Deformation in Micro Roll Forming of Bipolar Plate

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Abstract. Micro roll forming is a new processing technology to produce bipolar plates for Proton Exchange Membrane Fuel Cells (PEMFC) from thin stainless steel foil. To gain a better understanding of the deformation of the material in this process, numerical studies are necessary before experimental implementation. In general, solid elements with several layers through the material thickness are required to analyse material thinning in processes where the deformation mode is that of bending combined with tension, but this results in high computational costs. This pure solid element approach is especially time-consuming when analysing roll forming processes which generally involves feeding a long strip through a number of successive roll stands. In an attempt to develop a more efficient modelling approach without sacrificing accuracy, two solutions are numerically analysed with ABAQUS/Explicit in this paper. In the first, a small patch of solid elements over the strip width and in the centre of the “pre-cut” sheet is coupled with shell elements while in the second approach pure shell elements are used to discretize the full sheet. In the first approach, the shell element enables accounting for the effect of material being held in the roll stands on material flow while solid elements can be applied to analyse material thinning in a small discrete area of the sheet. Experimental micro roll forming trials are performed to prove that the coupling of solid and shell elements can give acceptable model accuracy while using shell elements alone is shown to result in major deviations between numerical and experimental results.

1. Introduction

Environmental concerns pressure the automotive industry to reduce fuel consumption and carbon emissions. This has led to the rapid development of fuel cells, with proton exchange membrane fuel cells (PEMFCs) in particular having the highest potential for application in electric vehicles. The PEMFCs convert oxygen and hydrogen into electricity with water as the only resultant of the chemical reaction, therefore providing an environmentally friendly alternative to combustion engines. Figure 1 shows a schematic of the structure of a typical PEMFC stack unit. One of the major components of a fuel cell is the bipolar plate, which generally has hundreds of flow channels in which the reactant gases interact. The performance of a bipolar plate (usually described in terms of its power density, W/m³) increases with the so-called aspect ratio $AR$, which is the ratio of the channel depth to the channel width.
Currently micro-stamping is considered as an efficient way for the mass production of stainless steel bipolar plates [1]. However, wrinkling defects and material rupture are two major issues in this process [2] and the maximum aspect ratio achievable for 0.1mm stainless steel was found to be 0.43 for micro-stamping [3]. This is significantly smaller than the maximum aspect ratio achievable via micro electrical discharge milling (EDM), where aspect ratios of up to 1 are possible but at low production rates. Numerous attempts have been made to develop micro-forming processes that enable the micro forming of high aspect ratios with high production rates. These include rubber pad stamping (where an aspect ratio of 1.33 has been reported [4]) and hydroforming (which can achieve aspect ratios of 1.5 [5]). Nevertheless, both rubber pad stamping and hydroforming do not provide economical solutions for rapid mass production. Some researchers have proposed methods that are based on bending. Nikam and Reddy [6] used a tube wringer to form a 0.25mm thick copper to a bipolar plate while Ni et al. [7] proposed a rolling production line to produce bipolar plates.

A new micro roll forming device aiming to form bipolar plates using commercially available 0.1 mm stainless steel was built at the Institute for Frontier Materials, Deakin University; the design of the micro roll former and of the forming sequence is further described in Section 2.2. In contrast to micro-stamping, the major deformation mode in roll forming is bending and the process has been shown to enable forming of hard to form materials into complex sections [8]. Nevertheless, rupture of the material can still be a limiting factor in the roll forming process. Material thinning is an indicator for the likelihood of fracture and, therefore, needs to be numerically analysed in detail to allow robust future designs to be produced. At the same time, the numerical model needs to accurately capture material flow in the roll forming process which generally includes the modelling of a long strip of metal sheet to take into account the effect of material being held in the various roll stands. This requires a smart modelling approach to keep the computational time within an acceptable limit. The current study will focus on developing such an advanced model approach. This is combined with experimental micro roll forming trials to verify the numerical results.

2. Experiment set up

2.1. Material

In the present study, SS304L austenite stainless steel of 0.1 mm thickness was selected. The microstructure analysed by Scanning Electron Microscopy (SEM) with an electron backscatter diffraction (AsB) detector in plane direction as well as along and transverse to the rolling direction is shown in Figure 2. The chemical composition determined with spectroscopy is given in Table 1. It can be seen from Figure 2 that the grains are homogeneously distributed in all directions with more than 10 grains through the material thickness. As reported by Lee et al. [9], when the thickness to grain size ratio is greater than ten, material size effects can generally be neglected.
Figure 2 Microstructure of SS304L (a) schematic of the direction of measurement (b) plane direction (c) cross section oriented 0° to the rolling direction (d) Cross section oriented 90° to the rolling direction

The tensile test samples were cut at 0°, 45° and 90° to the rolling direction and three tests were performed for each condition according to the ASTM E8 [10] in an Instron® 30kN tensile tester. The sample gauge length was 50 mm and a video extensometer was applied to measure forming strain. The forming speed was chosen to give a strain rate of 0.001s⁻¹. The results are shown in Figure 3 and suggest no significant difference between the three orientations despite some ageing in the 90° direction.

Table 1. Average chemical composition of SS304L stainless steel

| Element | C   | Cr   | Ni   | Mn   | Si   | Mo   | Co   |
|---------|-----|------|------|------|------|------|------|
| Amounts in weight % | 0.0577 | 18.795 | 7.7125 | 1.5725 | 0.3235 | 0.39 | 0.1205 |

Figure 3. True stress-strain curves determined for SS304L

2.2. Experimental micro roll forming trials

The chain driven micro roll former used for the experimental trials of this study contains three forming and one guide-in station (Figure 4a). The distance between the stations is 38mm, and the roll gap between the top and the bottom roll was adjusted to be the sheet thickness of 0.1 mm. The sheets tested
were 20 × 100 mm (width × length). The flower design illustrating the bending sequence is shown in Figure 4b. The aspect ratio for this process is 0.36 (width 1.16mm, depth 0.42mm).

3. Numerical Analysis

3.1. Model set up

The numerical analysis was first performed with ABAQUS/Explicit. The setup of the experimental roll forming trials (station distance, strip length, and roll gap) is reproduced in the numerical model. The forming rolls were defined as analytical rigid bodies while the sheet was deformable. The sheet material properties were defined by applying an isotropic material model in combination with the tensile curve obtained for samples tested in the rolling direction. This data was converted into plastic strain and Cauchy stress and inputted in tabular form into ABAQUS.

A mass scale factor of 3.162 (√10) was chosen to speed up the simulation; this led to a kinetic energy that was less than 5% of the internal energy suggesting quasi-static conditions [11]. The density of the material was assumed to be 7.8 g/cm³. The blank is fed into the roll former with an initial displacement of 5 mm to establish initial contact with the forming rolls after which the sheet is pulled in by the frictional force of the forming rolls. The rotation distance of the bottom rolls are 13.33 radians and top rolls are -6.34 radians (negative means opposite direction to the bottom rolls). The “general contact” interaction algorithm was defined between the rolls and the sheet surface and the coefficient of friction set to 0.25; this is close to the friction coefficients applied in previous studies that focused on the numerical analysis of roll forming processes [12, 13].

3.2. Element description

Although solid elements are able to capture fully three-dimensional stress states, generally more than five elements through the material thickness are required to achieve accurate results, thus leading to impractical calculation times. This is especially the case when modelling roll forming processes where a long strip is formed in several successive roll forming stands. This requires the modelling of a long strip to take into account the effect of the previous forming stations on the material flow when the strip makes contact with the next set of forming rolls and leads to a high amount of elements required. Therefore shell elements are commonly applied for simulating roll forming processes [14, 15]. However, shell elements do not give a good representation of springback or failure behaviour in bending-dominated forming if the bending radius is comparable to the sheet thickness [16-18]. The minimum radius in the profile of the bottom roll is 0.15mm which is very close to the sheet thickness. This violates the thin shell theory suggesting that thin shell elements will not lead to reliable results and that solid elements need to be applied instead.

To achieve an accurate result for material thinning using solid elements without sacrificing the model efficiency, a model combining shell and solid elements was employed. As shown in Figure 5a, a small patch of solid elements in the centre of the sheet is coupled with shell elements which are used to model the majority of the sheet. A half symmetry assumption is applied due to the symmetry of the geometry and boundary conditions across the sheet centreline.
The width of solid segment $W$ is 2.5mm and the length $L$ is 5mm (see Figure 5a). The width of the solid segment ensures that the width of all 1.5 channels (only half of the strip width is modelled) are covered by the solid elements. $L_1$ denotes the distance between the front end of the sheet to the front end of the solid patch and is 13.5mm. To avoid the bending lock problem, six C3D8R (reduced order linear brick element) elements are applied through the material thickness in the solid patch. The S4R shell element (4-node doubly curved thick shell, finite membrane strains) with five integration points through the thickness were used for the remainder of the sheet. The connecting edges of the shell elements are tied to the respective sides of the solid element patch (six layers) using the constraint option in ABAQUS. The element size applied for the solid elements is schematically shown in Figure 5a. A full S4R shell element model was also built for comparison purposes. The minimum size of the shell elements in the sheet area representing the solid patch used in the solid element model was identical to the element size applied for the solid elements. The full Finite Element (FE) model is shown in Figure 5b.

3.3. Springback analysis
After the forming simulation was completed in ABAQUS/Explicit, the formed sheet was imported into ABAQUS/Implicit for springback analysis. In the implicit model, all rolls and contact conditions were removed while the position of the blank was fixed in space by displacement boundaries applied at the centreline (as the symmetry line shown in the Figure 5a). A 2D section path transverse to the sheet length and consisting of 100 nodes was constructed to extract the coordinate data; the position of profile path is illustrated in Figure 5a. The FE results along with the experimental results are presented in Figure 7b.

4. Results and discussion

4.1. Thinning measurement
A 20×20mm section was cut out from the front of the formed part using scissors. To avoid the section profile damaged by the scissors, the surface of the front end is the section for microscope observation. After being hot mounted in the resin, the section was then grinded using sandpaper (600 to 1200 grit). Afterward the cross section surface was analysed with an Olympus® BX51 optical microscope at a
magnification of 100x. For the reason of symmetry, only half of the section was examined. Material thinning was analysed at ten measurement points positioned in the critical bending zones (Figure 6a) and compared with the numerical results (see Figure 6b). The experimental measurements show that a maximum thinning of 20.7% occurs at Point Number 2. The average thinning of all 10 points is 13.1%. Comparing the two FE models, it is evident that the pure shell model significantly underestimates material thinning, while the solid-shell model gives a more accurate representation. For example, for the ten data points examined, the correlation (R-squared value) between the FEA and the experiments is 0.70 for the solid-shell model compared to 0.35 for the pure shell model. The highest discrepancy between the solid-shell and the experimental material thinning results are observed for measurement point 7 which lies in the second valley. This may be due to misalignment of the tooling or some out-of-spec tooling dimensions in the experimental setup. Understanding the effect of minor tool misalignment and minor tool shape discrepancies on material thinning forms part of our ongoing research.

The combined shell-solid element model led to an increase in computational time of 100% in comparison to a pure shell element based model. This increase in computational time seems reasonable when compared to the significantly longer computational time that would be required for a full solid model (possibly 10-20 times longer). This suggests that the presented combined shell-solid element approach may be an efficient method for the numerical analysis of material thinning in the micro roll forming process.

**Figure 6.** (a) Cross-section analyzed in the optical microscope and (b) thinning measurement

### 4.2. Profile measurement

The profile of the final shape is acquired by the Alicona Infinite Focus® G5 (a non-contact optical surface profilometer system); the 3D images obtained are shown in Figure 7a. A profile path is then defined perpendicular to the formed corrugations in the top view of the acquired 3D image (Figure 7a) and the path coordinates exported and plotted.

As shown in Figure 6a, there is significant bow in the formed part. The comparison of bow is not included in this study and is part of ongoing model development. In terms of the springback prediction for the cross-sectional shape, it is evident that the combined shell-solid element model with springback analysis can give reasonable results. The second valley in Figure 7b shows a small difference; similar
to the discrepancies observed for thinning. This may be caused by very minor tool misalignment or out-of-spec tooling dimensions in the experimental setup.

Figure 7 (a) 3D shape of the final specimen and comparison of the solid-shell model results with the experimental cross sectional profile (b) before and after springback

5. Conclusion
This paper developed a model for the analysis of springback and material thinning in a micro roll forming process. For this, most of the metallic strip was discretised with shell elements while a small patch in the strip centre was modelled with six layers of solid elements through the material thickness. One numerical analysis was also performed using only shell elements for comparison followed by experimental micro roll forming trials for experimental validation. The following conclusion can be made:

- The model using shell elements in combination with a small patch of solid elements in the strip centre gave a good representation of material thinning observed in the experimental micro roll forming trials. Thereby computation time increases by 100% compared to the full shell element model.
- The full shell element model led to an insufficient representation of material thinning.
- Overall this study suggest that combining shell elements with a small patch of solid elements, with multiple elements through the material thickness, in the centre of the strip represents an accurate and cost effective method to analyse micro roll forming processes.

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