlled by the fracture limit of the surface grain. The damages in bending first initiated by formation of the shear bands. This then leads to surface undulations resulting in necking on the surface and then the final fracture[5]. This means the surface roughness in the bend corners grows into the formation of a crack. As bending progresses, the distributed micro cracks propagate and merge into wider, visible macro-cracks. This transition of the surface roughness to the onset of macro cracking is gradual and this makes the detection of the crack difficult [6,7]. The bend limit is directly affected by the accuracy of the crack detection and there is a high possibility for
overestimating the bend limit. The forming processes when designed based on such overestimated bend limit may then result in poor quality of the components. This issue is likely to occur when the detection of the crack is done by visual inspection which subjected to the operator’s perception of a crack. Kaupper et al., addressed this issue and proposed to identify the crack initiation by identifying the stagnation of the strain evolution curve in the material neighboring to a visible crack[7]. A practical limitation of this method is that the method involves complex DIC strain measurement.

Swillo et al. [6] investigated fracture initiation in aluminum with an optical image processing algorithm. The algorithm converts the grayscale image into a binary image using a histogram distribution of the original image. Due to the inherent color of the aluminum alloys, the cracks can be distinguished from the undamaged regions in the image processing routine. Another problem addressed in their study [6][8] was the in-situ measurement of strain. They used a modified angled line method (MALM) [6] and validated the approach in bending tests performed on two aluminum alloys. Above methods for detecting the crack and to measure forming strains in the bend test can be integrated into a simple bend test. This may provide a promising solution for estimating bend fracture limits in industrial production.

This paper presents a simple mechanical device combined with a camera that detects the crack initiation and measures strain at the onset of the crack. An optical image processing algorithm is developed in Matlab2019 that enables both crack detection and the strain measurement with the MALM method. The proposed device is tested for its robustness and repeatability using specimens of high and low ductile aluminum.

2. Materials

Two different aluminum alloys A1 with 2mm thickness and A2 with 1.5mm thickness were used. The tensile tests were performed according to ASTM E8/E8M-11 standard and with the specimen shape given in Figure 1. The crosshead speed was 3mm/min and the engineering strain was measured with a video extensometer. The tensile parameters are given in Table 1.

![Figure 1. Tensile test specimen.](image)

Table 1. mechanical properties of the aluminum alloys.

| Material | YP$_{0.2\%}$ (MPa) | Ultimate tensile stress (MPa) | Uniform elongation (%) | Total elongation (%) |
|---------|--------------------|-------------------------------|------------------------|---------------------|
| A1      | 224                | 339                           | 19.8                   | 27.1                |
| A2      | 498                | 556                           | 11.5                   | 15.8                |

3. Bending experiments

Rectangular strips of 90 mm length and 20 mm width (Figure 2b) were tested. The samples were cut using water jet and the rough edges cleaned using polishing paper. Two black lines with an angle inclination of 45° were marked on the sample surface. These lines were used to determine the bend strain using a modified angled line method explained in the section 5.
The bending device used in this study is shown in Figure 2a. The tooling is assembled in an Instron testing machine (see Figure 2a) which is equipped with a 30 kN load cell. It consists of a base plate with two vertical guide rods and a punch positioned in the centre having a 0.2 mm radius that provides the support point to the sample. The rollers are connected to the movable crosshead of the device with roller bearings to reduce friction. The diameter of the roller and the centre-to-centre distance are 25 mm and 33 mm, respectively. The specimen is inserted and initially held in place between the rollers and the punch by applying a small force. A crosshead movement of 5 mm/min is applied. A camera facing perpendicular to the sample surface is positioned at a distance of 40 mm (Figure 2a). The 2D images of the sample surface having a resolution of 1600 pixel x 1200 pixel were recorded with a rate of 1 picture/second. The punch remains stationary while the rollers move downwards (see Figure 2a). In this way the area of the sample in the punch contact region remains stationary and at a constant distance to the camera. This allows deformation being recorded without the risk of the viewing area moving out of focus. The tests were carried out with a speed of 5 mm/min until fracture occurred. 3 to 4 tests were performed for each material.

4. Automatic Crack Detection (ACD) software

A series of images captured during the bend test is processed in the automatic crack detection (ACD) software developed based on the pattern recognition algorithm presented in [6,8]. The algorithm differentiates the black and white pixels in the image and considers white pixels to be the crack (Figure 3d). The cracks developed are counted in each picture (Figure 3a and b). In the beginning the crack quantity increases due to number of microcracks emerging on the surface. The micro cracks then join to form a macro crack and the crack quantity decreases [6,8]. The crack is assumed to be initiated at an instance when the quantity of the cracks reaches a plateau and decreases. The software allows to change the threshold in order to change the curve shown in Figure 3c to show a distinct peak. This threshold is the minimum pixel size that will be considered as a crack.
Figure 3. The sample surface (a) before crack initiation (b) after crack (c) greyscale converted image (d) the evolution of the crack quantity.

5. Modified angled line method

The surface strain of the sample was measured using the modified angled line measurement method presented in [6,8]. For this, two inclined lines with an initial angle $\theta_0$ of $90^\circ$ were drawn on the sample surface. The ACD software then detects these lines and calculates the angle, $\theta$, between the two lines at every stage of bending. The angle, $\theta$, is then used to determine the maximum strain using Eq. 1. The change in angle during deformation is visually shown in Figure 4a, b and c.

$$\varepsilon_1 = \ln \frac{\cot \theta}{\cot \theta_0}$$  \hspace{1cm} (1)
6. Result and Discussion

6.1 Crack detection with the conventional load drop method

Figure 5a shows that load displacement curve for material A1. Using the recommended load drop of 30 N indicates fracture to occur at a punch displacement of approximately 10 mm, point A. However, no visual crack can be observed at this point (Figure 5b). Fracture initiation is visually observed at a later punch displacement of 12 mm (point B) representing a load drop of 230N.

![Figure 5. (a) Load-displacement curve for material A1 (b) crack initiation and growth on the outer sample surface.](image)

In case of material A2, the onset of cracking was clearly identified at the peak load at a punch stroke of approximately 7 mm, point A (Figure 6b)

![Figure 6. (a) Load-displacement curve for material A2 (b) crack initiation and growth on the outer sample surface.](image)
6.2 Crack quantity

Figure 7a shows an example of the evolution of the number of cracks determined with the ACD method for the ductile aluminum alloy, A1 for different thresholds. It can be seen that the number of cracks does not show a distinct maximum when the crack occurs (Figure a and b).

To facilitate the distinction between white and dark sample areas in the tests were repeated with the brittle A2 material and the outer surface painted with black ink. Figure 7a shows an example of the crack quantity evolution measured using ACD software for this condition for different threshold values. The results show that that the crack quantity increases initially and then drops after showing a peak. The crack quantity is higher for a lower value of threshold and vice-versa. Based on the theory the maximum in crack quantity represents the point where macro cracking initiates. The punch displacement at crack initiation measured with the ACD method is compared to that measure with the conventional force-drop approach in Figure 7b. A significant scatter in results can be observed for the ACD method. In addition the ACD method appears to significantly overestimate the punch displacement at crack initiation which was accurately estimated with the conventional load-drop method for the brittle A2 alloy. Further calibration of the ACD method may be possible to identify the optimum threshold. However, given that for all thresholds the punch displacement at cracking initiation has been overestimated the ACD method may not represent a valuable solution.
6.3 Strain measurement using MALM

The surface strain measured with the MALM method in the bending tests performed on the ductile A1 material are given in Table 2. There is some deviation between the strain measurements which may be due to crack initiation being identified visually. The min bend ratio, \( \frac{R_{\text{min}}}{\varepsilon_{\text{major}}} \), that can be formed before fracture can be estimated based on the strain measured on the outer sample surface, \( \varepsilon_{\text{major}} \) using the relation [3]

\[
\frac{R_{\text{min}}}{\varepsilon_{\text{major}}} = \frac{1}{2} \varepsilon_{\text{major}} - \frac{1}{2}
\]

with \( t \) being the material thickness. This gives a minimum bend ratio between 0.07 and 0.45 which is common for an aluminum alloy with high tensile ductility such as A1 (Table 1). Nevertheless future work needs to be aimed at validate the bending strain values determined with the MALM method using in-situ DIC strain measurement. To enable MALM strain measurement in combination with ACD crack detection will require future tests using white lines for strain measurement in combination with a black sample surface to facilitate micro crack identification.

Table 2. The strain measured using ACD software when the crack was visually detected for material A1 with no black paint.

| Sample 1 | Sample 2 | Sample 3 | Deviation |
|----------|----------|----------|-----------|
| \( \varepsilon_{\text{major}} \) (mm/mm) | 0.71 | 0.88 | 0.53 | 0.35 |
| Min bend radio | 0.2 | 0.07 | 0.45 |
Bend tests were performed on ductile and brittle Aluminium to validate an automatic crack detection software that identifies the initiation of fracture and measures the outer fibre strain with an optical approach. The main conclusions from this study are

1. The bend test device presented in this work maintains a fixed distance between the camera and the sample surface during the test. This leads to high quality imaging that allows optical crack detection and strain analysis.
2. The proposed method and software can be used to identify the crack initiation point but needs further calibration to achieve sufficient accuracy.
3. The results suggest that painting the outer sample surface with black ink is required to enable accurate identification of micro cracks. This requires the use of white lines for optical strain measurement which needs to be validated with additional trials.

Acknowledgements: The authors would like to acknowledge the University Research Project (URP) scheme of the Ford Motor Company for funding this work.

References

[1] ASTM S T M 2014 Bend Testing of Material for Ductility- E290 – 14
[2] Anon VDA 238-100 Plate bending test for metallic materials - VDA
[3] Deole A D, Barnett M and Weiss M 2018 Analysis of fracture in sheet bending and roll forming AIP Conference Proceedings vol 1960
[4] Yu T X and Johnson W 1981 The press-brake bending of rigid/linear work-hardening plates 23 307–18
[5] Mattei L, Daniel D, Guiglionda G, Klöcker H and Driver J 2013 Strain localization and damage mechanisms during bending of AA6016 sheet Mater. Sci. Eng. A 559 812–21
[6] Swillo S J, Iyer K and Jack Hu S 2006 Angled line method for measuring continuously distributed strain in sheet bending J. Manuf. Sci. Eng. Trans. ASME 128 651–8
[7] Kaupper M and Merklein M 2013 Bendability of advanced high strength steels - A new evaluation procedure CIRP Ann. - Manuf. Technol. 62 247–50
[8] Lin G, Jack Hu S and Cai W 2009 Evaluation of formability in bending/hemming of aluminum alloys using plane-strain tensile tests J. Manuf. Sci. Eng. Trans. ASME 131 0510091–9