Forming parts over small radii

S K Hazra[1], D J Hughes[1], M P Pereira[2] and B F Rolfe[2]
[1] WMG, University of Warwick, Coventry CV4 7AL, UK
[2] School of Engineering, Deakin University, Australia

Abstract. Stamping simulations usually make the plane stress simplifying assumption. However, this becomes less valid when material draws around features with radius to sheet thickness ratios less than 20. Pereira, Yan & Rolfe (Wear, Vol.265, p.1687 (2008)) predicted that out-of-plane stress equivalent to material yield can occur because a line contact forms briefly at the start of the draw process. The high transient stress can cause high rates of tool wear and may cause the 'die impact line' cosmetic defect. In this work, we present residual strain results of a channel section that was drawn over a small radius. Using the neutron source at the Institut Laue-Langevin, in-plane and out-of-plane strains were measured in the channel part to show some support for the conclusions of Pereira *et. al*.

1. Introduction

Sheet metal forming is a widely used manufacturing process that converts thin, flat sheet into a desired part using a set of tooling. The process is commonly simulated using finite element (FE) models, which assume that the plastic deformation in the sheet takes place under plane stress conditions, so that out-of-plane stresses are absent. However, it is common for tools to have features (e.g. the die radius) with a radius to sheet thickness ratio (*R/t*) of less than 20 [1], where the plane stress assumption becomes less valid. Recently, FE models of channel sections were carried out by Groche *et. al* [2] and Pereira *et. al* [3] to study the drawing of material around a 90° die radius with an *R/t* ratio less than 5. Their results predicted that the plane stress assumption is inaccurate because sheet material is subject to out-of-plane contact stresses that cause it to bend and unbend as it flows around the radius. Pereira *et. al* [4] predicted that the stress is of the order of the yield stress of the material. A similar observation was made earlier by Coubrough *et. al* [5] in steady-state draw experiments with an *R/t* of about 12. However, Pereira *et. al* [3] also suggested that contact stresses can exceed yield stress when the flat sheet first comes into contact with the tool radius because line contact conditions are momentarily formed [3]. The resulting high stress has two important implications. First, it can cause a high rate of wear in tooling, particularly during the pressing of high strength alloys. Second, it leaves a mark known as the 'die impact line' [6], which is a visible, geometrical defect that impairs the quality of a skin panel. A panel with such a defect may be trimmed to remove the defect from the final part, leading to waste. However, with recent trends in automotive styling, these sharp features may exist on outer body panels where the material is part of the final part surface and therefore cannot be removed.

This paper tests the assumption that the stress state in a sheet material as it draws around a small radius remains in plane stress. The authors are unaware of any experimental technique that is able to measure out-of-plane stresses or strains in a sheet in-situ as it is drawing over a small radius. For this reason, the residual strain distributions of channel sections were measured because they reflect the deformation history of the material making up the part. Withers *et. al* [7] described several measurement techniques including hole drilling, neutron diffraction and X-ray diffraction techniques. In this work, the neutron diffraction technique was utilised because of the availability of the facility and its ability to measure the strain state of a material within a small near cubic 'gauge volume'.

2. Method

20mm wide strips of automotive grade aluminium, AA6111-T4, were pressed into channel sections using purpose-built tooling mounted in an Erichsen sheet metal forming tester. The samples were prepared at the labs of the School of Engineering, Deakin University, Australia using the method described by Pereira *et al.* [8]. The residual stress of the sample was measured according to ISO/TS 21432:2005. The neutron instrument used was the SALSA diffractometer located at the Institute Laue-Langevin reactor in Grenoble, France [9]. The instrument uses a monochromatic beam, delivered via a double-focusing bent Si-crystal monochromator, with a wavelength of 1.66 Å (reflecting off the [4 0 0] plane). The collimator-controlled incident beam size was (height × depth) 0.6 mm × 25 mm (FWHM) and the 2θ diffracted beam angle was 84.5° (for the aluminium [3 1 1] plane). The diffraction angle ensured that the gauge volume was close to rectangular in geometry and the size of the gauge volume ensured that a sufficiently large number of grains (~2000) were sampled within it. Note that the long axis of the gauge volume was oriented along the width of the channel sample. This ensured that the spatial resolution through the thickness of the wall was determined by the smallest dimension of the gauge volume (0.6 mm) whilst also reducing the counting time to by averaging along the width of the channel (where there is no variation is residual strain). The SALSA instrument employs a 2D Position Sensitive Detector (PSD); the data was integrated and fitted using the LAMP software to provide diffraction peak positions (2θ). The sample was positioned in the beam by securing it on a hexapod with 6-degrees of freedom. To measure the in-plane and out-of-plane strain components, the hexapod table (Fig.2) was rotated as appropriate. In particular, the out of plane sample direction was aligned along the diffraction q-vector, which bisects the angle between the incident and diffracted beam and represents the measured component of strain.

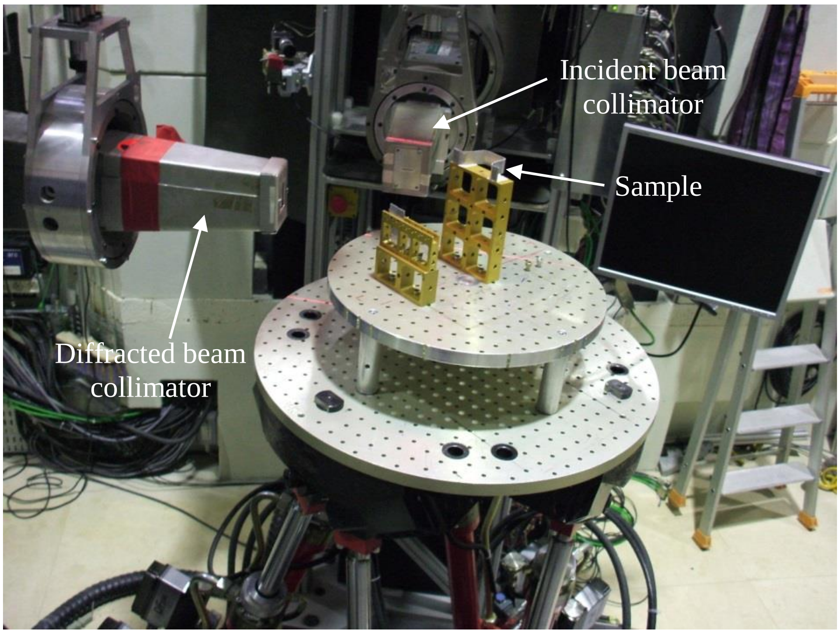

Fig.1 A photograph of the experimental setup showing the sample, hexapod, beam and detector slits

The samples were measured at 5 locations along their walls as shown in Fig.2. Location 1 corresponds to the location of the die impact line which had the appearance of a burnish. At each location, a through-thickness scan was performed.

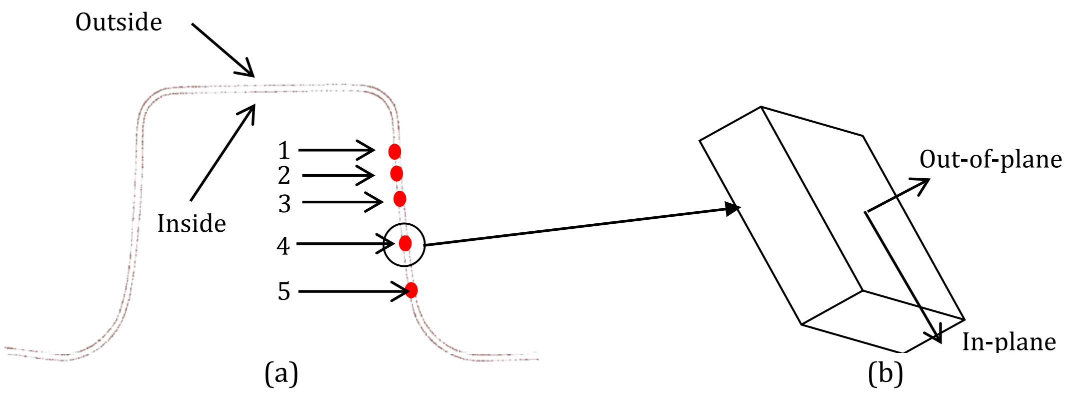

Fig.2(a) Locations of residual strain measurement (b) Orientation of out-of-plane and in-plane strains

Strains were calculated with the following relation:

$$\varepsilon = \frac{\Delta d}{d_0} = \Delta\theta \cot\theta_0$$

Where ε is the strain the in *hkl* [311] plane, d_0 is a reference lattice spacing, Δd is the change in the lattice spacing, $\Delta\theta$ is the change in the Bragg angle as a result of the change in lattice spacing and θ_0 is the Bragg angle for the reference lattice spacing. θ_0 was measured at the top of the channel where the material experienced minimal plastic deformation.

3. Results

The out-of-plane results and the in-plane results are shown in Fig.4.

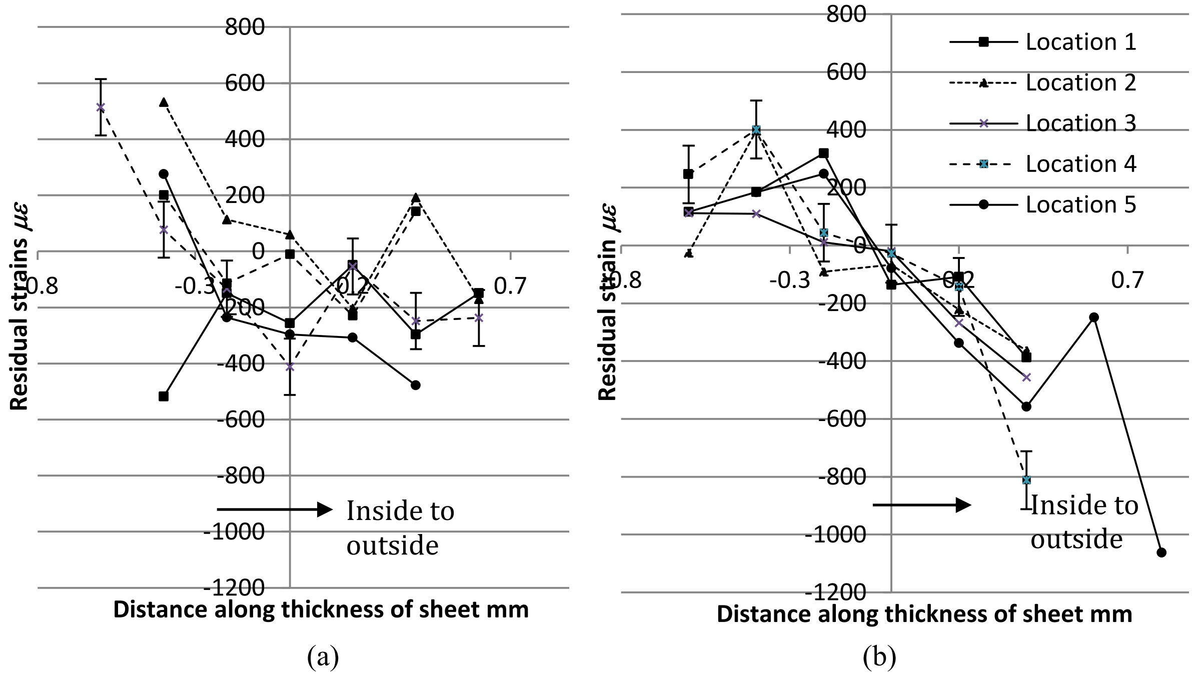

Fig.4(a) Out-of-plane strain (b) In-plane strains along the wall of the sample

At the location of the burnish (location 1), the out-of-plane strain distribution (Fig.4a) remains negative through the thickness of the sheet. In particular, it is about -520$\mu\varepsilon$ at the inside face and about -200$\mu\varepsilon$ at the outside face. Below the burnish (locations 2 to 5), the strain on the inside face is positive and becomes negative towards the outside face. The highest out-of-plane strain (531$\mu\varepsilon$) was measured on the inside face at location 2.

In-plane strains were positive in the inside face and negative in the outside face (Fig.4b). At the location of the burnish (location 1), the residual strain on the inside face was about 110$\mu\varepsilon$. The strain appears to increase slightly before decreasing to about -400$\mu\varepsilon$ at the outside face. The variation was approximately similar along the other cross-sections.

4. Discussion
Some strain measurements, such as the out-of-plane strains at location1 do not appear to balance across the thickness of the sample. This is for two reasons. First, the shear strains have not been accounted for in these measurement and second, the relatively large beam width used in contrast to the thickness of the sheet is likely to have smoothed out the actual distribution. Despite this, the measurements in Fig.4a show that the out-of-plane strain are significant compared to yield strain of AA6111-T4 (about 1500$\mu\varepsilon$). This observation supports the prediction made by Pereira *et. al* [3] that out-of-plane deformation takes place during the bending of sheet over small radii. The in-plane strains, which are the result of the stretching of the material, shows a distribution of varying strain that is consistent with bending in the sheet. The character of the distribution is likely to be the cause of the curl in the part.

5. Conclusions
The residual strains in a channel section were measured to identify out-of-plane and in-plane strains in the wall of the part. The significant out-of-plane strains that were measured are consistent with the prediction of Pereira *et. al* [3] of the existence of out-of-plane deformation during the drawing of material over small tooling radii. This observation implies that simulations over material forming over small radii should be modelled with elements that account for these strains in order to account for tool wear and the die impact line cosmetic defect. The results from this work will contribute to identifying the conditions that cause the cosmetic defects at the die impact line for automotive body panels.

Acknowledgements
The authors would like to acknowledge the beam time provided by the Institut Laue-Langevin for the duration of the experiment and the assistance provided by the scientists at the SALSA beamline.

References
[1] Bhattacharya R, Stanton M, Dargue I, Aylmore R, Williams G. Experimental Evaluation of Springback in Aluminium Alloys Using Optical Measurement and Numerical Analysis. In: Menary G, editor. The 14th International ESAFORM Conference on Material Forming; Belfast: AIP Conference Proceedings; 2011. p. 214.
[2] Groche P, Nitzsche G, Elsen A. Adhesive wear in deep drawing of aluminum sheets. CIRP Annals - Manufacturing Technology 2008;57:295 - 8.
[3] Pereira MP, Duncan JL, Yan W, Rolfe BF. Contact pressure evolution at the die radius in sheet metal stamping. Journal of Materials Processing Technology 2009;209:3532 - 41.
[4] Pereira M, Okonkwo P, Yan W, Rolfe B. Deformation and frictional heating in relation to wear in sheet metal stamping. Steel Research International 2010. p. 713-6.
[5] Coubrough GJ, Allinger MJ, Tyne CJV. Angle of contact between sheet and die during stretch–bend deformation as determined on the bending-under-tension friction test system. Journal of Materials Processing Technology. 2002;69:130-1.
[6] Marciniak Z, Duncan JL, Hu SJ. *Mechanics of Sheet Metal Forming*: Butterworth Heinemann; 2002.
[7] Withers PJ, Turski M, Edwards L, Bouchard PJ, Buttle DJ. Recent advances in residual stress measurement. International Journal of Pressure Vessels and Piping. 2008;85:118-27.
[8] Pereira M, Yan W, Rolfe B. Wear at the die radius in sheet metal stamping. Wear. 2012;274-275:355-67.
[9] Hughes DJ, Bruno G, Pirling T, Withers PJ. Scientific Review: First Impressions of SALSA: The New Engineering Instrument at ILL. Neutron News. 2006;17:28-32.