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Numerical and Experimental Study of Micro Single Point Incremental Forming Process

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Abstract

Single-point incremental sheet forming (SPISF) is a die-less forming process with advantages of high-flexibility, low-cost and short lead time. Recently, micro components have been employed in many applications, especially in medical industry using as implant components, surgical tool and tooth caring accessories etc. Therefore, the reduction of component size to micro-domain has becoming one of the key elements for the development of SPISF technique, which will encounter many challenges, such as reduction of formability, tool wear, inaccuracies in tooling fabrication, etc. This work combined numerical and experimental approaches to study the deformation mechanisms in micro SPISF process. Aluminum 1145 soft-temper foils with thickness of 38.1 μm and 50.8 μm were employed. A truncated pyramid with variable half-apex angle was proposed here as the standard geometry for measuring the maximum forming angle that could be achieved in micro-SPISF process. The influence of process parameters on forming behavior was studied. The result shows that forming angle has direct link with material formability. A full tool path micro-SPISF model has been developed with various 3D element types. It suggests that incompatible mode eight-node brick element C3D8I is capable to capture the shape and thickness distribution of the formed parts with most accuracy and least computational time. The thickness distribution of the workpiece was compared with the Sine Law to unveil the additional stretch region appearing at the top edge of the formed feature in the micro SPISF as compared to macro SPISF.

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Keywords: single point incremental sheet forming; micro forming; finite element simulation; maximum forming angle
1. Introduction

Incremental sheet forming (ISF) is a flexible manufacturing process which is able to produce customized components in short lead time. Many studies have been done to investigate the deformation mechanism of ISF in the macroscale. Kim and Park [1] showed the deformation mechanism of the process was the combination of stretching and spinning. Jackson and Allwood [2] indicated that the deformation in incremental forming process were caused by stretching and shear in the plane perpendicular to the tool direction, with shear in the plane parallel to the tool direction. There is a tendency to scale down the ISF part size to micro domain, which is driven by the diverse applications of micro-structure components like thin shell miniature. Saotome and Okamato [3] developed a specialized device to manufacture micro-structures in a scanning electron microscope to demonstrate the feasibility of scaling down SPISF. The micro SPISSF was initially demonstrated by Obikawa et al. [4]. They converted a conventional CNC machine into a micro SPISSF system to study the formability of aluminium foils. Geiger et al. [5] and Vollertsen [6] found the mechanical and physical behaviors of material are not similar between microscale and macroscale forming processes. To achieve forming micro-structural components by using different sheets materials, Dejardin et al. [7], Obikawa et al. [8], Sekine and Toshiyuki [9] and Otsu et al. [10] conducted experimental trials of micro ISF of thin copper alloys sheets, Stainless steels and Ti and Au foils. Regarding the ISF process simulation, Wang et al. [11] studied the effect of thickness/average grain size ratio on tangent modulus and yield stress by using the double–linear elastic–plastic constitutive equation. Bahloul et al. [12] developed a finite element model in ABAQUS to analysis elasto-plastic and large deformation case. Mirnia et al. [13] demonstrated that thickness distribution could be predicted more accurately using a sequential limit model. Li et al. [14] selected three kinds of materials (polyurethane material, rubber material, and wood material) and established a 3D elastic–plastic finite element model of incremental forming. It can be concluded that the experimental investigation and numerical simulation of the incremental sheet forming process have already been carried out extensively, and the deformation mechanism of the process has also been well established for the macro ISF. In the current work, we will focus on the deformation mechanism study in the micro ISF with both numerical and experimental investigation. A full micro-ISF process model has been developed with various 3D element types to compare their accuracy and efficiency in micro ISF. The thickness distribution of the workpiece was obtained both from experiment and simulation, and they are in good agreement with each other. Compared with the Sine Law, it indicated that there are three regions with different deformation modes (from outside to inside) in micro ISF: stretching/bending region, shear region (which agrees well with Sine Law) and stretch/shear region, the last one is the distinctive feature in micro ISF due to the difference between macro and micro ISF in the workpiece thickness.

2. Materials and Methods

2.1. Experimental Setup

The raw material is commercially available Aluminium 1145 Soft-Temper Foils with nominal thickness of 38.1 μm and 50.8 μm, density of 2.7 g/cm³, Young’s modulus of 68.9 GPa and Poisson’s ratio of 0.33. A single forming tool head with radius 0.5 mm was mounted at a micro CNC milling machine-MIKROTOOLS DT-110 to carry out micro incremental sheet forming. The travel speed of the forming tool is 10 mm/min. Water was used as a lubricant to reduce the friction. The workpiece is incrementally formed by the movement of the forming tool along prepared tool path. For different features, the tool path can be customized in different ways using Siemens NX software.

Forming the sheet into cone or pyramid shapes is generally employed to investigate the formability of sheet metal in micro incremental forming process [4]. However, it is very time consuming as it requires repeat work to form a series of cone or pyramid shapes with various apex angles. Here, a truncated pyramid shape with reduced half-apex angle from bottom to top is designed and formed to investigate the limit of forming angle as well as wall thickness distribution for micro ISF. This design largely reduces the total process time.

The half-apex angle θ varies gradually from 45° at the blank reference plane to 20° at the bottom surface of formed feature to cover a wide range of title angles. The wall profile is generated from the logarithmic function y=ln(x), the tangential angle α of this curve is equal to (90°−θ), so the half-apex angle θ can be linked directly with feature depth, which is even easier to measure. It is shown that at the same forming conditions, the foil with thickness of 50.8μm
was able to be formed into the designed truncated pyramid shape, but fracture occurred on the corner of truncated pyramid. Fig. 1a shows the formed truncated pyramid part and Fig. 1b shows the simulation result.

![Onset of fracture](image)

Fig. 1. (a) Truncated pyramid shape formed in experiment; (b) Simulation result: element type C3D8I.

To measure the thickness distribution along the wall, the formed parts were cold mounted and cut in half using a diamond wheel. The exposed cross-sections were polished and examined by optical microscope. Image were taken at about 0.5 mm intervals along the formed wall and stitched together for the thickness distribution measurement.

2.2. Finite element analysis (FEA)

Based on experimental setup, the full process simulation was carried out using ABAUQS/Explicit. The tool was modeled as analytic rigid body and the Al foil was considered as deformable. For the micro ISF, the thickness of the foil is comparable to the workpiece lateral dimension as well as the tool head radius, hence the deformation mechanism is no longer simple bending and 3D elements are deem to be appropriate for the current study. In the present work, C3D8R (8-node, tri-linear 3-D solid element, reduced integration), C3D8 (8-node, tri-linear 3-D solid element, full integration), C3D8I (8-node, tri-linear 3-D solid element, full integration and incompatible deformation modes), SC8R (8-node, quadrilateral in-plane general-purpose continuum shell, reduced integration with hourglass control, which turns to be a finite element topologically identical to a solid one, but with a kinematics of a shell finite element) are employed and compared. Results show that, wrinkle occurred when using C3D8R element, which was not observed in the experiment. If assigned 4 C3D8 elements through thickness, the simulation calculation is very time consuming. For SC8R element, the model seems to be numerically too soft and foil forms into an unnatural wavy shape. When using C3D8I element, the simulation run properly, as shown in Fig. 1. (b), which agrees well with experiment. Hence C3D8I was used for the current study. To add on, C3D8I element is an improved version of the C3D8 element. Particularly, shear locking is removed and volumetric locking is much reduced. This is obtained by supplementing the standard shape functions with so-called bubble functions, which have a zero value at all nodes and nonzero values in between.

3. Results and Discussion

3.1. Dimensional accuracy of the formed geometry

Workpiece dimension accuracy was determined by comparing the difference between the programmed tool path profile and the actual sample geometry. Figure 2 illustrates the workpiece geometry in comparison with the finite element simulation and the program tool path. We can see that for both thickness 50.8 μm and 38.1 μm, at the start of the process (~5mm from the center) the mismatch between the experiment and the planned tool path is evident. This is due to the bending nature at the start of the process, which has been reported previously in macro ISF [2]. It is worth noting that the horizontal dimension of the actual workpiece is smaller than the programmed tool path, which is due
to the springback of the workpiece. These phenomena can be well captured by the elasto-plastic finite element model as shown in the figure.

![Fig. 2. Shape comparison between experiments and tool path for sheet thickness of (a) 50.8μm; (b) 38.1μm](image)

### 3.2. Thickness distribution

The thickness of the workpiece was measured using optical microscope to compare with the result from finite element simulation. The thickness distributions along the cross section of the workpiece mid-plane were plotted in Fig. 3. Considering the symmetry and thickness distribution on profile of cross section in the middle line, the workpiece’s deformation could be divided into three distinctive regions as shown is Fig. 4. At the start of the ISF process, the main deformation mechanism is bending/stretching as stated previously. This was further validated by comparing the thickness distribution of the workpiece with the Sine Law prediction which only considers pure shear deformation (Fig. 3a and 3b). As bending/stretching doesn’t reduce the workpiece thickness as drastically as shear, the workpiece thickness is higher than the Sine Law prediction in the region (~4mm from the center). The second region is the near pure shear region (~3mm from the center) where the thickness continuously to drop due to decreasing apex angle. In this region, the simulation, experiment and Sine Law prediction agreed well with each other. This also provides the evidence of the monotonic relationship between the workpiece wall thickness and the half-apex angle. With the thinnest section tends to fracture first (as shown in Fig. 1.), this links the forming angle limit with the onset of the fracture directly, hence this geometry is suitable for testing the forming limit of the workpiece in terms of maximum forming angle. The third region, at the end of the process (~2mm from the center) and the corner of the workpiece, is characterized by the stretching/shear deformation around the tool tip (circled in Fig 1.). This region only became prominent when the sample thickness is small enough to allow the foil locally wrap around the tool tip (like the deformation in the stretch forming). In the thickness distribution (Fig. 3.), this region is characterized by the slower thickness recovery than that predicted by the Sine Law (~2mm from the center) due to the fact that stretching will result in further thickness reduction around the tool tip. Indicative locations of these three regions can be found in Fig. 4a and 4b. A more quantitative approach to study different deformation regions is to correlate them with the half-apex angle set in the program, which further has a monotonic relationship with the workpiece thickness after ISF.
The feed step size \( \Delta z \) has a direct impact on the formability and process time. Reducing the value of \( \Delta z \) will increase the formability, which has been reported extensively [1,4]. When the step size was too large, the axial feed in Z direction would cause large tensile stress in the foil around the tool tip and fracture in the contact region. In contrast, when the step size was too small, the forming time would increase rapidly. For our case with foil thickness 50.8 μm, the forming limit is almost constant as long as the step size is smaller than 0.18 mm, but would decrease rapidly if the value of step size goes beyond that. This indicates an optimal step size exists for micro ISF, considering the factors of both the forming limit and time. The optimal step size for foil thickness of 38.1 μm can also be found in a similar way.
as 0.16 mm.

Different sheet thicknesses possess different forming limits, which correspond to different minimum half-apex angles in the incremental forming process. The actual minimum half-apex angles (θ_{min}) could be obtained from experimental trials. For the sheet thickness of 38.1 μm, the forming height limit is ~5mm, corresponding to a θ_{min} of 31°; for the sheet thickness of 50.8 μm, the forming height limit is ~3.8mm, corresponding to a θ_{min} of 26°. This resonates with the general received knowledge that the thicker the foil is, the higher material formability [15]. This provides another proof that we can employ the current workpiece shape with varying half-apex angle as the standard geometry to test the material formability and angle limit.

4. Conclusion

To study the deformation mechanism of micro ISF process, a truncated pyramid shape with varying half-apex angle was proposed as the standard geometry for testing the material forming angle limit. Both numerical and experimental trials were carried out and compared with Sine Law. Some findings of the present study are as follow:

- The geometry fidelity of the ISF process varies at different regions, at the start of the process where bending/stretch deformation dominates, significant difference can be observed if sharp corner is present. The difference in the rest of part is mainly caused by the material springback.
- The prediction of thickness distribution by numerical simulation is close to that obtained by the experiment. Both of them indicate three regions with distinctive deformation mechanism exist: bending/stretching, shear and stretch/shear, latter of which is characteristic to the micro ISF.
- Reducing the value of feed step size would increase the formability but also the process time. Balance between the two factors will result in an optimal step size. Such step size is different for different foil thickness.
- The half-apex angle has direct link with material formability. The thicker the foil is, the smaller the half-apex angle becomes.

References