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Determination of the bendability of ductile materials

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Abstract. Understanding fracture in the bending of metal sheet is important but difficult especially for ductile materials were fracture is hard to quantify. New bend tests allow fracture analysis at higher bending strains, however, most of them are impractical for industrial application. This work investigates the link between material failure in bending of brittle and highly ductile materials and local tensile ductility which can be measured in a simple tensile test. For this, a 3-point bend test is developed based on the widely accepted VDA238-100, enabling the fracture of highly ductile aluminium alloys. The failure strain of brittle and ductile aluminium sheets in bending is determined. Uni-axial tensile tests are performed in combination with a digital image correlation (DIC) strain measurement system. Using the surface strain data, obtained from the DIC system during tensile testing and bend testing, a correlation between the local ductility in tensile testing and the fracture strain in bending was identified.

1. Introduction

Bending is one of the major deformation modes in sheet metal forming and the determination of bendability has seen a recent wave of interest due to the introduction of low density materials in automotive parts. The VDA238-100 standard [1] has been developed to identify fracture in tight radius bending of sheet materials. It describes a 3-point bend test with a sharp punch radius and two rolls which act as bend supports. The rolls are to be mounted as frictionless as possible. Fracture is determined using a predefined force threshold. Once the bending force reaches its maximum and drops below the threshold of 60N (for sheets thicker than 2 mm) fracture is expected. Even though the VDA standard has received a widespread acceptance within the sheet forming industry, there has been a drive towards improving this method. The main reason for this is, that the radius and bending strain cannot directly be measured. Newly developed setups combine the 3-point bend test with digital image correlation (DIC) systems [2, 3]. These new designs may provide a solution to measure bending radius and strain during testing. However, most setups are complex and impractical for industrial application. A more convenient testing method, like the tensile tests, would be preferable. Material failure in tension is generally not suited to investigate forming limits in bending as bending occurs in plane strain. Nevertheless, previous research suggests a possible correlation between the bendability of a metal sheet and the local ductility in tensile testing, which is the local deformation in the necking area post to uniform elongation. Penn et al. [4] found that the local ductility of a notched tensile sample is related to the materials performance in Edge-Compression Tests. C. Rogers and G. Hancock [5, 6] investigated the formability of G550 steel which is commonly used for structural application in Australia. By performing roll forming trials, which is

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essentially an incremental bending process, it was found that the G550 steel which only has 2 % uniform elongation but 70% reduction in area (the ratio between the fracture surface and the cross section of the gauge area outside of the necking region in a tensile sample) could be roll formed to complex parts. J. Datsko [7] found a direct correlation between the strains at which edge cracking occurs in rolling and the reduction in area in tensile testing.

The present work further explores this possible correlation between bendability and local ductility. For this, a 3-point bend test was developed and a total of six material conditions, which originated from industrial 5000 and 6000 aluminium alloys, tested. Material failure in bending was determined based on the VDA238-100 standard and uni-axial tensile tests performed in combination with a DIC strain measurement system. The local ductility was measured by analysing the surface strain before material failure. The findings of this work represent a first step towards a simple test-setup to determine the bendability of a sheet metal in an industrial environment.

2. Materials and experimental setup

Two aluminium alloys (AA5754 and AA6111) have been tested in rolling (RD) and transverse direction (TD). In addition, AA6111 samples oriented in TD underwent two aging procedures (30 min at 180 °C and 11 h at 180 °C) giving a total of six material conditions. The material compositions, analysed using atom emission spectroscopy, are shown in Table 1.

Table 1. Chemical composition in wt% of the commercial AA6111 and AA5754 alloys determined with atom emission spectroscopy.

	Al	Si	Fe	Cu	Mn	Mg	Ti	
5754	96.4	0.064	0.215	0.008	0.264	2.96		
6111	97.3	0.683	0.288	0.731	0.202	0.737	0.031	

Tensile specimen were cut with an initial gauge length and width of 25 mm and 6 mm respectively. The tensile tests were performed in a hydraulic Instron machine with a 30 kN load cell. All tests were performed at room temperature with a cross-head speed of 2 mm/min to give an initial strain rate of $1.3*10^{-2}$ s⁻¹. The uniform elongation was determined as the engineering strain at ultimate tensile stress (UTS). Since, in many cases necking occurred outside the measurement area (as indicated in Figure 5 – bottom right) the GOM Aramis system was used to determine post uniform elongation. For this a vertical line of 20 mm was placed along the gauge length of the undeformed samples and its length measured in the last image before fracture occurred (Figure 1). The difference in length was then used to determine the total elongation. The local ductility was determined, as the maximum major true strain (log) on the surface in the stage before material failure, as shown in Figure 1.



Figure 1. Determination of total elongation and local ductility using GOM Aramis surface strain data, shown for a sample of AA6111 TD.

The bend test setup (shown in Figure 2 a) was fitted to an Erichsen sheet metal testing machine. The rolls are suspended in roller bearings to allow easy rotation of the rolls even when high directional forces are applied. The roll gap has been set to 8mm. The punch is a 40 mm wide knife edge punch with a 30° angle towards the tip and a radius of 0.2 mm. The machined bending samples had a thickness of 2.5 mm and a length and width of 100 mm and 15 mm respectively. At the start of the test the sheet is held in place underneath the rollers by two small magnets. The punch moves upwards with 20 mm/minute and bends the sheet between the two rolls. Once the sheet starts to bend, the distance between the outer edges of the sheet (where the magnets are situated) and the upper tool increases and the magnets fall off. The bending strain is determined using an Aramis 5M system, which is positioned on top of the Erichsen machine.

The framerate was set to 3 frames per second for the bending trials and 1 frame pre second for the tensile trials, which resulted in 9 DIC measurements / mm punch stroke during bending and 90 DIC measurements / mm sample extension in tensile testing. For the bending trials, the cameras have been orientated perpendicular to the sheet direction, which allowed a larger viewing angle for the DIC. The bend test setup and the viewing field of the cameras is shown in Figure 2 b). A facet size of 12 x 12 pixels with a facet step size of 9 pixels was chosen for the bending and tensile setup. This resulted in 0.44 mm x 0.44 mm facets for the bending tests and 0.38 mm x 0.38 mm facets for the tensile tests with an overlay of 0.11 mm and 0.09 mm respectively.





To determine the bending strain at failure, the maximum forming force was identified, as suggested by the VDA-238 standard, as the punch stroke at which a force drop of at least 60 N occurred. Figure 3 shows the force – displacement graph for a ductile (Figure 3 a) and a brittle (Figure 3 b) aluminium sheet. It can be seen, that for a brittle material the maximum punch force can be easily determined (displayed as dashed line), however, for the ductile materials the point at which the force drops is difficult to determine due to the slow rate at which the force decreases and the noise in the data. To overcome this a polygonal function was fitted to the force-displacement curves of the ductile samples. The punch stroke at the maximum of this function was then defined as the fracture point. Only the AA6111 11h that was aged for 11 hours showed brittle fracture while for all other conditions fracture was ductile.

Next the GOM Aramis data was evaluated for the last stage before fracture. Figure 3 c) displays the major strain (log) one of the surface of a bent sample, used to determine the bending strain at failure. It can be seen that with the developed setup, the entire bending radius can be evaluated. Despite this only the centreline of the sample (highlighted in Figure 3 c) was investigated, to avoid the impact of edge

effects. The maximum strain in the centre line was selected as 'bending strain at maximum bending force' for further analysis.





2.1. Strain path verification

As the sample shape used in this study varies (reduced width) from the shape suggested by the VDA it has to be ensured that fracture still occurs in the plain strain condition. For this, the strain path during bending (of the sample center and the sample edge) has been investigated (Figure 4 a). The sample center is formed in plain strain while the sample edge experiences almost uni-axial deformation. In addition, strain at the edges is slightly higher compared with the strain measured in the sample center. However, a secondary curvature (as has been found in pure bending [8]) has not been observed, i.e. most of the centerline (everything highlighted in Figure 3 c) is not curved in the X-direction.

Figure 4 b) shows the crack initiation during the bending process. For all materials tested crack initiation was observed at the center of the sample. With increasing bending strain this crack propagated towards the sample edges. Thus, it is expected that the fracture observed with the present bending test

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setup occurs in plain strain. However, visiual observation of the surface of the bending sample during testing revealed that macro cracking does not occur until later in the bending process, when the bending force decreased significantly below the maximum (except for the brittle material which showed an abrupt failure). This suggests, that the point chosen as material failure point (the maximum bending strain, as suggested by the VDA standard) does underrepresent the fracture strain of the highly ductile materials. This is in agreement with Cheong *et al.* [2] who found that in some cases the VDA criteria underrepresents the onset of cracking. However, Cheong *et al.* further stated that in this case the over or underrepresentation of failure depends on the definition of cracking (onset of hairline crack vs. macro crack) which may vary depending on the desired application.

For the present study, the authors believe, that even though the bending strain at the point of maximum bending force may over- (hairline crack) or under- (macro crack) represent material fracture, the results can be used to investigate a potential relationship between fracture in bending and local ductility in uniaxial tension.



Figure 4. Verification of fracture in plain strain; a) Strain path of the sample edge and center during bending; b) Crack initiation during bend testing observed in the sample center.

3. Results

The individual orientations of the bending and tensile test samples tested in this study are indicated with RD (rolling direction) and TD (transverse direction) as shown in Figure 5 b). The engineering stress strain curves of the six conditions are presented in Figure 5 a) and the results obtained during tensile testing (maximum uniform elongation, total elongation and local ductility) compared with the bending strain at material failure in Figure 6.



Figure 5. a) Engineering stress-strain curves of the 6 tested material conditions. Dashed line indicates necking outside of the gauge area; b) Schematic of the sample orientations used in this study.

No clear trend can be observed between the bending strain at maximum force and the maximum uniform elongation or total elongation (Figure 6 a). The comparison of the local ductility with the bending strain at maximum force (Figure 6 b) show a linear correlation. The maximum bending strain increases with increasing local ductility. However, the strain determined with the DIC in tensile testing over-represents the strain observed in bending. One reason behind this discrepancy is, that the bending strain at maximum bending force underrepresents the point of material fracture, as cracking occurs later than indicated by the maximum bending force. Another explanation is the difference in strain path occurring in the different testing procedures. While the tensile test sample experience uni-axial tension (until necking) the bend test sample is formed in plane strain. Future testing with notched samples (which can provide a plane strain path before necking) is necessary to further investigate the observed relationship.

The error bars in Figure 6 are a combination of material variations and the error in identifying bending strain at maximum force due to the noise in force measurement and the frame rate sensitivity of the experimental setup. In bending (the error bars displayed for the bending strain at fracture) it can be seen that the noise in the measurements is negligible and the chosen framerate of 9 frames per 1 mm punch stroke is sufficient, as the error bars are within reasonable expectations. The large horizontal error bars of the measured local ductility for both 5754 directions, shown in Figure 5 b), may be a result of the rapid thinning at the moment of sample failure. Here, a higher DIC frame-rate towards the end should be used for future trials to optimise the experimental setup and minimise the scatter in results.



Figure 6. Comparison of the bending strain at fracture with the maximum uniform elongation, total elongation and local ductility.

4. Conclusion

Using a newly developed 3-point bend test the bendability of ductile aluminium alloys was tested and compared with the local ductility measured in uni-axial tensile testing. It was found that:

- Standard tensile test data cannot be used to determine failure in bending.
- A relationship between the local ductility in tensile testing, determined as the maximum localised strain before fracture, and materials bendability was observed for the ductile specimen.
- Further testing of notched samples and other materials / alloys is necessary to refine this relationship.

This work is a first step towards measuring material bendability without the need for complicated bend test setups.

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