Multi Stage Strategies for Single Point Incremental Forming of a Cup

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ABSTRACT: A five stage forming strategy for Single Point Incremental Forming of a circular cylindrical cup with a height/radius ratio of one is presented. Geometrical relations are discussed and theoretical strains are calculated. The influence of forming direction (upwards or downwards) is investigated for the second stage comparing explicit FE analysis with experiments. Good agreement is found between calculated and measured thickness distribution, overall geometry and strains. Using the proposed multi stage strategy it is shown possible to produce a cup with a height close to the radius and sides parallel to the symmetry axis in about half of the depth.

Key words: Incremental forming, multi stage, FEM

1 INTRODUCTION

Single Point Incremental Forming (SPIF) is a relative new sheet forming process which offers the possibility of forming complex parts without dedicated dies using only a single point tool and a standard 3-axis CNC machine. The process enables strains much higher than traditional sheet forming processes, but is limited by the type of deformation which is close to plane strain for geometries formed in one stage. A consequence of this is the sine-law, $t = t_0 \cdot \sin(90° - \alpha)$, which relates the drawing angle α with the thickness after forming. This law has proven to give a good description of the thickness distribution and as a result it is not possible to form parts with drawing angles higher than about 60-80° in one stage. For a 90° drawing angle the sine-law predicts a thickness equal to zero and strains going towards infinity. One way to get around the limitations prescribed by the sine-law is to use a multi stage strategy, and this is the subject of the present paper.

2 MULTI STAGE STRATEGIES

Using a multi stage forming strategy is not a new idea in SPIF. Kitazawa et al. [1] used different two stage strategies to produce hemi ellipsoidal shapes and investigated the limits before fracture varying the radius and the height of the geometry. Jeswiet et al. [2] used a three stage strategy to form an automotive headlight reflector. As far as the authors know, no work has yet been presented in literature, where a multi stage strategy allows forming of a part with a 90° drawing angle in SPIF. In two point incremental forming (TPIF) a 90° drawing angle has been achieved, [3,4].

3 MULTI STAGE STRATEGY

3.1 *Forming of cups*

A fundamental difference between deep drawing and SPIF is the plate area included in the deformation. In deep drawing it is the drawn-in flange, which is deformed, whereas limited deformation is introduced in the bottom of the cup. For deep drawing steel forming of cups with a height/radius ratio h/r ≈ 2 is possible. SPIF of a cup with a ratio h/r = 1 is considered almost impossible. The plate area included in the deformation in SPIF is the area surrounded by the first round of the tool path or the hole in the backing plate, i.e. forming may be characterized as stretching. Fig. 1 shows the thickness strain for a round and a square cup assuming that thickness is evenly distributed. In SPIF the distribution of thickness is normally far from this.

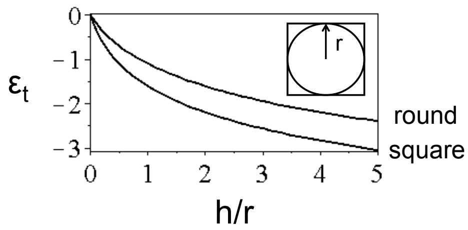

Fig. 1. Thickness strain for different h/r ratios.

3.2 5 stage strategy

The idea in the present work is to extend deformation to all the material available which is indicated by the horizontal, dotted line in Fig. 2. The first stage stretches this into a 45° cone. The following stages will gradually move the middle of this section towards the corner. All stages except the first can be performed going either downwards or upwards. This gives a total of 16 different strategies.

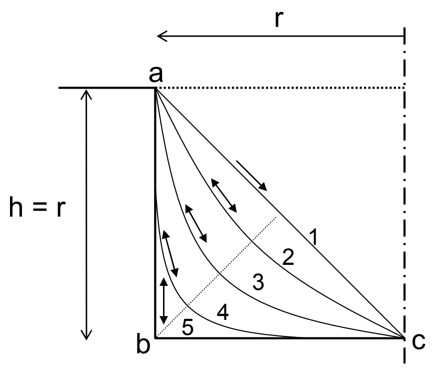

Fig. 2. Five stage strategy for forming a cup with h/r = 1.

In the present paper only the first four stages are considered and in those, two different strategies are investigated, i.e. down-up-down-down (DUDD) and down-down-down-up (DDDU). Influence from direction of forming is investigated in detail for the second stage. Theoretical principal strains can be calculated assuming the deformation to be pure stretching and the meridional strain to be evenly distributed. The circumferential strain is zero at points *a* and *c* and maximum in *b* in Fig. 2. The maximum thickness strain is higher than in Fig. 1 for h/r = 1. This is because the circumferential strain is not evenly distributed.

$$\varepsilon_{\phi} = \ln\left(\frac{2r}{r}\right) = \ln(2) \quad (1)$$

$$\varepsilon_{\theta,\max} = \ln\left(\frac{2\pi r}{\pi r}\right) = \ln(2) \quad (2)$$

$$\varepsilon_{t,\max} = -\ln(4) \approx -1.4 \quad (3)$$

4 SIMULTION AND EXPERIMENTAL SETUP

4.1 Setup of FE model

LS-DYNA version ls971s is adopted to simulate the process using explicit time integration. The forming tool and the backing plate are considered rigid. Time scaling is used simulating the process to be 1500 times faster than the actual experiments. The influence from time scaling and the use of rigid tools are investigated by Qin et al. [5] and the applied settings are considered reasonable. Maximum time step is based on a characteristic length equal to shell area divided by the longest diagonal. As a precaution DYNA uses 0.9 times this value. Fully integrated shells (type 16 in DYNA) are used with five integration points in thickness. Adaptive remeshing is adopted. The movement of the tool in the simulation is identical to that in the experiments including the rotation. The sheet material used is AA1050 H111/O and considered isotropic with a flow stress as stated in equation 4. The values for *C* and *n* are average of what is used by Hirt et al. [6] and Filice et al. [7]. Coulomb friction is assumed with μ = 0.1.

$$\sigma_y = C \cdot \varepsilon^n = 111 \cdot \varepsilon^{0.14}\, MPa \quad (4)$$

4.2 Experimental setup

Experiments are conducted on a 3-axis milling machine. All sheets are 1 mm thick and the forming speed is 1000 mm/min. The tool, which has a radius of 6 mm and a semi-spherical tip, is rotated at 27 rpm. The rotational speed ensures a surface speed at the maximum radius equal to the forming speed. Diluted cutting fluid is used as lubrication, and the part is cleaned between each stage to remove loose wear particles. Tool paths are programmed using Pro/ENGINEER. First stage has a fixed vertical step size of 0.5 mm and following stages have a distance between tool paths below 1 mm. The geometries used for the different stages are as shown in Fig. 2 with h = 70 mm and r = 80.5 mm. A small undeformed section remains in the middle (r = 0-10 mm) since the tool cannot form a cone with a sharp pointed end.

5 RESULTS

5.1 First two stages

Experiments are compared with simulations for the first two stages only, i.e. down-down (DD) and down-up (DU). A comparison of the achieved geometries can be seen in Fig. 3. There is almost perfect agreement for the DD strategy. Regarding the DU strategy the simulated geometry is more pointed in the center region and about 10 mm too deep.

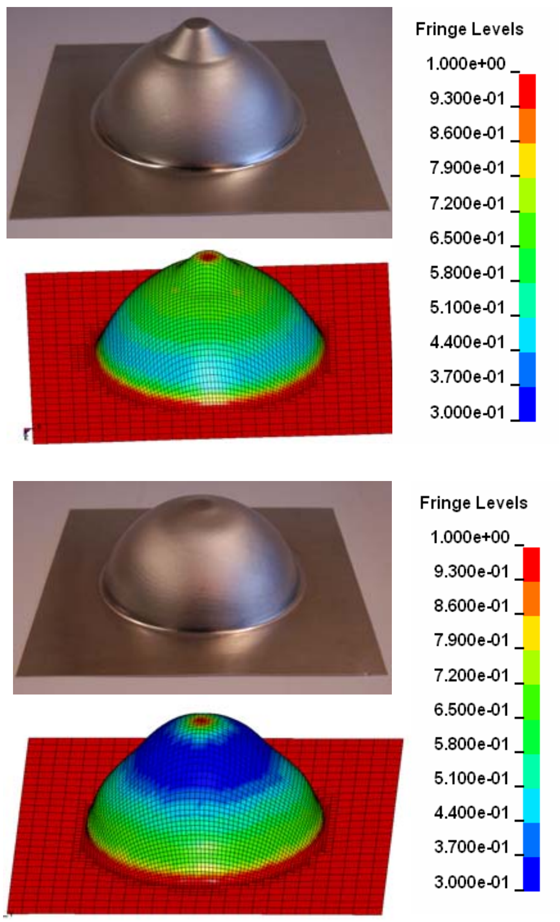

Fig. 3 Comparison of geometry achieved by simulation and by experiment for DD strategy (top) and DU strategy (bottom). Legend displays thickness in mm.

Fig. 4 compares the measured thickness distribution with the calculated one. For both geometries very good agreement is obtained until a depth of 60 mm. The DD strategy causes a distribution similar to a normal, one stage SPIF, where increasing angle causes decreasing thickness. Using the DU strategy this is not the case, and most of the reduction in thickness occurs in the center part where the drawing angle is low. This is necessary if vertical sides are to be achieved in the subsequent stages.

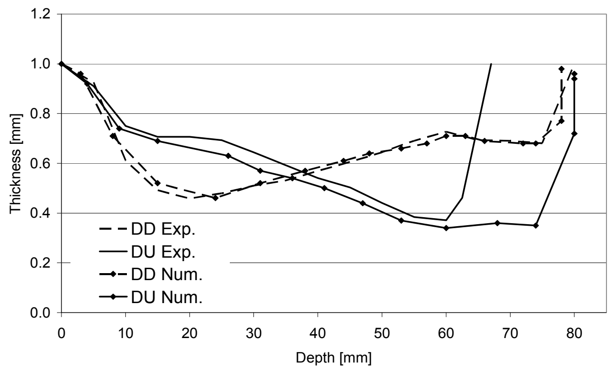

Fig. 4 Comparison of thickness from experiments and simulations as function of depth.

5.1.a Two stages: down-down (DD)

Adopting the strategy DD not all of the geometry is formed during the second stage, leaving a residual cone in the center. This is because the depth of the part is increased in the second stage, whereas the tool path only goes 70 mm down as in the first stage. As the tool moves down during the second stage a small plateau is formed beneath it. This plateau is observed experimentally as well as in the simulation, Fig. 5. Kitazawa et al. [1] obtained similar experimental results.

5.1.b Two stages: down-up (DU)

Adopting the strategy DU no residual cone is observed after the second stage, but material build up in front of the tool is noticed, which changes the point contact to a line contact, Fig. 5. Again this phenomenon is observed in both experiments and simulations. A similar observation is found in experiments by Kitazawa et al. [8]. The line contact causes process forces in the XY plane to increase and care should be taken not to exceed the force limits of the machine when forming harder materials.

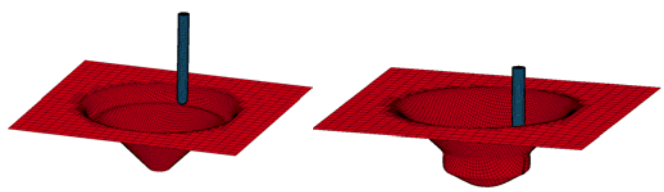

Fig. 5 Left: formation of plateau (DD strategy), right: formation of line contact (DU strategy).

5.2 *Strategy DUDD and DDDU*

The DDDU strategy can be performed without fracture, whereas the DUDD strategy results in fracture in stage 4 just after finishing the vertical section of the part, Fig. 6. The fracture appears in a zone with heavy thickness strain, see Fig. 7. Thickness measurements below this point are for the first three stages only since the fourth stage could not be completed. Both strategies give minimum thickness in the bending section between the vertical and the horizontal work piece parts. This corresponds well with the theoretical strains which indicate a maximum thickness strain in the corner of the cup. Using the suggested strategy it seems that the critical area is not the vertical sides themselves but the transition zone between vertical and horizontal. The reason is that this zone experiences a deformation close to equal bi-axial stretching.

Fig. 6 Geometry after 4 stages of forming (left DDDU and right DUDD).

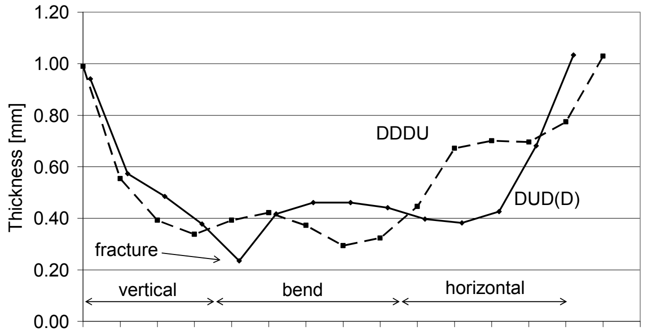

Fig. 7 Measured thickness as function of the distance along the surface for the two strategies DDDU and DUDD.

Both strategies increase the maximum drawing angle since they allow forming of the third stage. Experiments show, that the geometry obtained after this stage cannot be formed in single stage SPIF. The DDDU strategy also allows forming of the fourth stage which has vertical sides to a depth equal to 35 mm and a total depth approximately equal to the radius.

6 CONCLUSION

The multi stage strategy presented is able to produce a cup with a 90° drawing angle which has not been possible before. It demonstrates that strains far from plane strain can be achieved in SPIF and that strain paths may be far from linear. The distribution of strains is not only depending on the geometry of the tool path but also on the direction (downwards or upwards). The proposed strategy needs to be refined by further research but presents a promising concept for forming parts with vertical sides in SPIF.

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